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ORIGINAL ARTICLE

Rice yields and nitrogen use efficiency with different fertilizers and water management under intensive lowland rice cropping systems in Bangladesh

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Abstract Optimum nitrogen rates and methods of application increase crop productivity and farm income while reducing negative environmental effects. Field experiments were conducted during four consecutive rice growing seasons in 2012–2013 to determine the effects of different N rates and methods of fertilizer application on floodwater ammonium concentration, rice yields and N use efficiency under two water regimes: continuous standing water and alternate wetting and drying (AWD). Fertilizer treatments included the use of deep placed urea briquettes and NPK briquettes (NPK), broadcast prilled urea (PU) and a control (without N). Deep placed fertilizer treatments irrespective of N rates and water regimes reduced floodwater ammonium similar to the control treatment, while broadcast PU treatment caused floodwater ammonium to increase as N rates increased. Deep placement of fertilizer above 52 and 78 kg N ha^{-1} during the *Aus*–*Aman* seasons (wet seasons) and during the *Boro* season (dry season), respectively, had no significant effects on grain yields but reduced N recovery. Although the differences in grain yields among deep placed and PU treatments were not significant, deep placement of 30 % less N compared to broadcast PU significantly increased N recovery (30–35 % vs. 48–55 %). AWD irrigation increased grain yield by 16 % along with increased harvest index, particularly under deep placed treatments. However, the effects of AWD on yield varied with seasons suggesting the need for long-term studies across different rice growing seasons and sites to arrive at more definitive conclusions.

Keywords Bangladesh · Fertilizer deep placement · Nitrogen management · Lowland rice · Alternate wetting and drying

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Introduction

Nitrogen (N) is one of the most important plant nutrients and plays a crucial role in increasing crop production and farm income. Nitrogen fertilizer consumption is increasing along with world crop production. However, more than 50 % of applied N is not assimilated by the rice plant, particularly when N fertilizer is applied using conventional broadcast methods. Most of the N not assimilated by the plant is lost through different mechanisms including ammonia (NH_3) volatilization, surface runoff, nitrification–denitrification and leaching (Dong et al. 2012; Rochette et al. 2013; Savant and Stangel 1990). Among these loss mechanisms, the most significant amount of loss occurs through NH_3 volatilization which reaches up to 50 % of applied N (Sommer et al. 2004). These losses decrease N use efficiency (NUE) of conventional split broadcast prilled urea (PU) (Savant and Stangel 1990; Sommer et al. 2004).

Under submerged soil conditions, urea is hydrolyzed to ammonium (NH_4^+) and bicarbonate anion, which results in a temporary increase in floodwater pH (Singh et al. 1995). The increase in pH favors the production of NH_3 from NH_4^+ ($NH_4^+ + OH^- \rightarrow NH_3 + H_2O$). Volatilization loss increases with NH_4^+ concentration in floodwater (Hayashi et al. 2006), which increases with broadcast PU (Kapoor et al. 2008). However, the dynamics of NH_4^+ in floodwater may vary from season to season depending upon weather and soil conditions. The floodwater NH_4^+ may lost through surface runoff in rainfed ecosystems and in the areas where farmers has no control over irrigation. The magnitude of losses by different mechanisms varies with soil and environmental conditions and with management practices regarding the time, rates and methods of applications. Losses of broadcast applied N increase with increasing N rates. Therefore, increasing N use has negative environmental consequences including nitrate pollution, eutrophication and emissions of greenhouse gas nitrous oxide and atmospheric pollutant nitric oxide (Gaihre et al. 2015; UNEP 2013, 2014).

Alternative N fertilizer management strategies that increase crop productivity and NUE while reducing negative environmental consequences are needed. Management practices, therefore, should focus on optimum time, rate and placement methods that synchronize plant N requirements with N supply to reduce N losses and maximize uptake of applied N in the crop. In lowland rice fields, fertilizer deep placement (FDP: deep placement of any fertilizers briquettes, either urea or multi-nutrient briquettes containing N, P and K), particularly urea deep placement (UDP) is one of the best N management practices to achieve these multiple benefits (IFDC 2013; Savant and Stangel 1990). Deep placed N in a reduced zone reduces NH_4-N concentration in floodwater (Kapoor et al. 2008), resulting in a reduction in N loss from surface runoff and ammonia volatilization (Huda et al. 2016; Rochette et al. 2013; Sommer et al. 2004), while ensuring a continuous supply of N to the plants. Moreover, UDP reduces N loss from nitrification and denitrification (Chien et al. 2009). With the reduction of N losses from the soil, plant N recovery increases.

In developing countries such as Bangladesh, farmers do not often use balanced fertilization practices. They often use excessive N fertilizer (urea) and relatively less P and K fertilizers (Quamruzzaman 2006), along with little or no secondary and micronutrient fertilizers. Over time, these practices not only affect crop productivity but also soil fertility. Therefore, to promote balanced fertilization and reduce fertilizer use, the Government of Bangladesh, with support from the International Fertilizer Development Center (IFDC), is disseminating multi-nutrient fertilizer briquettes that contain N, P and K (NPK briquettes, hereafter NPK). Deep placement of NPK is gradually gaining in popularity not only for rice, but also for upland crops such as vegetables (Azam et al. 2012; Bhattarai et al. 2010). Deep placement of NPK has additional benefits as compared to UDP; for example, it supplies all primary nutrients at once and saves additional labor required for broadcast application and incorporation of separate P and K during land preparation. Moreover, deep placement of NPK reduces the loss of P and K as surface runoff, particularly during wet seasons, and thereby reduces eutrophication in water bodies. NPK deep placement can therefore help to increase nutrient use efficiency and reduce negative environmental consequences (Kapoor et al. 2008).

In Bangladesh, rice is cultivated in three rice growing seasons per year: the *Aus* (pre-monsoon, May–August) and *Aman* (monsoon, July/August–November/December) seasons are wet seasons, while the *Boro* season is the dry season (January–May) and is fully irrigated. Among these three seasons, area and production of *Boro* rice is higher than *Aus* and *Aman* rice. *Boro* rice cultivation requires high amounts of irrigation water. Although Bangladesh is commonly recognized as a country dominated by abundant water, some regions experience water shortage, particularly during the *Boro* season. As groundwater is the major water source for irrigated rice cultivation, the ongoing intensification of rice production adds additional pressures to underground water resources (Kürschner et al. 2010). With the depletion of groundwater, the cost of pumping increases, leading to increased irrigation costs for farmers. Therefore, the importance of water saving irrigation methods such as alternate wetting and drying (AWD) is increasing; AWD saves irrigation water by up to 38 % without any yield penalty (Lampayan et al. 2015). AWD technology is therefore expected to be widely adopted by farmers in the country for *Boro* rice cultivation.

Although AWD saves water and reduces irrigation cost, its effects on rice yield vary depending on its management (timing and intensity of drying) and soil conditions. Previous studies reveal contradictory results (Bouman and Tuong 2000; Lampayan et al. 2015; Richards and Sander 2014). Moreover, the change of water management from continuous flooding to AWD may affect the dynamics of soil carbon (C) and N, and soil fertility. AWD makes soil C and N unstable compared with continuous flooding, and it increases C and N losses to the environment. Most fertilizer management practices (for example, broadcast PU or deep placement of UB or NPK) were widely tested under continuously flooded conditions, which means that the effects of these N management practices on yield and NUE under AWD irrigation practices is not yet clear. Moreover, studies on the effects of deep placement of NPK on rice and NUE are lacking. Therefore, we conducted field experiments to compare the effects of broadcast PU and the deep placement of UB or NPK on floodwater ammonium, NUE and yield under different water regimes with the following specific objectives:

- To compare floodwater NH_4-N dynamics between broadcast PU and deep placed urea briquette (UB) or NPK at different N rates across different rice growing seasons.
- To compare the effects of broadcast PU and deep placed UB or NPK at different N rates on N uptake, NUE and yield under continuous standing water (CSW) and AWD conditions.
- To assess the interaction effects of fertilizer and water regimes on yield and NUE.

Materials and methods

Experimental site and weather conditions

The field experiments were conducted at the Bangladesh Rice Research Institute (BRRI), Gazipur (latitude: 23°59′25″, longitude: 90°24′33″) during four consecutive rice growing seasons in 2012–2013. *Boro* is the dry season rice and grown from January/February–April/May. *Aus* (May/June–August/September) and *Aman* (July/August–November/December) are wet season rice. The climate is humid subtropical monsoon. Average annual rainfall is about 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 (soil type) before the start of the experiment are shown in Table 1.

Experimental design and treatments

The fertilizer treatments with different sources and N rates (Table 2) were arranged in a split-plot design with three replications. Water regimes, i.e., continuous standing water (CSW) and alternate wetting and drying (AWD) were considered as main plots, while fertilizer treatments were as sub-plots. Fertilizer treatments were combinations of N rates and methods of application, i.e. broadcast PU versus deep placement of UB and NPK. N rates either for PU or briquettes were different between *Aus* and *Aman* and *Boro* based on seasonal crop requirements. Each season, lower N rates (excluding control) started with the existing recommended rate, they were 52 and 78 kg N ha^{-1} for deep placement and 78 and 104 kg N ha^{-1} for broadcast, respectively, for *Aus*–*Aman* and *Boro* seasons.

For the deep placed treatments, briquettes of two sizes were used, i.e., 1.8 and 2.7 g for UB and 2.4 g (25–6–15 % N–P–K) and 3.4 g (28–5.4–14 % N–P–K) for NPK. Fertilizer briquettes of either urea or NPK were deep placed at 40 × 40 cm spacing (62,500 placement sites per hectare [ha]) (Table 2). Size and numbers of briquette per placement site were determined based on the N rates. Deep placement of UB of one-1.8 g and one-2.7 g at a spacing of 40 × 40 cm supplied 52 and 78 kg N ha^{-1}, respectively. Similarly, for NPK briquettes, one-3.4 g and two-2.4 g provided the same N rates (±2 kg ha^{-1}) as compared to urea briquettes of one-1. 8 g and one-2.7 g, respectively. The small variation in N rates (±2 kg ha^{-1}) in NPK is due to the mixing ratio of three fertilizers, i.e., PU, di-ammonium phosphate (DAP) and muriate of potash (MOP). Similarly, P and K rates in 2.4 g NPK briquette was maintained as

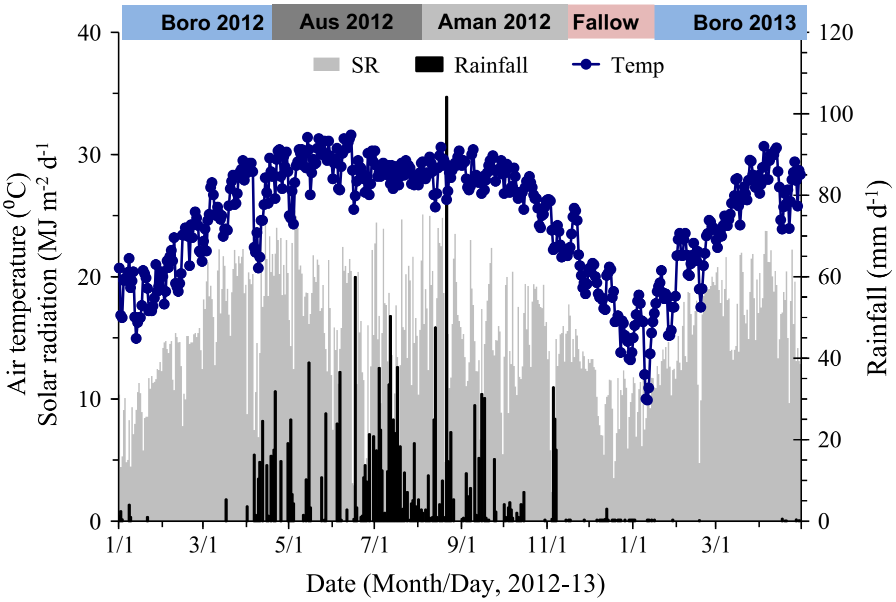

Fig. 1 Daily average of rainfall, air temperature and solar radiation (SR) during experiment period (Jan 2012–April 2013) (Data source: Weather station, Bangladesh Rice Research Institute)

Table 1 Physicochemical properties of soil before start of the experiments

Soil property	Value
pH-H_2O	6.2
Organic carbon (%)	1.75
Total N (%)	0.17
Available P (mg kg^{-1})	16
Available K ($cmol_c$ kg^{-1})	0.25
Texture	Clay loam

recommended and were relatively lower in 3.4 g briquettes.

Crop management

Phosphorus (triple super phosphate) and potassium (MOP) fertilizers were applied in all experimental plots, except in the plots receiving NPK briquettes, at 16–42 kg P-K ha^{-1} in the *Aus–Aman* seasons and 25–64 kg P-K ha^{-1} in the *Boro* season, respectively, as basal applications. P and K in NPK briquette treatments were applied along with briquette placement at the rates

Table 2 Nitrogen source and rates used during *Boro–Aus–Aman* seasons. The treatments were same for both continuously standing water (CSW) and alternate wetting and drying (AWD) conditions

Source	N Rate (kg ha^{-1})			Briq wt. (g) and no/four hills		
	(*Boro* 2012 and 2013)	*Aus* 2012	*Aman* 2012	(*Boro* 2012 and 2013)	*Aus* 2012	*Aman* 2012
Control	0	0	0	–	–	–
Prilled urea (PU)	78	78	78	–	–	–
	104			–	–	
	156	120	120	–	–	–
Urea briq (UB)	78	52	52	2.7 (1)	1.8 (1)	1.8 (1)
	104	78	78	1.8 (2)	2.7 (1)	2.7 (1)
NPK briq (NPK-B)	78	52	52	2.4 (2)	3.4 (1)	3.4 (1)
	104	78	78	2.4 (3)	2.4 (2)	2.4 (2)

Number in parenthesis indicates the number of briquettes used per application site similar with other treatments. N fertilizer PU was applied as broadcast in three equal splits at final land preparation, maximum tillering and panicle initiation stages, while UB and NPK were deep placed at a depth of 7–10 cm between four hills in alternate rows 7–10 days after transplanting (DAT). Rice seedlings (2–3 per hill) were transplanted with a spacing of 20 cm × 20 cm. Rice varieties grown in *Boro 2012, Boro 2013*, *Aus* and *Aman* seasons were BRRI dhan 29, BRRI dhan 28, BRRI dhan 27 and BR 22, respectively.

All plots under CSW conditions were maintained continuously flooded until 2 weeks before harvesting. Plots under AWD conditions were irrigated following safe AWD principle. A 25 cm long, 10 cm in diameter PVC pipe, perforated up to 15 cm, was inserted 15 cm into the soil, perforated side down, leaving 10 cm above the ground. Soil inside the pipes was removed to make a hole up to the depth of 15 cm. Water depth inside the PVC pipes was monitored, and plots were irrigated when water depth in AWD pipes was 12–15 cm below the soil surface. The AWD treatment started at 25 DAT and continued until 2 weeks before harvesting. However, plots were maintained continuously flooded for a week after the topdressing of PU to measure floodwater ammonium dynamics, and for 2 weeks during the flowering stage.

Floodwater Ammonium-N, rice yield and nitrogen use efficiency

Floodwater samples were collected for seven consecutive days after fertilizer application, i.e., basal fertilization, deep placement of fertilizers and topdressings. Floodwater samples (5 mL floodwater plus 0.5 mL Nessler's reagent) were analyzed for NH_4-N using a spectrophotometer at 420 nm wave length. Grain (14 % moisture content) and straw yields were recorded at harvest from a 5.28 m^2 area. At harvest, agronomic efficiency (AE_N: kg grain increase per kg^{-1} N applied) and recovery efficiency (RE_N: kg N uptake per kg^{-1} applied N) were calculated for all of the fertilizer treatments (Singh et al. 1999).

Data analysis

Analysis of variance (ANOVA) of grain yield, total dry matter (TDM), total N uptake (TNU) and NUE was done with Statistical Tool for Agricultural Research (STAR 2.0.1, International Rice Research Institute, Philippines). ANOVA was performed with a split-plot structure considering the water management regime as the main plot and fertilizer treatments as the sub-plot. Treatments between two *Boro* seasons and between *Aus* and *Aman* were the same. Therefore, combined ANOVA was done separately for two *Boro* seasons, and for one *Aus* and one *Aman* season. A pairwise means comparison of treatments was done with Tukey's honest significant difference (HSD) test at 5 %.

Results

Dynamics of floodwater ammonium-N

Changes in floodwater ammonium-N (NH_4^+-N) concentration were monitored for 7–9 consecutive days after N application. The deep placement of UB and NPK significantly reduced the concentration of NH_4^+-N in floodwater irrespective of N rates, application time (across topdressings) and growing seasons compared to broadcast PU (Fig. 2). The highest concentration was observed from 2 to 5 days of broadcast PU, which increased with increasing N rates (Table 3). The peaks in floodwater NH_4^+-N were up to 16 times higher in PU treatments, while in deep placed treatments they were close to control. Thereafter, the concentration declined sharply, becoming similar to the N0 (control) treatment after 6–7 days. The patterns of NH_4^+-N were similar in all three measurements and growing seasons. On the other hand, the floodwater NH_4^+-N in UB and NPK treatments was negligible and similar with the control treatment throughout the measurement. Increasing N rates in deep placed treatments had no effects on floodwater NH_4^+-N. Since both CSW and AWD plots were continuously flooded during the measurement period (*Boro* 2012), the pattern and magnitudes were similar between CSW and AWD conditions. Similarly, treatments in the 2012 and 2013 *Boro* seasons were the same, and the magnitudes and patterns of NH_4^+-N in floodwater were similar. Therefore, the results from the 2012 and 2013 *Boro* seasons were combined.

Grain yield and above ground biomass

Fertilizer treatments significantly affected grain yield, total above ground biomass (TDM, total dry matter) and harvest index during both dry (*Boro*, Tables 4, 5)

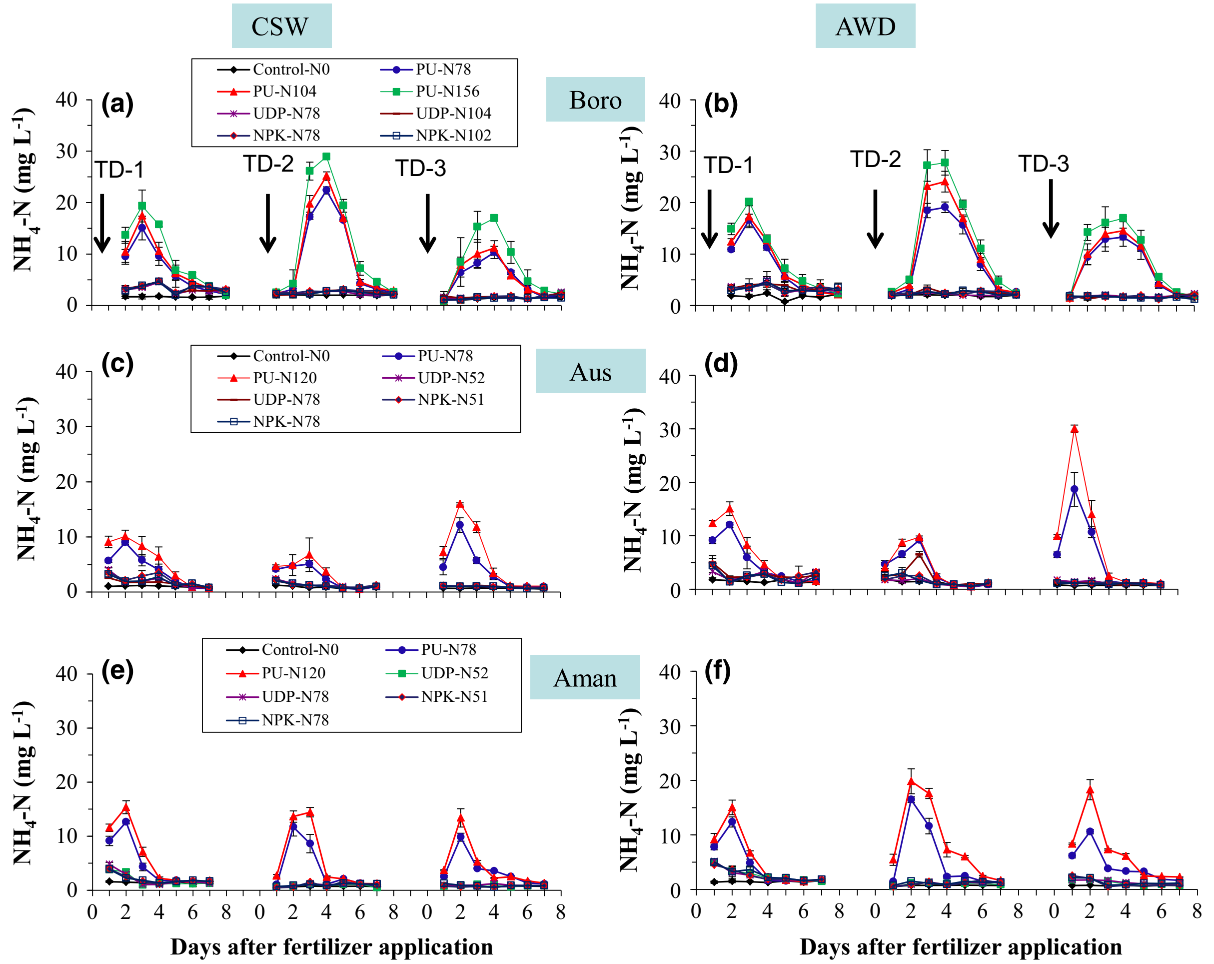

Fig. 2 Dynamics of floodwater ammonium (NH_4-N) concentration in different N rates and application methods under continuous standing water (CSW) and alternate wetting and drying (AWD) conditions in 2012–2013. PU, UDP and NPK represent broadcast prilled urea, deep placement of urea and NPK briquettes, respectively. 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). *Number* followed by N represents kg N ha^{-1}

and wet (*Aus* and *Aman*, Table 6) seasons compared to the control. Response of N rates and methods of application on grain yield was consistent among the seasons. Generally, the addition of N either as broadcast PU or FDP increased grain yield significantly over control (N0), but increasing N rates beyond 52 kg ha^{-1} during the wet season and 78 kg ha^{-1} during the *Boro* (dry) season did not have significant effects on grain yields. Yields between broadcast PU and deep placed treatments were similar. Unlike grain yields, TDM production was higher in FDP treatments as compared to broadcast PU. However, the effect was statistically significant ($p < 0.05$) only during the *Boro* 2012 season, particularly at lower N rates. The interaction effects of fertilizer and water management treatments were not significant to any responding variables except harvest index; therefore, the data across water management treatments were combined. Similarly, data across *Aus* and *Aman* seasons were combined because there was no interaction between season and fertilizer treatments (Table 4). However, grain yield was significantly higher with AWD during *Boro* 2012 season.

Nitrogen uptake and nitrogen use efficiency

Fertilizer treatments increased total N uptake (TNU) significantly over control, irrespective of N rates and

Table 3 Floodwater ammonium (NH_4-N) peaks in different fertilizer treatments after topdressing of urea or deep placement during *Boro*, *Aus* and *Aman* seasons, values under *Aus* and *Aman* seasons are means of two water regimes (n = 6), while they are average of 2012 and 2013 for *Boro* season (n = 12)

N source	N rate	First TD[a]		Second TD		Third TD		Average	
		NH_4-N (mg L^{-1})	% increase	NH_4-N (mg L^{-1})	% increase	NH_4-N (mg L^{-1})	% increase	NH_4-N (mg L^{-1})	% increase
Boro									
Control	0	1.8	–	1.9	–	1.8	–	1.8	–
PU	78	13.1	698	22.3	1124	12.0	581	15.8	801
	104	13.9	740	27.3	1410	17.5	893	19.6	1014
	156	15.9	856	31.8	1660	25.8	1362	24.5	1293
UB	78	4.0	125	2.4	27	2.6	48	3.0	67
	104	6.2	282	2.7	43	2.9	67	3.9	131
NPK	78	4.3	149	2.5	32	2.4	35	3.0	72
	104	4.4	160	2.5	32	2.3	29	3.1	74
Aus									
Control	0	1.6		0.8		0.8		1.1	
PU	78	12.5	658	14.1	1701	10.2	1210	12.3	1190
	120	15.2	822	17.1	2092	15.8	1932	16.1	1615
UB	52	4.4	165	1.2	51	1.4	82	2.3	99
	78	5.0	201	1.3	69	1.5	94	2.6	121
NPK	52	4.2	155	1.7	119	1.7	114	2.5	129
	78	4.4	169	1.4	80	1.7	120	2.5	123
Aman									
Control	0	1.5		1.5		0.8		1.3	
PU	78	10.5	619	7.1	354	15.4	1868	11.0	947
	120	12.6	750	8.3	439	23.0	2816	14.6	1335
UB	52	3.6	162	2.2	50	1.4	84	2.4	99
	78	3.8	149	4.3	158	1.2	61	3.1	123
NPK	52	4.1	181	2.4	65	1.3	70	2.6	105
	78	3.8	160	2.5	63	1.1	45	2.5	90

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

methods of application. On average, TNU with FDP was 8 kg N ha^{-1} higher than with PU during *Boro* season. However, as with grain yield, increasing N rates either with broadcast PU or deep placement did not have significant effects on N uptake, except in the *Aus* 2012 season where TNU increased significantly with increasing PU application rates. Similarly, nitrogen harvest index among fertilizer treatments were not significantly different (Table 5). Nonetheless, deep placement significantly increased N recovery efficiency (RE_N) compared to broadcast PU at lower N rates, i.e., UB-N78 during *Boro* and NPK-N51 during *Aus*–*Aman*. NUE (AE_N and RE_N) decreased with increasing N rates under both broadcast and deep placed treatments.

Effects of water regimes on grain yield and nitrogen use efficiency

Water regimes significantly affected grain yield during the *Boro* season. Water regimes had no interaction effect with fertilizer treatment on grain yield. However, there were significant interaction effects between water regime and year on grain yield (Table 4). Across

Table 4 Analysis of variance (ANOVA) of panicles, grain yield, total aboveground dry biomass (TDM) and harvest index (HI) in fertilizer and water treatments in 2012 and 2013 (*Boro* season)

Water regime	Treatments	Panicles (m^{-2})		Grain yield (t ha^{-1})[a]		TDM (t ha^{-1})		Harvest index			
		2012	2013	2012	2013	2012	2013	2012		2013	
								CSW	AWD	CSW	AWD
Mean	N0	195c	206b	4.4b	4.19b	7.9c	6.7b	0.55a	0.57a	0.57a	0.57a
	PU-N78	255b	267a	5.5a	5.12a	10.3b	8.9a	0.52bc	0.54ab	0.54ab	0.52abc
	PU-N104	304a	261a	5.2a	4.86a	11.2ab	9.0a	0.46bc	0.45c	0.48bc	0.53ab
	PU-N156	288ab	263a	5.4a	4.99a	10.9ab	9.1a	0.47bc	0.53ab	0.53abc	0.49bc
	UB-N78	306a	264a	5.6a	4.88a	11.5a	9.3a	0.45bc	0.51abc	0.52abc	0.46c
	UB-N104	313a	261a	5.4a	4.93a	11.7a	9.2a	0.42c	0.50bc	0.49bc	0.51abc
	NPK-N78	300a	264a	5.4a	4.96a	11.4ab	9.3a	0.43c	0.51abc	0.47c	0.52abc
	NPK-N102	317a	268a	5.4a	5.17a	11.3ab	9.9a	0.45c	0.50bc	0.49bc	0.48bc
	Mean	287A	258B					0.47A	0.51B	0.51A	0.51A
CSW	Mean			4.9Ab	4.9Aa	10.7Aa	9.0Ba				
AWD	Mean			5.7Aa	4.8Ba	10.9Aa	8.8Ba				
ANOVA (*p* values)											
Year (Y)	0.0004		0.0034		0.0003		0.0306				
Water regime (W)	0.2059		0.0188		0.6225		0.0388				
Y × W	0.6945		0.0063		0.0312		0.0313				
Treatment (T)	<0.0001		<0.0001		<0.0001		0.0000				
W × T	0.1933		0.0608		0.2301		0.0166				
Y × T	0.0001		0.1097		0.0373		0.2352				
Y × W × T	0.1858		0.7264		0.8308		0.0144				

Within a column and year, means followed by same small case letters and within a row and response variable means followed by same capital case letters are not significantly different at 5 % probability level by Tukeys's honest significant difference (HSD) test

CSW continuous standing water, *AWD* alternate wetting and drying. *PU* prilled urea, *UB* urea briquette, *NPK* fertilizer briquette containing NPK

[a] Grain yield is at 14 % moisture content

fertilizer treatments, AWD produced about 16 % higher grain yield (significantly different at $p < 0.05$) than continuous flooding in *Boro* 2012, while yields were similar between CSW and AWD water regimes in *Boro* 2013. TDM was significantly higher in *Boro* 2012 compared to *Boro* 2013, irrespective of water regimes. On the other hand, TNU and RE_N were not affected by either water regime or by its interaction with fertilizer and year. There was no interaction of fertilizer and water regime on any responding variables at $p < 0.05$ except harvest index. Across fertilizer treatments, harvest index was significantly increased by AWD irrigation, particularly in *Boro* 2012 (Table 4).

In *Aus* and *Aman* seasons, water regimes did not have significant effects on grain yield and TDM. However, their effect on TNU and AE_N was significant. Across fertilizer treatments, TNU was significantly higher under CSW (79 kg ha^{-1}) conditions as compared to AWD conditions (73 kg ha^{-1}). However, *Aus* and *Aman* rice are grown during monsoon seasons, and therefore the effects of AWD irrigation are rarely observed.

Discussion

Dynamics of floodwater ammonium under different rates and methods of fertilizer applications

Deep placement of urea and NPK briquettes resulted in a drastic reduction in floodwater NH_4^+-N. The

Table 5 Analysis of variance (ANOVA) of total nitrogen uptake (TNU), nitrogen harvest index (grain N uptake/total above ground N uptake) and agronomic efficiency (AE_N) and nitrogen recovery (RE_N) in fertilizer and water treatments in 2012 and 2013 (*Boro* season)

Water regime	Treatments	TNU (kg ha^{-1})		Nitrogen harvest index	AE_N (kg grain kg N^{-1})	RE_N (%)
		2012	2013	Mean of 2 years	Mean of 2 years	Mean of 2 years
Mean	N0	50b	61b	0.64a	–	–
	PU-N78	86a	77a	0.62ab	12.7a	33b
	PU-N104	90a	83a	0.60bc	9.6abc	30bc
	PU-N156	95a	83a	0.59bc	5.8c	21c
	UB-N78	99a	87a	0.57c	11.7ab	48a
	UB-N104	91a	91a	0.58c	8.1bc	34b
	NPK-N78	98a	92a	0.58bc	11.1ab	50a
	NPK-N102	96a	90a	0.58bc	9.4abc	36b
	Mean					
ANOVA (*p* values)						
Year (Y)	0.1272		0.1727		0.1007	0.0065
Water regime (W)	0.2210		0.2027		0.0750	0.7629
Y × W	0.1360		0.6296		0.5771	0.9446
Treatment (T)	<0.0001		0.0000		<0.0001	<0.0001
W × T	0.9869		0.0706		0.0640	0.9537
Y × T	0.0147		0.1723		0.1234	0.0938
Y × W × T	0.9913		0.2065		0.5843	0.9942

Within a column and year, 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^{-1} N), *RE_N* kg N uptake kg^{-1} N applied and expressed in percentage, two water regimes are: *CSW* continuous standing water, *AWD* alternate wetting and drying. *PU* prilled urea, *UB* Urea briquette, *NPK* fertilizer briquette containing NPK

floodwater NH_4^+-N concentration in deep placed urea or NPK briquette treatments was similar to that in the zero N plots irrespective of N rates because deep (subsoil) placement increases the retention of NH_4^+-N in soil and reduces its movement to the floodwater (Fig. 2). Previous studies reported that NH_3 volatilization was positively correlated with floodwater NH_4^+-N (Hayashi et al. 2006, 2008; Liu et al. 2015). Since floodwater NH_4^+-N is negligible, deep placement contributes to the reduction of NH_3 volatilization (Hayashi et al. 2006; Huda et al. 2016; Rochette et al. 2013). The amount of NH_4^+-N present in floodwater could be a good indicator to estimate potential NH_3 volatilization and N runoff losses.

On the other hand, higher floodwater NH_4^+-N in PU treatments during 2–4 days after topdressings—and which reached its maximum level at 4 days—may be due to enzymatic hydrolysis of PU. N present in floodwater is mainly lost by volatilization and surface runoff, depending upon irrigation practices and rice growing seasons. Surface runoff occurs during wet seasons (*Aus–Aman*) but not commonly during the dry season (*Boro*). A sharp decline in the concentration of floodwater NH_4^+-N after 4–5 days could be attributed to its losses, particularly NH_3 volatilization. Moreover, the decline could also be associated with diffusion of NH_4^+-N into the soil, nitrification in the oxidized soil layer and plant uptake. This is supported by Watanabe et al. (2009); they observed peaks in the ammonia flux at 1–3 days of urea application, followed by a sharp decline. NH_3 volatilization losses from rice fields increase further with floodwater pH (Dong et al. 2012). The conversion of NH_4^+-N to NH_3 increases sharply when the floodwater pH is above 8. Similarly, urea hydrolysis and ammonia volatilization loss increases with increasing temperature (Hayashi et al. 2008).

Table 6 Analysis of variance (ANOVA) of grain yield, total aboveground dry biomass (TDM), total nitrogen uptake (TNU) and agronomic efficiency (AEN) and nitrogen recovery (REN) in different fertilizer treatments during *Aus* and *Aman* seasons in 2012

Water regime	Treatments	Grain yield (t ha^{-1})[a]	TDM (t ha^{-1})	TNU (kg ha^{-1})		AE$_N$ (kg grain kg N^{-1})	RE$_N$ (%)
		Mean of 2 seasons	Mean of 2 seasons	Aus	Aman	Mean of 2 seasons	Mean of 2 seasons
Mean	N0	3.5b	6.5b	59d	40b	–	–
	PU-N78	4.2a	8.3a	88bc	66a	10.0ab	35bc
	PU-N120	4.4a	9.1a	105a	69a	8.2b	31c
	UB-N52	4.2a	8.6a	83c	67a	15.1a	49ab
	UB-N78	4.4a	8.8a	97abc	65a	11.6ab	41abc
	NPK-N51	4.2a	8.5a	88bc	67a	15.6a	55a
	NPK-N78	4.4a	9.0a	98ab	69a	11.8ab	44abc
ANOVA (*p* values)							
Season (S)	<0.0001	<0.0001	0.0002		0.0452	0.1215	
Water regime (W)	0.3568	0.1443	0.0272		0.0352	0.0955	
S × W	0.4235	0.4871	0.0665		0.0278	0.6785	
Treatment (T)	<0.0001	<0.0001	<0.0001		0.0028	0.0007	
W × T	0.3700	0.0970	0.4852		0.3302	0.5552	
S × T	0.5103	0.1955	0.0409		0.1719	0.2932	
S × W × T	0.3228	0.8159	0.8700		0.1994	0.8344	

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

CSW continuous standing water, *AWD* alternate wetting and drying. *PU* prilled urea, *UB* urea briquette, *NPK* fertilizer briquette containing NPK. *AE*$_N$ agronomic efficiency (kg grain kg^{-1} N), *RE*$_N$ kg N uptake kg^{-1} N applied and expressed in percentage

[a] Grain yield is at 14 % moisture content

Effects of methods and rates of nitrogen applications on grain yield and nitrogen use efficiency

UDP increases N recovery by 30–40 % and grain yield by 15–20 % over broadcast PU (Gregory et al. 2010; Huda et al. 2016; Miah Md et al. 2015; Savant and Stangel 1990). However, in this study there were no differencs among N fertilizer rates (excluding control treatment); hence, it's not surprising that no significant yield increase occurred with deep placement of either urea or NPK briquettes compared to broadcast PU. The deep placement of either urea or NPK briquettes saved urea by at least 30 % as compared to broadcast PU without significant yield loss. Increasing N rates above 52 kg ha^{-1} during the *Aus*–*Aman* seasons and 78 kg ha^{-1} during the *Boro* season had no significant effects on yields. Nitrogen uptake increased significantly with increasing grain yields (Fig. 3). In Bangladesh, these constitute the existing recommended rates for UDP, which is generally calibrated at 30–35 % less than broadcast PU (FRG 2012). Field trials conducted in farmers' fields across different agro-ecological zones (AEZ) showed that UDP with 25–35 % less urea produced up to 20 % higher yield compared to broadcast PU (Miah Md et al. 2015; Gregory et al. 2010; IFDC 2013). However, considering the declining soil fertility status of the country, and in keeping with the target of achieving a high yield goal against a medium yield goal set by earlier recommendations (FRG 2005), the Bangladesh Agriculture Research Council (BARC) has updated the fertilizer recommendation (FRG 2012), increasing recommended N rates up to 120 and 200 kg N ha^{-1} for *Aus*–*Aman* and *Boro* rice, respectively. Recommendations are based on soil test value, with recommended N rates increasing mainly in areas with low soil fertility.

In this study, however, there were no significant yield differences under N rates from 52 to 120 kg ha^{-1} during the *Aus–Aman* seasons, and from 78 to 156 kg ha^{-1} during the *Boro* season. Contrary to this study, Huda et al. (2016) who conducted an experiment in another AEZ with similar treatments structure reported increased yields with increasing N rates from 78 to 156 kg N ha^{-1} during the *Boro* season, particularly in broadcast PU. Moreover, the yield plateau observed in this study at 5.6 t ha^{-1} (UB-N78, *Boro* 2012) and 5.17 t ha^{-1} (NPK-N102, *Boro* 2013) were much lower than those reported by others for the same varieties. Alam et al. (2013) reported yields up to 8.3 t ha^{-1}, while Huda et al. (2016) reported up to 6.75 t ha^{-1}. Therefore, the limited yield response with additional N inputs observed in this study may not be explained by varietal yield potential nor negative effects of N alone. The yield plateau above 52 kg N ha^{-1} (*Aus–Aman*) or 78 kg N ha^{-1} (*Boro*) might be due to the presence of yield-limiting factors other than N (Cassman et al. 1996). Micronutrient deficiency such as zinc, boron and copper could have limited rice yield since they were not applied in the experiment, while Huda et al. (2016) applied both Zinc and Sulfur in their experiment. In addition to this, the water holding capacity of the soils in their study was much higher (42 %) compared to this study (32 %). This suggests that some of the applied N in this study might have leached with increased frequency of irrigation (data not shown). Another reason could be the lower solar radiation leading to low yield potential. The averages of daily solar radiation of rice-growing season for *Boro* 2012 and 2013 in this study were 15.5 and 15.8 MJ m^{-2} d^{-1} compared to 18.59 and 17.9 MJ m^{-2} d^{-1} in their study, respectively. The higher solar radiation in their study has potential to increase biomass yield by 3.4 and 2.2 t ha^{-1} in 2012 and 2013, respectively. Timsina et al. (2001) also showed that year to year variability due to weather affected rice yield more than the varietal differences.

Generally, rice yield increases with increasing N rates up to the optimum level and then declines. The supply of excess N beyond plant requirements has negative effects on plant growth and yield, while at the same time causing negative environmental impacts (http://www.knowledgebank.irri.org, accessed on 28 Dec. 2015). The effect of increasing N rates on grain yield depends on indigenous N supply, which is highly variable among fields with similar soil types and in the same field over time. Therefore, higher spatial and seasonal variations are observed in grain yields within similar soil, climate and management practices (Cassman et al. 1996). The reported N uptake and grain yields—4.2 to 4.4 t ha^{-1} during *Boro* and 3.5 t ha^{-1} during *Aus–Aman* (Tables 4, 6) from control plots—are relatively high, as compared to other studies (Huda et al. 2016; Islam et al. 2011). These results suggest high indigenous N supply and further highlight the requirement for site-specific N management. The combination of higher indigenous N supply and yield-limitations resulted in non-significant N fertilizer treatment effect (N rates and application methods).

As expected, increasing N rates reduced NUE (AE_N and RE_N) and reached the lowest point at the highest N rate (Tables 3, 4). These results confirmed that the UDP-N52 and UDP-N78 are the optimum N rates for increasing grain yields and NUE in *Aus–Aman* and *Boro*, respectively, in the areas with climate, soils and

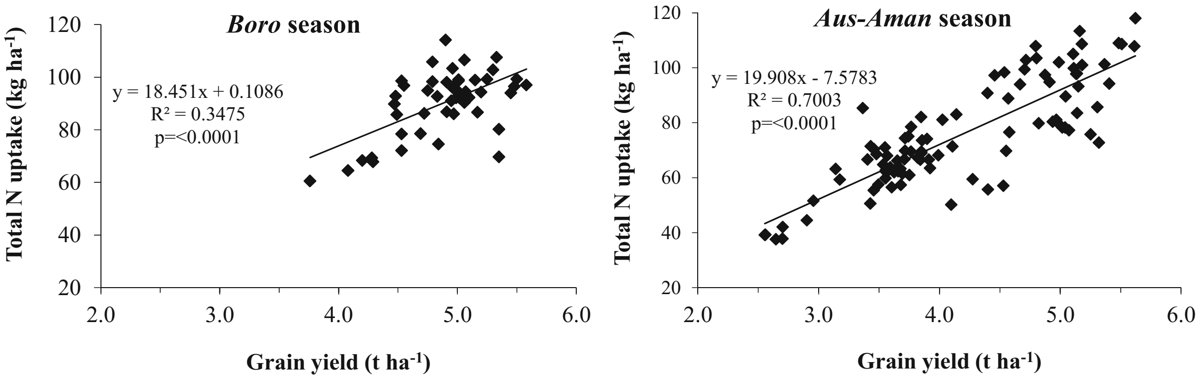

Fig. 3 Relationship between grain yields and total above ground nitrogen uptake during *Boro* and *Aus–Aman* seasons (n = 96)

management practices similar to this experimental site. However, more on-farm research is needed with different N rates, including with N rates lower than existing recommended rates (i.e., less than 52 kg ha^{-1} during the *Aus*–*Aman* seasons and 78 kg ha^{-1} during the *Boro* season to determine whether existing N rates for urea or NPK briquettes require an update).

The increased N recovery with deep placement of urea or NPK briquettes, as compared with broadcast PU, observed in this study are consistent with the results of previous studies (Bandaogo et al. 2014; Kapoor et al. 2008; Liu et al. 2015). However, the magnitudes of increases in RE_N in deep placed treatments compared to broadcast PU were lower than those reported by previous studies (Huda et al. 2016). At 78 kg N ha^{-1} (*Boro*), deep placement of urea or NPK briquettes increased N recovery up to 48–50 % from 33 % of broadcast PU. Higher N uptake in deep placed treatments was associated with increased availability of applied N (lower N losses) for plant growth and increased aboveground biomass (Tables 3, 4). 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). 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). These results also confirmed that deep placement of NPK is equally as effective as UB for increasing fertilizer N use efficiency in lowland rice fields, as compared to broadcast PU.

Increasing N rates had no significant effects on N uptake. It is reported by Dong et al. (2012) that fertilizer N contributed only 20 % of the N taken up by plants when soil was rich in N. This can also explain our results, since the highest N recovery occurred at the lowest N rates for both broadcast and deep placed treatments and declined with increasing N rates. Decreased AE_N and RE_N are expected when N is applied in excess of plant uptake or when other non-N limiting factors affect plant growth.

Effects of water regimes on yields and nitrogen use efficiency

AWD saves irrigation water by up to 38 % without significant effects on grain yields (Lampayan et al. 2015). The magnitudes of water savings and the effects on grain yield depend on the intensity of soil drying and soil types (Bouman and Tuong 2000). In this study, AWD increased grain yield by 16 % as compared with CSW irrigation in the *Boro* 2012 season. It is not clear why yield increased only during the first year, although soil fertility is expected to decline due to three continuous rice crops. Under higher soil fertility conditions, AWD might have increased nutrient availability and crop growth. Previous studies show that AWD increased total root biomass (Dong et al. 2012) and N recovery (Liu et al. 2013; Ye et al. 2013) as compared to CSW. Increased yield and N uptake under AWD compared to CSW could be associated with an increase in effective tillers (panicles) and increased root growth of rice plants (Richards and Sander 2014). However, in this study, AWD had no significant effects on N uptake and N recovery efficiency. Moreover, our results show no interaction effects between AWD and fertilizer treatments, suggesting that deep placement of UB or NPK as a single application is as effective as the split broadcast application of PU.

These results suggest that the AWD has potential not only to save irrigation water and reduce the irrigation costs incurred by farmers, but also to increase grain yields. More importantly, AWD is a climate-smart technology because it significantly reduces emissions of methane, one of the major greenhouse gases responsible for global warming and climate change (Richards and Sander 2014). However, the interaction effects of AWD and year on yield suggest the need for long-term studies across different rice growing seasons and sites. Those studies should investigate the interaction effects of AWD and N fertilizer on rice productivity and soil fertility (Huda et al. 2016).

Conclusions

Deep placements of either UB or NPK briquettes are effective in reducing ammonium (NH_4-N) concentration in floodwater compared to broadcast PU. Deep placement of UB or NPK saved 30 % N fertilizer without any yield penalty. Differences in grain yields between broadcast PU and deep placed treatments were not significant because N fertilizer rates independent of N application methods did not give significant differences. These results are in contrast to most of other studies that have shown yield advantage of deep placement over broadcast application which further highlights the importance of site specific fertilizer management. The existing recommended N rates for deep placement (i.e., 52 kg ha^{-1} during the *Aus–Aman* seasons and 78 kg ha^{-1} during the *Boro* season) were found to be the optimum rates. At the existing recommended N rates, deep placement of UB and NPK increased N recovery up to 48–55 % from 33 to 35 % of broadcast PU. The difference in floodwater ammonium, grain yield and N recovery between UB and NPK were not significant. AWD irrigation increased grain yield by 16 % and harvest index in dry season The combination of UB or NPK deep placement and AWD could increase grain yield and N recovery while saving irrigation water and N fertilizer. However, the interaction effects of AWD and year on yield suggest the need for long-term studies across different rice growing seasons and sites. Those studies should investigate the interaction effects of AWD and N fertilizer on rice productivity and soil fertility.

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