Floodwater ammonium, nitrogen use efficiency and rice yields with fertilizer deep placement and alternate wetting and drying under triple rice cropping systems

Article *in* Nutrient Cycling in Agroecosystems · January 2016

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Nutr Cycl Agroecosyst (2016) 104:53–66
DOI 10.1007/s10705-015-9758-6

ORIGINAL ARTICLE

Floodwater ammonium, nitrogen use efficiency and rice yields with fertilizer deep placement and alternate wetting and drying under triple rice cropping systems

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Received: 11 August 2015 / Accepted: 31 December 2015 / Published online: 8 January 2016

Abstract Fertilizer management should consider optimum time, rates and methods of application to increase use efficiency and crop yield. We conducted field experiments at Bangladesh Agricultural University, Bangladesh, to investigate the effects of deep placement of urea briquettes (UB) and NPK briquettes (NPK) compared to broadcast prilled urea (PU) at different N rates on dynamics of floodwater NH_4^+-N, ammonia (NH_3) volatilization, rice yield and nitrogen use efficiency (NUE) during four consecutive rice-growing seasons in 2012–2013. The floodwater NH_4^+-N and NH_3 volatilization in broadcast PU increased with N rates, while in deep-placed treatments irrespective of N rates it was similar to the control. Across seasons and water regime, UB or NPK significantly ($P < 0.05$) increased grain yield and nitrogen recovery compared to broadcast PU. During the *Boro* season (across water regime), UB78 and NPK78 increased grain yield by 40 and 29 %, respectively, compared to broadcast PU78, while N recovery increased from 35 % of PU to 63–67 % in deep placement. Deep placement of UB52 or NPK52 during *Aus–Aman* and UB78 or NPK78 during *Boro* can be one of the best N management options for increasing NUE and crop yield. Alternate wetting and drying irrigation, though, had no significant effect on grain yield or on NUE. Its adoption could save irrigation water without any yield reduction during the *Boro* season. However, more studies across different soils, climate and management practices are needed for further understanding the interactive effects of fertilizer and water management on yield, NUE and soil fertility.

Keywords Best nitrogen management · Fertilizer deep placement · Nitrogen use efficiency · Lowland rice

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Introduction

Nitrogen (N) use efficiency (NUE) of broadcast applied prilled urea (PU) in lowland rice field is only 30–45 % due to the losses from ammonia (NH_3) volatilization, surface runoff, nitrification–denitrification and leaching (Dong et al. 2012; Hayashi et al. 2008; Savant and Stangel 1990; Singh et al. 1995; Sommer et al. 2004; Watanabe et al. 2009; Zhao et al. 2009). Broadcast application of PU results in higher amounts of ammonium (NH_4^+) N in floodwater compared with deep placement of urea (Kapoor et al. 2008) that increases NH_3 volatilization. Fertilizer-N that escapes NH_3 volatilization is also susceptible to losses through nitrification and subsequent denitrification because much of the N remains near the soil surface—a partially aerobic zone (Buresh et al. 2008; Freney et al. 1990; Singh et al. 1995). Nitrification and denitrification cause atmospheric pollution due to emissions of nitrous oxide and nitric oxide. Moreover, after broadcast application of fertilizer, the high percentage of applied nutrients present in floodwater (Singh et al. 1995; Kapoor et al. 2008) increases the chance of runoff losses particularly in the situation where water flows from field to field without any drainage systems. The nutrient-enriched runoff water has the potential for environmental pollution such as eutrophication (Savant and Stangel 1990) and groundwater nitrate (NO_3^-) pollution (leaching loss). Therefore, fertilizer broadcast not only causes substantial monetary losses to farmers, but also causes a high environmental cost to the society (Mohanty et al. 1999).

In addition to N, broadcast applied P and K fertilizer could be lost via surface runoff and cause eutrophication in water bodies, particularly in rainfed rice during periods of high rainfall. There is an urgent need for alternative fertilizer management strategies that increase crop yield and maximize nutrient use efficiency. Fertilizer deep placement (FDP) of urea briquettes (UB) and N, P, K briquettes (NPK) is an effective management practice for increasing grain yield and nutrient use efficiency in lowland rice fields (Savant and Stangel 1990; Kapoor et al. 2008; Bandaogo et al. 2014) and for reducing nutrient losses, particularly from NH_3 volatilization, surface runoff of N and P (Rochette et al. 2013; Sommer et al. 2004) and from nitrification and denitrification (Chien et al. 2009) leading to reduced nitrous oxide and nitric oxide emissions (Gaihre et al. 2015). Deep-placed fertilizer remains in a reduced soil layer for a longer time, and its movement to soil surface/floodwater is negligible. Due to reduced nutrient concentration in floodwater, any water runoff from rice paddies reduces nutrient loss and the potential eutrophication problem (Chien et al. 2009; Kapoor et al. 2008; Singh et al. 1995). The deep placement of NPK through balanced fertilization also increases fertilizer use efficiency and crop production and reduces negative environmental consequences. FDP, in addition to performing well with lowland rice, also performed better in aerobic rice (Xiang et al. 2013) and upland crops such as potato (Azam et al. 2012) and cabbage (Hussain et al. 2010), showing the potential for its adoption on upland crops. Limited evaluation of FDP with NPK has taken place in India (Daftardar et al. 1997; Kapoor et al. 2008), Cambodia (Bhattarai et al. 2010) and Bangladesh (Islam al. 2011). In addition to increasing yields and improving soil fertility, it reduces labor cost because all three nutrients can be applied at the same time.

In Bangladesh, rice is grown two to three seasons per year in about 11 million hectares (ha) of land, which covers almost 80 % of the agricultural land. *Boro*, or dry season, rice is the main rice crop, and it is completely dependent upon irrigation. The need for water-saving irrigation practices such as alternate wetting and drying (AWD) is increasing in Bangladesh (Price et al. 2013; Lampayan et al. 2015) due to groundwater depletion. It is reported that AWD can reduce water use by up to 38 % while maintaining rice yield (Lampayan et al. 2015) and is expected to be widely adopted by farmers in the country. However, the effect of AWD on soil C and N dynamics and nutrient use efficiency is not well quantified, particularly with FDP. Most of the previous studies on FDP were conducted under continuously standing water (CSW) conditions. Moreover, studies on the effects of deep placement of NPK on rice cultivation are still limited under both CSW and AWD conditions. Therefore, field experiments were conducted to determine the effects of FDP and water management (AWD vs CSW) on rice yield and NUE. The specific objectives of this study were:

- To determine the effects of FDP and broadcast PU at different N rates on dynamics of floodwater NH_4-N and NH_3 volatilization.
- To assess the effects of FDP and AWD on rice yield and NUE in different rice-growing seasons.
- To determine season-specific optimum N rates for broadcast PU and FDP.

Materials and methods

Experimental site and weather conditions

The field experiments were conducted at Bangladesh Agricultural University (BAU), Mymensingh, Bangladesh (latitude: 24° 42′ 55″, longitude: 90° 25′ 47″),

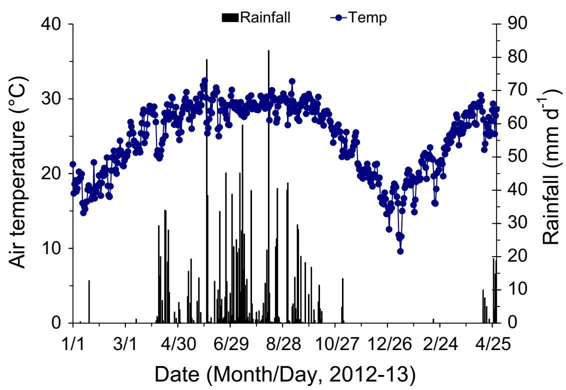

Fig. 1 Daily average of rainfall and air temperature during experiment period (Jan 2012–April 2013) (*data source* Department of Irrigation and Water Management, Bangladesh Agricultural University)

during four rice-growing seasons in January 2012–May 2013. There are three rice-growing seasons in a year, i.e., *Boro* (Dec/Jan–April/May), *Aus* (May/June–Aug/Sep) and *Aman* (Aug/Sep–Nov/Dec). The climate is humid subtropical monsoon. Average annual rainfall is ca. 1500 mm, primarily received from June to October. Daily rainfall and mean temperature for the experiment period are shown in Fig. 1. The physicochemical properties of the soil from both experiments (CSW and AWD) before start of the experiment are shown in Table 1.

Table 1 Physicochemical properties of soil before start of the experiments

Soil property	CSW	AWD
pH–H_2O	5.37	5.44
Organic carbon (%)	1.76	1.28
Total N (%)	0.17	0.14
Available P (mg kg^{-1})	2.88	3.04
Available K ($cmol_c$ kg^{-1})	0.09	0.08
Available S (mg kg^{-1})	12.66	11.07
Particle size (%)		
Sand	11.44	29.96
Silt	72.4	40.10
Clay	16.16	29.94

Experimental design and treatments

The eight treatments with different sources and rates of N fertilizer were tested (Table 2). The sources of N fertilizer were PU, UB and NPK. PU was applied as a conventional broadcast method, while UB and NPK were deep placed as described later. Treatments were arranged in a randomized complete block design with three replications. Each experimental plot (6 m × 4 m) was separated by 50 cm wide bund. Experiments were conducted under CSW condition in 2012 (all three rice growing seasons). But in *Boro* 2013, experiment was conducted under two water regimes—CSW and AWD—following the same treatments. There were slight variations in soil physicochemical properties, particularly organic carbon between CSW and AWD experiments (Table 1).

Size and numbers of briquette per placement site were determined based on the N rates. The N rates were fixed at 52, 78, 104, and 156 kg ha^{-1} for deep placement of N. The N rates for broadcast and deep placed treatments increased from the existing recommended rate. The recommended N rate for UB or NPK is 30 % less than broadcast PU, i.e., 52 and 78 kg ha^{-1}, respectively for *Aus*–*Aman* and *Boro* seasons. This is because deep placement saves 30–35 % urea compared with surface broadcast and increases yield by 15–20 % (FRG 2012; Miah et al. 2015). On the other hand, higher N rate during dry (*Boro*) season than during wet (*Aus* and *Aman*) season was due to the higher rice yield potential. N rates for NPK varied ±3 kg ha^{-1} compared with N rates of UB due to mixing ratio of three fertilizers, i.e., PU, di-ammonium phosphate (DAP) and muriate of potash (MOP). One or two briquettes of either 1.8 or 2.7 g were deep-placed at 40 cm by 40 cm spacing (62,500 placement sites per ha) (Table 2). The dice (briquetting rolls) in briquetting machine used to produce 1.8 and 2.7 g UB produced NPK of 2.4 and 3.4 g, respectively. While preparing NPK, the recommended rate of P and K were maintained.

Crop management

P (triple super phosphate, TSP) and K (MOP) fertilizers were applied basally in all the plots (except plots receiving NPK) during final land preparation at 16 kg and 25 kg P ha^{-1} and 42 kg and 64 kg K ha^{-1} in *Aus*–*Aman* and *Boro* seasons, respectively. P and K in NPK treatments were applied along with briquette. PU was applied as broadcast in three splits at 7–10 days after transplanting (DAT), at maximum tillering and at panicle initiation stages while urea, and NPK briquettes were applied at one time during the first broadcast application of PU. The briquettes were deep-placed at a depth of 7–10 cm between four hills

Table 2 Nitrogen source and rates used in the experiments during different rice-growing seasons (*Boro–Aus–Aman*)

Fertilizer/nitrogen source	N rate (kg ha^{-1})		Briq wt. (g) and no/four hills	
	Boro	*Aus–Aman*	*Boro*	*Aus–Aman*
Control	0	0	–	–
Prilled urea (PU)	78	78	–	–
	156	120	–	–
Urea briquette (UB)	78	52	2.7 (1)	1.8 (1)
	104	78	1.8 (2)	2.7 (1)
	156	104	2.7 (2)	1.8 (2)
NPK briquette (NPK)	78	52	3.4 (2)	3.4 (1)
	102	78	2.4 (3)	2.4 (2)

The treatments were same for both continuously standing water (CSW) and alternate wetting and drying (AWD) conditions for *Boro* 2013

Values in parenthesis indicates the number of briquettes used per application site; fertilizer briquettes were deep-placed between four hills of rice, PU was broadcasted in two (*Aus–Aman*) to three (*Boro*) equal splits

of rice at the alternate rows. In addition, sulfur (S) and zinc (Zn) were applied to all plots at the rate of 20 kg S ha^{-1} as gypsum and 3 kg Zn ha^{-1} as zinc oxide. Rice seedlings (two to three per hill) were transplanted at a spacing of 20 cm × 20 cm. Rice varieties grown in *Boro*, *Aus* and *Aman* seasons were BRRI dhan 28, BRRI dhan 27 and BR 22, respectively.

All the plots under CSW conditions were continuously flooded until 2 weeks before harvesting, while plots under AWD conditions (*Boro* 2013) were irrigated following safe AWD principle, i.e., plots were irrigated when water depth in AWD pipes was 12–15 cm below soil surface. However, plots were maintained continuously flooded for a week after topdressing of PU for the purpose of floodwater ammonium dynamics.

Floodwater ammonium-N (NH_4^+-N) and ammonia volatilization measurement

Floodwater samples were collected every day from each experimental plot for a week after topdressing of PU as described by Kapoor et al. (2008). After topdressing of PU, floodwater sampling was collected 2 h after application of fertilizers and then once a day from 0800 to 1000H for six consecutive days. Samples were collected in acid-washed plastic bottles and brought to the laboratory. Ammonium-N was measured with Phenol-hypochlorite method (Solorzano et al. 1969). The concentration of floodwater NH_4-N (mg L^{-1}) is converted to kg ha^{-1} after adjusting with floodwater depth. The modified ammonia volatilization equation (Freney et al. 1983) was used to determine NH_3 loss from floodwater using NH_4-N, floodwater pH and wind speed.

Rice growth, yield and nitrogen recovery

Plant samples for total dry biomass were collected two times from 1.2 m^2 (3 hills × 10 hills), first at panicle initiation (PI) stage and then at heading stage. Grain and straw yield were recorded at final harvest of the crop from 5 m^2 in each plot. In addition to the biomass, plant N content was determined at each growth stage. The total nitrogen uptake was determined at PI, heading and maturity stages to determine the N recovery by plants. Agronomic efficiency (AE_N) and recovery efficiency (RE_N) were calculated from total N uptake at harvest using following formula (Singh et al. 1999).

$$\begin{aligned} AE_N &= \text{kg grain increase kg}^{-1}\text{ N applied} \\ &= (Y_N - Y_0)/F_N \end{aligned}$$

where Y_N is rice grain yield (kg ha^{-1}) at a certain level of applied fertilizer N (F_N, kg ha^{-1}), and Y_0 is the rice grain yield (kg ha^{-1}) measured in a control plot with no N application.

$$\begin{aligned} &RE_N\left(\text{kg N taken up kg}^{-1}\text{ N applied}\right) \\ &= (U_N - U_0)/F_N \end{aligned}$$

where U_N is the total N in aboveground plant biomass (grain plus straw) at physiological maturity (kg ha^{-1}) in a plot receiving N at the rate of F_N (kg ha^{-1}), and U_0 is the total plant N without N addition.

Data analysis

ANOVA of different response variables within a season in 2012 was done using SAS mixed procedure. While ANOVA for the combination of the two experiments (AWD and CSW) in *Boro* 2013 were conducted with a split-plot generalized linear mixed model where the water regime was used as the main plot and the treatments as sub-plots. After testing errors for normality and variance homogeneity, it was decided to use the normal distribution as the probability distribution for the model, and a non-homogenous variance–covariance matrix for calculation of standard errors. Treatment, water regime, and water regime × treatment were handled as fixed effects; and replication together with the residual were handled as random effects. The effect water × treatment was tested with the residual as error term. The residual denominator degrees of freedom were used for calculations of the F statistic. Pairwise mean comparisons of interaction (water × treatment) or within water regime were done using Tukey–Kramer method.

Results

Dynamics of floodwater NH_4^+-N and ammonia volatilization

Floodwater NH_4^+-N was measured in all rice-growing seasons in 2012 and showed a similar pattern to *Boro* 2013. Magnitudes of floodwater NH_4^+-N in deep-placed treatments were negligible irrespective of N rates and growing season. Therefore, ammonium dynamics during *Boro*, *Aus* and *Aman* in 2012 is combined (Fig. 2a), but it was not combined with *Boro* 2013 because it was measured under two water regimes unlike one water regime in 2012. To synchronize N rate variations across seasons in 2012, they were categorized as low, medium and high for particular fertilizer.

The dynamics in floodwater NH_4^+-N during 2012 (average across seasons) and *Boro* 2013 under CSW and AWD conditions are shown in Fig. 2. The results clearly show that the deep placement of fertilizer N either as UB or NPK resulted in significantly lower amounts of floodwater NH_4^+-N. Even though the amount of broadcast PU was only one-third (3 split application) the rate of UB and NPK, it resulted in

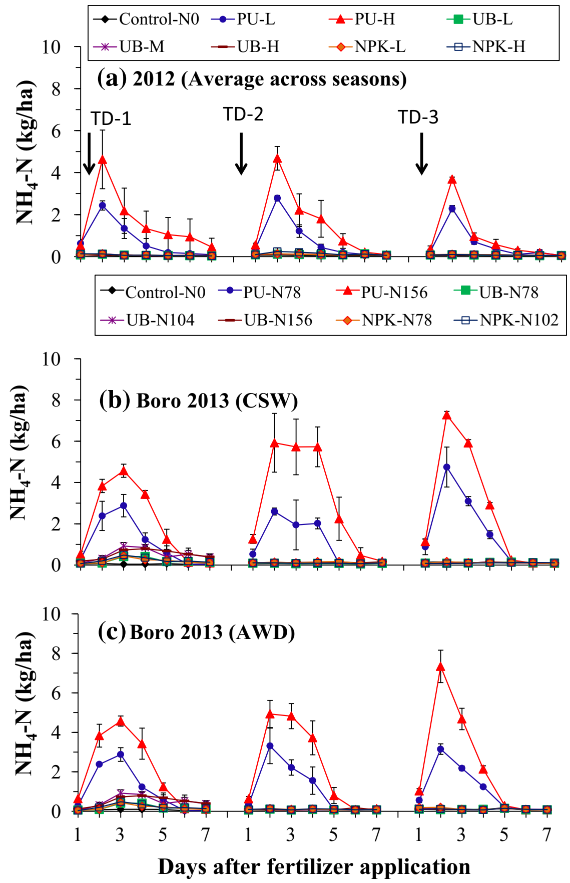

Fig. 2 Dynamics of floodwater NH_4^+-N under different N rates and application methods—broadcast PU versus deep placement of urea and NPK briquettes in 2012–2013; TD-1, TD-2 and TD-3 represent first, second and third topdressing of PU, respectively. *Vertical bars* indicate standard error of mean (n = 3). *CSW* continuous standing water, *AWD* alternate wetting and drying. PU, UB and NPK represent broadcast prilled urea, urea briquette deep placement and NPK briquette deep placement, respectively. L, M and H in 2012 represent low, medium and high N rates, respectively. Experiments in 2012 were conducted only under CSW condition

significantly higher amounts of NH_4^+-N in floodwater. Floodwater NH_4^+-N in broadcast PU treatments reached its peak (5–8 kg N ha^{-1}) at 2–3 days after its broadcast and then showed sharp decline, becoming similar to the level in the N0 treatment after 5–6 days. The amount of floodwater NH_4^+-N in PU increased with N rates. But for UB and NPK treatments, the amount of NH_4^+-N in floodwater remained negligible and was similar to the control (N0) plot throughout the 7 days of measurement period irrespective of the N rates. The magnitudes and pattern of NH_4^+-N was

Table 3 Cumulative ammonia losses across seasons, N treatments and timing of application, values are total of seven consecutive days after top dressing of PU

N source	N rate	First TD[a]		Second TD		Third TD		Total	
		NH_3-N (kg ha^{-1})	N (%)	NH_3-N (kg ha^{-1})	N (%)	NH_3-N (kg ha^{-1})	N (%)	NH_3-N (kg ha^{-1})	N (%)
Boro 2012									
Control	0	0.48b	–	0.51b	–	0.62c	–	1.61c	–
PU	78	3.61b	12.33	4.61b	15.80	3.69b	11.83	11.92b	13.23
	156	8.92a	16.36	10.92a	20.02	11.55a	21.02	31.38a	19.08
UB	78	0.80b	0.50	0.90b	0.50	0.73c	0.15	2.43c	1.05
	104	0.95b	0.52	0.98b	0.46	0.75c	0.13	2.68c	1.03
	156	0.88b	0.30	0.92b	0.26	0.77c	0.10	2.57c	0.62
NPK	78	0.95b	0.70	0.99b	0.62	0.93c	0.40	2.88c	1.63
	102	1.10b	0.68	1.57b	1.04	0.80c	0.18	3.47c	1.83
Aus 2012									
Control	0	1.73c	–	1.49c	–	1.28c	–	4.49c	–
PU	78	6.26b	17.45	6.04b	17.49	4.23b	11.36	16.53b	15.44
	120	10.01a	20.70	11.45a	24.90	7.41a	15.33	28.87a	20.31
UB	52	1.78c	0.10	1.56c	0.13	1.35c	0.13	4.68c	0.36
	78	1.82c	0.13	1.58c	0.12	1.41c	0.17	4.82c	0.41
	104	1.89c	0.16	1.62c	0.13	1.47c	0.18	4.98c	0.47
NPK	52	1.84c	0.22	1.64c	0.29	1.39c	0.21	4.86c	0.72
	78	1.89c	0.21	1.62c	0.17	1.44c	0.21	4.95c	0.59
Aman 2012									
Control	0	0.76b	–	0.25b	–	0.32b	–	1.32c	–
PU	78	3.22a	9.46	2.97a	10.50	2.51a	8.41	8.70b	9.46
	120	4.10a	8.35	3.75a	8.76	3.64a	8.31	11.49a	8.47
UB	52	0.78b	0.05	0.23b	−0.03	0.27b	−0.09	1.29c	−0.07
	78	0.81b	0.06	0.21b	−0.04	0.32b	0.00	1.34c	0.02
	104	0.80b	0.04	0.22b	−0.02	0.33b	0.02	1.36c	0.04
NPK	52	0.77b	0.03	0.21b	−0.06	0.31b	−0.02	1.29c	−0.06
	78	0.77b	0.02	0.20b	−0.05	0.28b	−0.05	1.25c	−0.09
Boro 2013									
Control	0	0.36c	–	0.59c	–	0.99c	–	1.93c	–
PU	78	5.08b	18.16	5.45b	18.71	9.65b	33.32	20.18b	23.40
	156	9.42a	17.43	16.29a	30.19	18.41a	33.51	44.12a	27.04
UB	78	1.06c	0.91	0.60c	0.02	0.97c	−0.02	2.64c	0.91
	104	2.26c	1.83	0.66c	0.07	0.96c	−0.02	3.88c	1.88
	156	2.31c	1.26	0.84c	0.16	0.95c	−0.02	4.11c	1.39
NPK	78	0.99c	0.81	0.86c	0.34	1.01c	0.02	2.85c	1.17
	102	0.82c	0.82	0.67c	0.08	0.96c	−0.02	2.83c	0.88

Within a column and season, means followed by same letters are not significantly different at 5 % probability level by Tukeys's honest significant difference (HSD) test

PU prilled urea, *UB* urea briquette, *NPK* fertilizer briquette containing NPK

[a] Fertilizer briquettes were deep-placed at a time during first topdressing of PU

similar in all three split measurements. Similarly, magnitudes and pattern of the NH_4^+-N in floodwater were similar between CSW and AWD conditions during *Boro* 2013.

Ammonia volatilization was calculated using floodwater ammonium, temperature and wind speed. As with floodwater ammonium, magnitudes of ammonia loss from deep-placed treatments were negligible. They were significantly higher from broadcast treatments compared with deep-placed treatments, which increased with increasing N rates (Table 3).

Rice growth, yield and agronomic efficiency

Biomass accumulation at panicle initiation (PI), heading and maturity stages during different rice-growing seasons are shown in Figs. 3 and 4. In general, total biomass accumulation at all growth stages increased with N rate irrespective of method of application. At each growth stage, response of increasing N rate on biomass accumulation was more distinct at PU treatments (except during *Aus* 2012) compared with deep-placed treatments. In deep-placed treatments, increase in total biomass accumulation was higher at lower N rates; therefore, increasing N rates had lower response, indicating more efficient use of N at lower rate.

The ANOVA of grain yield and yield components and their mean comparison is shown in Table 4. Response of N rates on grain yield was not consistent among the seasons. Generally, grain yield increased with N rate in PU during *Aman* and *Boro* seasons but not during the *Aus* season; while for FDP treatments, increasing N rate did not have significant effects on grain yield in any season. Nevertheless, in *Aman* season, deep placement of UB52 and NPK 52 significantly increased grain yield by 8–15 % compared to PU78. However, during the *Aus* season, a grain yield increase of 5–12 % was not significantly different for UB52 and NPK52 versus PU78.

During the *Boro* season, UB78 or NPK78 increased grain yield by 40–46 % in 2012 and by 29–39 % in 2013 over PU78. Deep placement of UB156 increased yield by only 11 % over PU156. Though the NPK deep placement increased grain yields significantly over broadcast PU, it did not have significant yield

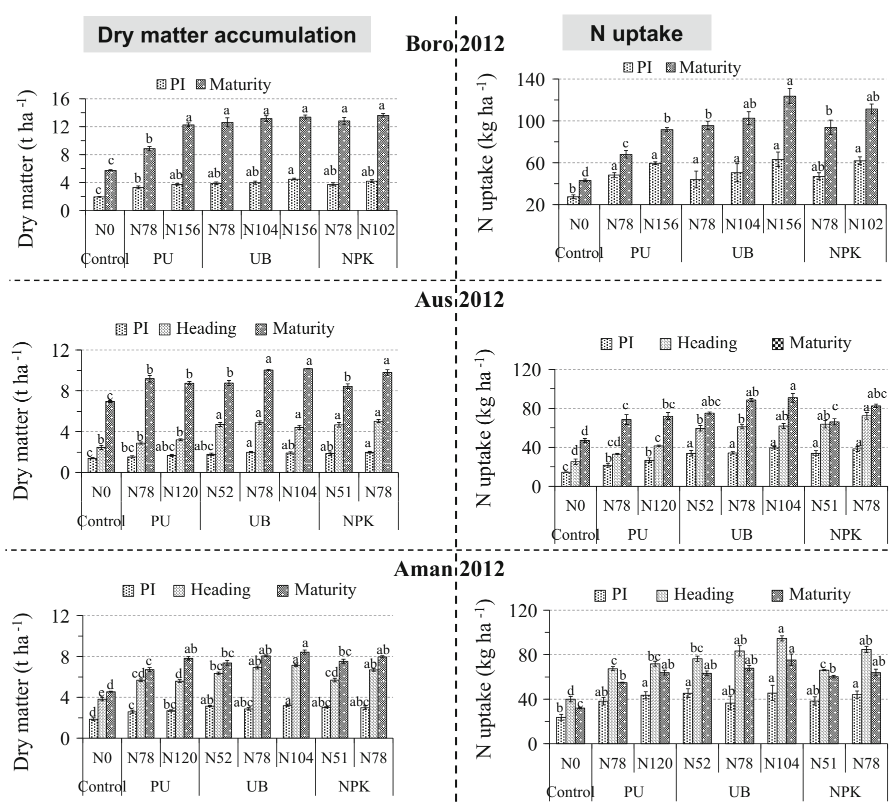

Fig. 3 Accumulation of biomass (dry matter) and nitrogen at different growth stages of rice in *Boro*, *Aus* and *Aman* seasons in 2012. *Vertical bar* indicates standard error of mean (n = 3). Within a growth stage and response variable, means followed by same letters are not significantly different at $P \leq 0.05$. All experiments were conducted under CSW conditions. *PU* broadcast prilled urea, *UB* deep placement of urea briquettes, *NPK* deep placement of NPK briquettes; in x-axis, numbers followed by N represent kg N ha^{-1}

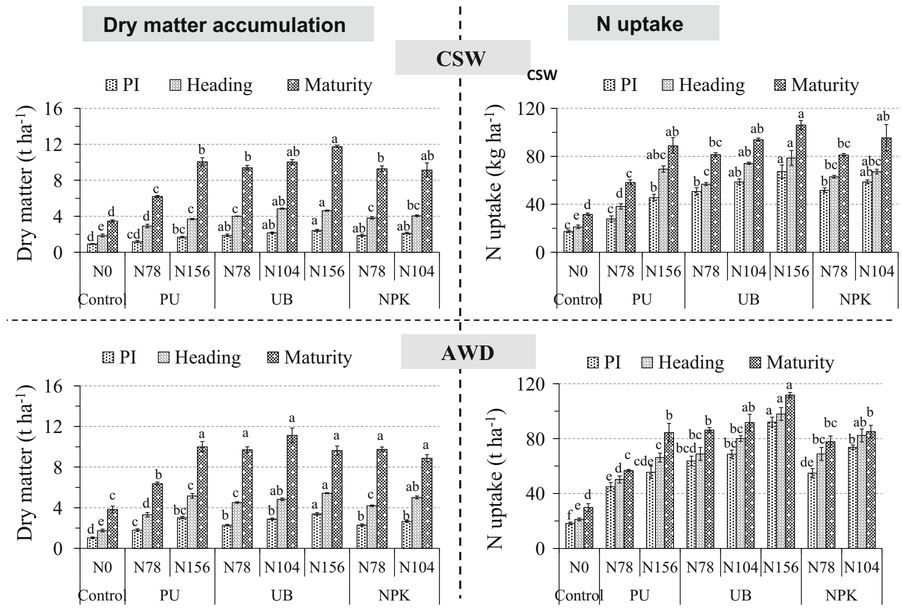

Fig. 4 Accumulation of biomass (dry matter) and nitrogen at different growth stages of rice in *Boro* 2013 under CSW and AWD conditions. *Vertical bar* indicates standard error of mean (n = 3). Within a growth stage and response variable, means followed by same letters are not significantly different at $P \leq 0.05$. *PU* broadcast prilled urea, *UB* deep placement of urea briquettes, *NPK* deep placement of NPK briquettes; in x-axis, numbers followed by N represent kg N ha^{-1}

increase over UB deep placement. The higher grain and straw yield in deep-placed treatments were associated with higher numbers of panicles (effective tillers) per hill and spikelet per panicle (Table 4).

Agronomic efficiency of N (AE_N) was significantly affected by fertilizer treatment in all rice-growing seasons. In deep-placed treatments, the highest AE_N was observed at its lower N rates (Table 4). In *Aus* and *Aman* seasons, significantly higher (20–25 kg kg^{-1} N) AE_N was observed with UB52 or NPK52 compared to PU78 (10–12 kg kg^{-1} N). In *Boro* season, AE_N of UB78 or NPK78 was significantly higher (38–46 kg kg^{-1}N) than broadcast PU78 (19–22 kg kg^{-1}N).

Nitrogen uptake and recovery

N uptake at different crop growth stages increased with N rate irrespective of its method of application (Figs. 3, 4). Highest total N uptake (grain and straw) was observed at UB104 in *Aus–Aman* seasons and at UB156 during *Boro* season. Though magnitude of uptake increased with growth stages, the pattern of uptake among fertilizer treatments was similar between PI and heading and maturity stages. However, in *Aman* 2012, slightly lower N accumulation was observed at maturity stage than at heading stage. Across fertilizer treatments, higher N uptake was observed during *Boro* than during *Aus–Aman* seasons. Contrary to fertilizer treatments, N uptake from N0 plot was higher during *Aus–Aman* seasons than during *Boro* season, probably due to increased N supply from biological N fixation, rainwater and increased N mineralization (Cassman et al. 1996; Timsina et al. 2001).

Nitrogen recovery (RE_N) at maturity showed a similar trend with AE_N, higher in lower N rates particularly in UB and NPK treatments (Table 5). Deep placement of UB52 or NPK52 during *Aus–Aman* increased RE_N up to 54–60 % from 27–29 % of PU78. Similarly, RE_N at UB78 or NPK78 in *Boro* season increased up to 64–67 % from 32–34 % of PU78. RE_N decreased with increasing N rate except at NPK78 during *Aus* 2012. Deep placement of UB and NPK, particularly at its lower N rate increased RE_N consistently over PU at all rice growth stages in *Aus–Aman* 2012 and *Boro* 2013. Moreover, RE_N in deep-placed treatments increased consistently with plant growth stages during *Boro* season. On the other hand, RE_N for all treatments decreased at maturity stage compared to heading stage during the *Aus* season. RE_N for PU remained almost similar at all growth stages during the *Aman* and *Boro* seasons.

Effects of water regimes on grain yield and nitrogen use efficiency

Rice cultivation in *Aus* and *Aman* (wet season) was rainfed. Water saving irrigation (AWD) was practiced only during *Boro* season. For *Boro* 2013, ANOVA of

Table 4 Grain yield, yield components and agronomic efficiency (AE_N) in different fertilizer treatments in *Boro*, *Aus* and *Aman* 2012 and *Boro* 2013

N source	N rate	Grain yield (t ha^{-1})[a]	Effective tillers $hill^{-2}$	Spikelets $panicle^{-1}$	1000 grain weight (g)	Agronomic efficiency (AE_N)
Boro 2012						
Control	0	3.03c	8.2d	96c	23.7a	–
PU	78	4.57b	13.2b	140ab	24.3a	19.7c
	156	6.04a	13.2b	147ab	23.4a	19.3c
UB	78	6.66a	9.7cd	120bc	23.9a	46.5a
	104	6.75a	11.6bc	142ab	23.6a	35.7b
	156	6.68a	13.0b	138ab	23.6a	23.4c
NPK	78	6.41a	14.2ab	135ab	23.9a	43.3ab
	102	6.69a	16.0a	159a	23.8a	35.9b
Aus 2012						
Control	0	3.50c	7.5b	77a	22.8b	–
PU	78	4.37ab	8.9ab	84a	23.5ab	11.1ab
	120	4.13b	9.8a	81a	23.8a	5.3b
UB	52	4.73ab	10.0a	91a	23.5a	23.7a
	78	4.63ab	9.8a	87a	23.4ab	14.4ab
	104	4.57ab	10.0a	88a	23.9a	10.3ab
NPK	52	4.57ab	10.0a	92a	23.5a	21.0a
	78	4.93a	9.7a	93a	23.7a	18.4ab
Aman 2012						
Control	0	2.12c	6.6d	56c	25.9a	–
PU	78	2.97b	7.2cd	59bc	29.4a	10.8b
	120	3.71a	8.5a	71a	25.9a	13.2ab
UB	52	3.42ab	7.5abcd	69ab	28.1a	25.0a
	78	3.58ab	8.0abc	71a	27.4a	18.8ab
	104	3.95a	7.7abcd	74a	29.3a	17.5ab
NPK	52	3.34ab	7.3bcd	67ab	28.8a	23.9a
	78	3.80a	8.3ab	76a	26.6a	21.5ab
Boro 2013 (Average of CSW and AWD)						
Control	0	2.37d	7.3d	66d	22.0b	–
PU	78	4.07c	9.3c	91c	22.4ab	21.9c
	156	5.55ab	10.5bc	97bc	23.0ab	20.4c
UB	78	5.68ab	11.7ab	111a	22.5ab	42.4a
	104	6.00a	12.2a	107a	22.3ab	34.9b
	156	6.14a	12.1ab	105ab	23.6a	24.2c
NPK	78	5.24b	11.8ab	105ab	23.0ab	36.8ab
	102	5.55ab	11.8ab	102ab	23.1ab	31.2b
ANOVA (*Boro* 2013)						
Water regime (W)		NS	NS	NS	NS	NS
Fertilizer treatment (T)		*	*	*	*	*
W × T		NS	NS	NS	NS	NS

Within a column and season, means followed by same letters are not significantly different at 5 % probability level by Tukeys's honest significant difference (HSD) test

AE_N agronomic efficiency (kg grain/kg N), *CSW* continuous standing water, *AWD* alternate wetting and drying, *PU* prilled urea, *UB* urea briquette, *NPK* fertilizer briquette containing NPK

* Significant difference at $P \leq 0.05$

[a] Grain yield is at 14 % moisture content

Table 5 Changes in recovery efficiency of fertilizer N over crop growth stages, N treatments and seasons

N source	N rate	Recovery efficiency (RE_N)		
		PI	Heading	Maturity
Boro 2012				
PU	78	0.40a	–	0.32bc
	156	0.31a	–	0.31c
UB	78	0.21a	–	0.67a
	104	0.22a	–	0.57ab
	156	0.23a	–	0.52abc
NPK	78	0.31a	–	0.65a
	102	0.34a	–	0.67a
Aus 2012				
PU	78	0.18d	–	0.27bc
	120	0.20 cd	–	0.21c
UB	52	0.37ab	–	0.54a
	78	0.25bcd	–	0.53a
	104	0.24 cd	–	0.42ab
NPK	52	0.38a	–	0.37abc
	78	0.30abc	–	0.45ab
Aman 2012				
PU	78	0.37a	0.35bc	0.29c
	120	0.33a	0.27c	0.26c
UB	52	0.42a	0.70a	0.60a
	78	0.17a	0.56a	0.46ab
	104	0.21a	0.53ab	0.42abc
NPK	52	0.29a	0.51ab	0.55ab
	78	0.26a	0.57a	0.41bc
Boro 2013 (CSW)				
PU	78	0.20b	0.22d	0.34b
	156	0.27ab	0.31 cd	0.37b
UB	78	0.43a	0.46ab	0.64a
	104	0.40a	0.51a	0.60a
	156	0.32ab	0.37bc	0.48ab
NPK	78	0.43a	0.56a	0.63a
	102	0.40a	0.45ab	0.63a

Within a column and season, means followed by same letters are not significantly different at 5 % probability level by Tukeys's honest significant difference (HSD) test

RE_N recovery efficiency (kg N uptake/kg N), *PU* prilled urea, *UB* urea briquette, *NPK* fertilizer briquette containing NPK

biomass yield, N uptake and AE_N was done separately to see the effect of water management and its interaction with fertilizer treatments (Table 4). Though all the parameters were affected by fertilizer treatments, none of them was affected by water management. However, significant interaction was observed between fertilizer treatment and water regime on aboveground biomass (Fig. 4). Straw yield and total aboveground biomass were significantly higher in UB N156 under CSW condition.

Discussion

Dynamics of ammonium in floodwater and ammonia volatilization

Deep placement of UB and NPK significantly reduced the amount of NH_4^+-N in floodwater (Fig. 2). When fertilizer briquettes were deep-placed, the movement of NH_4^+ from the deep soil layer to the soil's surface or floodwater was very slow (Fig. 2; Rochette et al. 2013). Therefore, a very low to negligible amount of floodwater NH_4^+-N was observed in UB and NPK. On the other hand, in broadcast PU, a significant amount of NH_4^+ from urea hydrolysis was present in floodwater and could be lost via NH_3 volatilization and surface run off. The amount of floodwater NH_4^+-N could be a good indicator to estimate potential NH_3 volatilization loss (Hayashi et al. 2006; Rochette et al. 2013). This was evident from estimated NH_3 volatilization which showed a similar trend with floodwater ammonium, i.e., significantly higher emissions from PU treatments compared to deep-placed treatments (Table 3). This trend was consistent across all rice-growing seasons. However, in addition to floodwater NH_4-N, the NH_3 volatilization can be affected by other factors including pH, water temperature, water depth and wind speed (Hayashi et al. 2008). Since these factors changes with season (and site), the magnitudes of NH_3 volatilization may vary across seasons.

The sharp decline in the amount of floodwater NH_4^+-N from 2 to 3 days after urea broadcast may be attributed to volatilization loss, diffusion of NH_4^+-N into soil, and/or nitrification in the oxidized soil layer (Kapoor et al. 2008). Watanabe et al. (2009) observed similar results, peaks in the ammonia flux at 1–3 days of urea application followed by a sharp decline. This clearly suggests that the NH_4^+-N present in floodwater is volatilized, nitrified to nitrate, and plant uptake (Figs. 3, 4); thus, its magnitude decreased sharply after its peak at 2–3 days of application. Since there is negligible floodwater NH_4^+-N in UB and NPK treatments irrespective of N rates and seasons, deep placement can significantly reduce potential N losses from ammonia volatilization and surface run off over broadcast PU.

Effects of FDP on rice growth and yield

The benefits of UB deep placement (commonly called urea deep placement, UDP)—increased NUE, 30 % urea-savings and increased grain yield compared to broadcast application in lowland rice fields—are well documented. In this study, deep placement of either UB or NPK significantly ($P < 0.05$) increased the grain yield at 52 kg N ha^{-1} during *Aus–Aman* and at 78 kg N ha^{-1} during *Boro* compared with broadcast PU. These results are in close agreement with previous studies (Kapoor et al. 2008; Mohanty et al. 1999) that UB deep placement saves urea by up to 50 % compared to broadcast PU without significant yield loss. The yield advantage, particularly at lower N rate, could be attributed to increased plant uptake or doubling of the fertilizer N recovery (Table 4). There was a significant positive correlation between grain yield and N recovery ($R^2 = 0.52$, $P < 0.001$), particularly during *Boro* season. Several field research conducted in Bangladesh showed that UB deep placement with 30 % less urea produced up to 20 % higher yield (Savant and Stangel 1990; Gregory et al. 2010; IFDC 2013). Therefore, recommended N rate for rice in this region, based on past fertilizer trials, was adjusted to 30 % less at 52 and 78 kg N ha^{-1} for UB deep placement, compared to 78 and 112 kg N ha^{-1} of broadcast PU, for *Aus–Aman* and *Boro* seasons, respectively (FRG 2012). Our results confirm that the UB52 and UB78 recommendations could continue for increasing grain yields and NUE in *Aus–Aman* and *Boro*, respectively, in areas with climate, soils and management similar to this experimental site.

Though UB deep placement has been practiced for a long time in Bangladesh, the deep placement of NPK briquettes to farmers has recently been introduced. One of the major benefits of NPK deep placement over UB deep placement is to ensure balanced fertilization. Apart from the agronomic and environmental benefits that are achieved with UB, NPK deep placement eliminates the need for multiple fertilizer applications, as is the standard practice, and consolidates the labor requirement compared to UB deep placement and broadcast incorporation of P and K. Deep placement of NPK in Bangladesh is being practiced not only in rice, but also in upland crops (Azam et al. 2012; Islam et al. 2011; IFDC 2015; Miah et al. 2015). Moreover, its application is expanding in other south-east Asian countries such as Cambodia (Bhattarai et al. 2010). The use of multi-nutrient fertilizer briquettes is also reported in India where deep placement of urea-DAP briquettes increased grain yield by 45–89 % over farmers' practice and by 27–52 % over recommended management practice (Daftardar et al. 1997). Similarly, Kapoor et al. (2008) observed increased grain yields and NUE by NPK deep placement over UDP in eastern India. Contrary to their study, NPK response was similar to UDP in this study, probably because the soil had low available P (3 mg kg^{-1}), which might have affected plant P uptake due to the time lag for the roots to access deep-placed P versus uniformly-broadcast P, particularly during early plant establishment. This may result in poor crop growth and affect yields. Such an effect will be crucial for soils with low to very low P status (Kapoor et al. 2008). Thus, the deep placement of P and K should be site specific and generally not recommended for soils with very low P and K status in terms of rice yield response. In spite of low P status, our results showed that the deep placement of NPK did not have any significant negative effects on the yields compared with UB deep placement and significantly increased rice yields over broadcast PU. Nevertheless, NPK may have significant effects over UB in farmers' fields because farmers use more N and less P and K fertilizers. Use of NPK ensures a balanced supply of nutrients and increased yields as well as soil fertility. Miah et al. (2015) evaluated UB and NPK across different districts in southern Bangladesh where NPK increased grain yield and economic returns compared to UB.

Comparison of NUE between broadcast and deep placement

Across all the seasons, total N uptake was higher with FDP (UB and NPK) at each application rate compared with broadcast PU following the same trend with total biomass. Higher N uptake in deep-placed treatments might be due to increased availability of applied N (lower N losses) for plant growth resulting in increased N content of straw and grain (data not shown) and increased aboveground biomass (Figs. 3, 4). The total N uptake (including straw) in this study ranged from 13 to 18 kg per ton of rough rice similar with the ranges reported in previous studies (Choudhury and Kennedy 2005; Kapoor et al. 2008; Dong et al. 2012).

UB and NPK increased N recovery efficiency by almost double and agronomic N efficiency by up to 29 % (kg grain kg^{-1} N) over broadcast PU. At 78 kg N ha^{-1} (*Boro*), UDP increased N recovery up to 64–67 % from 35 % of broadcast PU. Even with a single fertilizer application, N recovery consistently increased up to heading to maturity stages (Table 4) suggesting that deep placement supplied N continuously throughout the growing period. These results also confirmed that deep placement of NPK is equally effective as UB for increasing fertilizer N use efficiency in lowland rice fields as compared with the broadcast PU. The increase in NUE could be mainly due to reduction of losses from NH_3 volatilization, surface run off, nitrification and denitrification (Savant and Stangel 1990; Mohanty et al. 1999), which was evident from negligible amount of NH_4^+ in floodwater (Fig. 2), estimated NH_3 volatilization loss and increased plant uptake and N recovery (Table 3). When N is deep-placed in a reduced zone (anaerobic zone), most of the N is retained in soil as NH_4^+-N for a longer time, ensuring continuous availability of N for the rice crop (Kapoor et al. 2008). Increased NUE with UB was also reported in West Africa (Bandaogo et al. 2014). In general, decreased AE_N and RE_N are expected when N rate is increased beyond the recommended rates with greater opportunities for N losses. Generally, losses increase when N is applied in excess of plant uptake (Liang et al. 2013).

Effects of water regimes

Most previous studies have shown that the water-saving AWD irrigation practice has no significant effect on grain yield compared to farmer practice, i.e., continuous flooding. In a recent review study, Lampayan et al. (2015) reported that AWD saves irrigation water by up to 38 % without reducing grain yields. In this study, water regime had no significant effect on grain yields in any fertilizer treatments because soil drying in AWD plots was very mild, which did not affect rice growth. However, only one season of data would not be sufficient to see the long-term effects of AWD on rice production as well as changes in soil fertility status such as organic C and N. More studies are needed to understand the interaction effect of AWD and FDP for sustainable rice production while coping with water scarcity.

Conclusions

Deep placement of UB and NPK significantly reduced floodwater NH_4-N and NH_3 volatilization compared with broadcast PU. Across seasons and years, UB and NPK increased grain yields and NUE (AE_N and RE_N) over broadcast PU. The effect of deep placement on grain yield was distinct and significant at lower N rates than that of higher rates and in *Boro* season than in *Aus–Aman*. Among all rice-growing seasons (except *Aus* 2012), increase N rate in PU increased yields significantly. But in deep-placed treatments, the effects of increasing N rates on grain yields were not significant, confirming the current N recommendation rate for FDP as used in this study is appropriate. Significantly higher N recovery efficiency ($P < 0.05$) was observed in deep-placed treatment at its recommended N rates (52 kg N ha^{-1} in *Aus–Aman* and N78 kg N ha^{-1} in *Boro*) than broadcast PU (64–72 vs 32–35 %). Since grain yield at UB or NPK at 52 kg or 78 kg N ha^{-1} was not significantly different compared with PU120 or PU156, deep placement may save up to 50 % urea without any yield penalty.

The difference in grain yields and NUE between UB and NPK were not significant. However, deep placement of NPK in farmers' fields increased grain yield and nutrient use efficiency and net economic returns (Miah et al. 2015). Based on grain yield and NUE, the existing recommended N rate 52 kg N ha^{-1} for *Aus* and *Aman* seasons and 78 kg N ha^{-1} for *Boro* as UB or NPK could be continued for rice production in the areas with soils, climate and management similar to this study site. On the other hand, AWD did not have significant effects on grain yields and NUE, suggesting that deep placement is equally effective under AWD conditions. Combination of both FDP and AWD technologies in rice cultivation could increase fertilizer use efficiency, save water (*Boro* season) and increase grain yields. However, these results were from the experiment conducted in one location, more studies across different soils, climate and management practices are needed to understand the site and season specific response of fertilizer and water management and their possible interaction effects on yields, NUE and soil fertility.

Acknowledgments The United States Agency for International Development (USAID) provided support for this research through the project "Accelerating Agriculture Productivity Improvement-Integrating Greenhouse Gas Emissions Mitigation into the Feed the Future Bangladesh Fertilizer Deep Placement Rice Intensification (cooperative agreement number AID-388-A-10-00002)."

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