Nitrogen use efficiency, crop productivity and environmental impacts of urea deep placement in lowland rice fields

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Abstract
Nitrogen (N) fertilization is critical for cereal production; however, its low use efficiency poses both economic and environmental concerns. Urea deep placement (UDP) in lowland rice fields is one of the best currently applicable management techniques to increase N use efficiency (NUE) and crop productivity. Multi-location experiments conducted in Bangladesh in 2014-2015 have demonstrated several benefits of UDP use including reduced N losses through ammonia volatilization and greenhouse gas nitrous oxide (N_2O) and nitric oxide (NO) emissions. Nitrogen loss as N_2O and NO emissions were measured continuously throughout rice-growing and fallow seasons using an automated gas sampling and analysis system. Across the years and sites, UDP increased yield on average by 21% as compared to broadcast urea while using at least 25% less fertilizer. UDP reduced floodwater ammonium and ammonia volatilization similar to the control (N0) treatment, while both were significantly higher in broadcast urea treatments. UDP reduced N_2O emissions by up to 80% as compared to broadcast urea under continuous flooded (CF) conditions. The effects of UDP on N_2O emissions under alternate wetting and drying (AWD) irrigation practices were site specific: depending on the duration and intensity of soil drying, emissions were reduced under mild soil drying but increased with more intense soil drying. These results confirm that UDP not only increases NUE and grain yields but also reduces negative environmental impacts including N_2O emissions.

Key Words
Fertilizer deep placement, nitrogen management, environment, rice, greenhouse gas emissions

Introduction
The use of nitrogen (N) fertilizer for cereal crop production has increased consistently since the 1960s. N fertilizers are being used widely in most Asian countries and in some cases the use is excessive. The excessive use of N fertilizers poses an environmental cost in addition to reduced farm profitability, particularly in light of more recent discussions of planetary boundaries associated with anthropogenic N removed from the atmosphere (Rockström et al. 2009). N fertilizer is the most consumed fertilizer in the world, with use projected to rise by 1.4% each year through 2018 (FAO 2015). However, more than 50% of applied N is not utilized by plants and lost to the environment (Savant and Stangel 1990; Huda et al. 2016; Rochette et al. 2013). Therefore, concerns regarding fertilizer use efficiency are growing, with immediately applicable N use efficiency enhancing measures being of paramount importance.

Over the past three decades, many research and development groups including the International Fertilizer Development Center (IFDC) have worked on improving N use efficiency (NUE) through urea deep placement (UDP), urease inhibitors, and slow and controlled N fertilizers such as polymer- and sulfur-coated fertilizers. Research conducted across different countries demonstrated that the use of UDP could achieve the multiple benefits of increasing grain yield, farm profits, and nitrogen use efficiency (NUE) while reducing negative environmental effects (Mohanty et al. 1999); in short, more yield with less fertilizer (Savant and Stangel 1990; IFDC 2013; Miah et al. 2016). UDP in lowland rice fields has been widely recognized as an effective management practice that reduces N use by 25-40% and increases yield by an average of 15-20% (Huda et al. 2016; Miah et al. 2016).

It has been established both in research and on-farm conditions that UDP reduces N fertilizer use and increases crop productivity, leading to increased farm profits, while reducing government fertilizer subsidy burdens for countries in which N fertilizers are subsidized. Moreover, UDP was also found to reduce negative environmental impacts by reducing N losses including through runoff and ammonia volatilization (IFDC 2013; Rochette et al. 2013). However, research regarding the environmental impacts of UDP use, particularly on nitrous oxide (N_2O) and nitric oxide (NO) emissions, is still limited.

Agricultural N_2O and NO emissions data are generally reported with uncertainty. These uncertainties are not only associated with the variations of soil, climate and crop management practices but also with measurement methodologies. For example, extrapolation of the results of discrete measurements taken at weekly or biweekly intervals may either over- or under-estimate total emissions compared to the results of continuous measurements. Fluxes that are estimated from continuous measurements are more reliable because they include all temporal variations. Despite large variations in emissions, N_2O direct soil emissions from agriculture are often estimated using the default IPCC emissions factor (EF) of 1% of applied N (IPCC, 2006). More intensive measurements are needed to develop season, site and crop specific emissions factors. In this paper, we present high resolution N_2O and NO emissions results measured using an automated continuous sampling and analysis system (Gaihre et al. 2014) along with yields and NUE.

Methods

Study sites and fertilizer treatments

Field experiments were conducted at two locations of Bangladesh—Bangladesh Agricultural University (BAU) and Bangladesh Rice Research Institute (BRRI) — in 2014-2015 during the *Boro* season (dry season, Jan-April) to compare the effects of UDP on grain yields, NUE and N losses. Treatments included control, broadcast prilled urea (PU) and UDP at N rates 0, 104 and 78 kg ha^{-1}, respectively. Treatments were tested under two water management regimes—continuous standing water (CSW) and alternate wetting and drying (AWD) with three replications— to assess interaction between N fertilizer and water management regimes. Several previous studies have demonstrated that UDP increases NUE by up to 25-40% when compared to conventional broadcast application (Savant and Stangel 1990; FRG 2012; Miah et al. 2015); for this reason, the N rate applied in UDP treatments in the referenced field experiments was 25% less than the N rate applied in PU treatments and this N rate is widely used in Bangladesh. PU was applied in three equal splits at one week after transplanting, maximum tillering and panicle initiation stages. For UDP treatments, urea briquettes (2.7 g) were deep placed (7-10 cm depth) at 40 cm x 40 cm spacing (62,500 placement sites per hectare) between 4 hills of rice at every alternate row to meet recommended N rates in a single application.

Quantification of nitrogen losses

Nitrogen losses including floodwater ammonium (NH_4^+), ammonia (NH_3) volatilization, and N_2O and NO emissions were measured from both BAU and BRRI sites. Floodwater NH_4 was measured every day for a week after topdressing of PU (Huda et al. 2016). NH_3 volatilization was measured using 'dynamic closed chamber and acid trap methods'. Similarly, N_2O and NO emissions were measured with the static automated closed chamber technique continuously throughout the rice growing seasons (Gaihre et al. 2014). N_2O and NO emissions were measured under the CSW water management regime in *Boro* 2014 and under the AWD water management regime in *Boro* 2015. Effects of water regimes on emissions were not studied because measurements within a season were done only under a single water regime.

Analysis of variance (ANOVA) of grain yields and NUE (agronomic and recovery efficiencies) by location and year was conducted following a split-plot structure where water management regime was considered as the main plot and fertilizer treatment as the sub-plot, while ANOVA of ammonia (NH_3) volatilization, and N_2O and NO emissions were done separately for location and year to determine the effects of fertilizer treatments.

Results

Grain yields and nitrogen use efficiency

UDP increased grain yield by 3-35% (average 21%) compared to broadcast PU in the dry (*Boro*) season (Table 1). The increase in yields with UDP over broadcast PU was consistent and significantly higher except during Boro 2014 at BRRI (CSW water regime). Similarly, UDP improved agronomic efficiency and nitrogen recovery as compared to broadcast PU, resulting in higher yields with less N fertilizer. These results are consistent with previous studies conducted across different districts in Bangladesh (Huda et al. 2016, Miah et al. 2016). Huda et al. (2016) reported that increasing N rates of broadcast PU from 78 to 156 kg N ha^{-1} increased grain yields significantly, whereas yield gains from increasing rates of UDP use plateaued above 78 kg N ha^{-1}. Water management regime and fertilizer treatment had significant interaction effects on N recovery (RE_N) at BRRI site. AWD irrigation significantly increased RE_N in UDP treatment (Boro 2014), while CSW increased in broadcast PU (Boro 2015).

Table 1. Grain yield and NUE in different fertilizer treatments during dry (*Boro*) seasons at Bangladesh Agricultural University and Bangladesh Rice Research Institute (mean±standard error)

Water retimes	N source	N rate (kg ha^{-1})	Grain yield (t ha^{-1})^{ǂ}	Agronomic efficiency (AE_N)	Recovery efficiency (RE_N)	Grain yield (t ha^{-1})^{ǂ}	Agronomic efficiency (AE_N)	Recovery efficiency (RE_N)
Bangladesh Agricultural University (BAU)								
			2014			***2015***		
Mean	Control	0	1.96±0.05c	-	-	2.38±0.11c	-	-
	Broadcast PU	104	4.73±0.01b	26.7±0.79b	39±1.0b	4.60±0.11b	21.4±0.97b	29±1.4b
	UDP	78	6.14±0.13a	53.7±1.46a	80±1.7a	6.40±0.09a	51.6±2.22a	77±3.4a
ANOVA (p values)								
Treatment (T)			<0.0001	<0.0001	<0.0001	<0.0001	0.0002	0.0001
Water (W)			0.3794	0.2207	0.0016	0.8018	0.4975	0.8919
W x T			0.1131	0.3968	0.4375	0.5217	0.7031	0.9120
Bangladesh Rice Research Institute (BRRI)								
			2014			***2015***		
CSW	Control	0	2.04±0.08b		-			-
	Broadcast PU	104	5.34±0.04a		61±2.8b			31±5.0b
	UDP	78	5.49±0.25a		78±3.4a			53±3.0a
AWD	Control	0	2.56±0.13c		-			-
	Broadcast PU	104	5.02±0.07b		54±0.6b			21±2.1b
	UDP	78	5.58±0.04a		88±1.0a			56±5.7a
Mean	Control			-		1.69±0.10c	-	
	Broadcast PU			27.6±1.93b		4.00±0.16b	22.2±1.34b	
	UDP			41.5±2.01a		4.81±0.18a	39.9±1.85a	
ANOVA (p values)								
Treatment (T)			<0.0001	0.0014	<0.0001	<0.0001	0.0009	0.0002
Water (W)			0.3411	0.1498	0.6415	0.2239	0.3911	0.1835
W x T			0.0315	0.4983	0.0026	0.4990	0.5149	0.0430

Within a column, season and water regime, means followed by the same letters are not significantly different at 5% probability level by Tukey's honest significant difference (HSD) test. ^{ǂ}Grain yield is at 14% moisture content. AE_N= agronomic efficiency (Y_T-Y_0/F_N, kg kg^{-1}), RE_N= Recovery efficiency (U_T-U_0/F_N, kg kg^{-1}, expressed in percentage); Y_T and Y_0 represent yield from treatment and control while U_T, U_0 represent N uptake from treatment and control in Kg, respectively.

Floodwater ammonium, ammonia volatilization and nitrous oxide emissions

Figure 1 shows that broadcast PU produced significantly higher amounts of NH_4^+ in floodwater, which is prone to runoff and volatilization losses. On the other hand, floodwater NH_4^+ levels in UDP treatment were similar to floodwater NH_4^+ levels in control treatment. Deep placement of urea briquettes at 7-10 cm depth ensures retention of NH_4^+-N in the soil, thereby reducing floodwater ammonium and surface runoff loss.

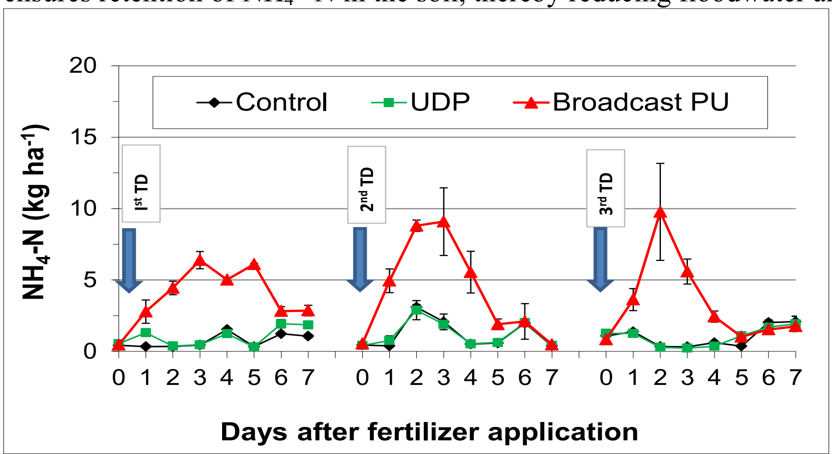

Figure 1. Dynamics of floodwater ammonium (NH_4-N) under control (N0), broadcast PU and urea deep placement (UDP) at Bangladesh Rice Research Institute (BRRI) during dry season (Boro) 2015. TD-1, TD-2, TD-3 represent first, second and third topdressing of urea, respectively. Deep placement was done at a time during first topdressing of urea; vertical bars represent standard error (n=3)

In addition to surface runoff, the negligible amount of floodwater NH_4^+ from UDP ensures a reduction in volatilization loss (Table 2). Moreover, UDP reduced N_2O emissions. Table 2 shows the cumulative N_2O emissions measured continuously throughout the dry (*Boro*) seasons of 2014 and 2015 at BAU and BRRI sites. UDP reduced emissions by up to 80% as compared to broadcast PU under the CSW water management regime. In comparison, the effects of UDP under the AWD water management regime were site specific. Emissions reduction with UDP under the AWD water management regime depended on the duration and intensity of soil drying. Emissions were reduced under mild soil drying but increased with more intense soil drying, probably due to increased nitrification. On the other hand, fertilizer treatments had no effects on NO emissions.

Table 1. Ammonia (NH_3) volatilization, nitrous oxide (N_2O) and nitric oxide (NO) emissions in different fertilizer treatments during dry (*Boro*) seasons at Bangladesh Agricultural University and Bangladesh Rice Research Institute (mean±standard error, n=3)

N source	N rate (kg ha^{-1})	NH_3-N (kg ha^{-1})	N_2O-N (g ha^{-1})	NO-N (g ha^{-1})	NH_3-N (kg ha^{-1})	N_2O-N (g ha^{-1})	NO-N (g ha^{-1})
Bangladesh Agricultural University (BAU)							
		2014 (CSW)			***2015 (AWD)***		
Control	0	-	37±3b	7.5±2.1a	0.09±0.01b	67±24b	2.7±1.2a
Broadcast PU	104	-	586±132a	6.1±0.7a	3.21±0.2a	421±55a	9.4±8.6a
UDP	78	-	116±10b	7.1±0.5a	0.32±0.03b	155±54b	2.0±0.5a
Bangladesh Rice Research Institute (BRRI)							
		2014 (CSW)			***2015 (AWD)***		
Control	0	-	27±17b	30.5±1.5a	0.07±0.01b	93±22a	12.2±4.8a
Broadcast PU	104	-	148±37a	23.5±2.6a	2.16±0.1a	428±19a	16.8±3.0a
UDP	78	-	55±27b	28.1±1.3a	0.30±0.02b	808±469a	26.8±7.6a

Within a column and season, means followed by same letters are not significantly different at 5% probability level by Tukey's honest significant difference (HSD) test; AWD, alternate wetting and drying; CSW, Continuous standing water

Conclusion

UDP (78 kg N ha^{-1}) increased rice yields by an average 21% compared with the broadcast PU treatment (104 kg N ha^{-1}), resulting in significant improvements in agronomic and recovery efficiency of N. Moreover, UDP reduced N losses to the environment, including N_2O and NO emissions.

References

FAO (Food and Agriculture Organization of the United Nations) (2015) World fertilizer trend and outlook to 2018. FAO, Rome. http://www.fao.org/3/a-i4324e.pdf

FRG (2012) Fertilizer recommendation guide. Bangladesh Agricultural Research Council (BARC), Farmgate, Dhaka 1215.

Gaihre YK, Satter MA, Singh U, Austin R (2014) Operating manual on automated continuous measurement of greenhouse gas emissions. IFDC Technical Bulletin No. T-76. International Fertilizer development Center, Muscle Shoals, AL 35662 USA. P. 82. http://www.ifdc.org/Publications/Technical-Bulletins/

Huda A, Gaihre YK, Islam MR, Singh U, Islam Md. R, Sanabria J, Satter MA Afroz H, Halder A, Jahiruddin M (2016). Floodwater ammonium, nitrogen use efficiency and rice yields with fertilizer deep placement and alternate wetting and drying under triple rice cropping systems. Nutrient Cycling in Agroecosystems 104: 53-66.

IFDC (International Fertilizer Development Center) (2013). Fertilizer deep placement. IFDC solutions. IFDC, muscle shoals, AL 35662 USA, p 6. http://issuu.com/ifdcinfo/docs/fdp_8pg_final_web?e=1773260/1756718

IPCC, 2006. National Greenhouse Gas Inventory Guidelines. Institute of Global Environmental Strategies (IGES), Kanagawa, Japan.

Miah MAM, Gaihre YK, Hunter G, Singh U, Hossain SA (2016). Fertilizer deep placement increases rice production: evidence from farmers' fields in southern Bangladesh. Agronomy Journal 108: 1-8.

Rochette P, Angers DA, Chantigny MH, Gasser MO, MacDonald JD, Pelster DE, Bertrand N (2013) Ammonia volatilization and nitrogen retention: how deep to incorporate urea?" Journal of Environmental Quality 42:1635-1642.

Rockström J, Steffen W, Noone K, Persson A, Chapin SC et al. (2009) A safe operating space for humanity. Nature 461:472-475.

Savant NK, Stangel PJ (1990) Deep placement of urea supergranules in transplanted rice: principles and practices. Fert Res 25: 1-85.