Nitrogen Sources and Timing Effects on Nitrogen Loss and Uptake in Delayed Flood Rice

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ABSTRACT

Field experiments were conducted in 2009 and 2010 in Louisiana and Mississippi to evaluate ammonia volatilization loss and subsequent effects on apparent nitrogen recovery efficiency (ANRE) and grain yield for rice (*Oryza sativa* L.). A semi-open static chamber approach was used to measure ammonia volatilization loss from multiple N sources applied 10 days before flood (dbf) at the rate of 168 kg N ha^{-1}. Cumulative ammonia volatilization losses for urea for Louisiana environments were 19 and 33% compared to 7% for both Mississippi environments. Urea + [N-(n-butyl) thiophosphoric triamide] (NBPT), urea + NBPT + dicyandiamide (DCD), and ammonium sulfate (AS) all minimized volatilization losses over all environments (range of 1.9–4.9%). Additionally, ammonia volatilization data fitted to the Gompertz model demonstrated that urea + NBPT and urea + NBPT + DCD had longer lag phases (7.2–7.7 d) relative to urea, AS, and urea + ammonium sulfate (UAS) blend (3.6 d). The same N sources and rate of N was applied 10, 7, 4, and 1 dbf to determine the effects on ANRE and yield. Apparent N recovery efficiency ranged from 43 to 71%. Grain yield was influenced by application time for two environments. Nitrogen application 10 dbf resulted in the least grain yield and yields tended to increase with fewer days between application and permanent flood. In Louisiana, urea + NBPT and urea + NBPT + DCD resulted in yields greater than urea alone. Where volatilization potential is substantial, NBPT should be included with the urea application to protect yield potential.

Nitrogen fertilization for southern U.S. rice can account for approximately 25% of the variable costs associated with commercial production (Watkins et al., 2008a, 2008b). The recent high volatility of fertilizer prices has led to increased desire among rice producers to apply N optimally in the most profitable amount (Watkins et al., 2010). In addition to economic factors, N use efficiency in rice production and the subsequent impacts on environmental quality are under constant scrutiny.

The majority of rice production occurs in an anaerobic environment, thus N fertilizer sources should be ammonium or ammonium forming. The two N fertilizers used in dry-seeded, delayed-flood rice culture common to the southern United States are urea and ammonium sulfate. Urea is the most widely used N fertilizer in rice production due to its high N content (44–46% N) and relatively low cost (Bufogle et al., 1998; Norman et al., 2003; Griggs et al., 2007). Ammonium sulfate (21% N) is an excellent source of N but application costs are greater compared to urea due to its lower N concentration. Regardless of which type of N fertilizer is applied before permanent flood establishment in the delayed-flood system, it is imperative to establish a flood within a few days following application to maintain N in the ammonium form.

Managing urea appropriately is critical to minimize potential N loss, especially through ammonia volatilization which has been shown to account for 20 to 80% of N loss in rice production (Mikkelsen et al., 1978; Beyrouty et al., 1988; Griggs et al., 2007; Norman et al., 2009). Ammonia volatilization occurs in the dry-seeded delayed flood rice culture when urea is hydrolyzed to ammonium carbonate [$(NH_4)_2CO_3$] by the urease enzyme and ammonium carbonate decomposes to produce NH_3 and CO_2. The proportion of NH_3 to NH_4^+ is determined by the local pH (Boswell et al., 1985). Soil and floodwater pH, soil and air temperature, cation exchange capacity, H^+-buffering capacity, N source, wind speed, humidity, soil moisture, and NH_3 concentrations all affect the rate of NH_3 volatilization (Harper et al., 1983; Boswell et al., 1985; Bouwmeester et al., 1985).

Urease enzyme inhibitors have been shown to effectively reduce NH_3 volatilization from urea (Bremner and Chai, 1989; McCarty et al., 1989; Watson, 2000). Urease inhibitors accomplish a reduction in NH_3 volatilization by slowing the rate of urea hydrolysis and conversion to NH_4^+ (Norman et al., 2009). The NBPT has been reported to be an effective urease inhibitor which can significantly minimize NH_3 volatilization

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Abbreviations: ANRE, apparent nitrogen recovery efficiency; AS, ammonium sulfate; daa, days after application; dbf, days before flood; DCD, dicyandiamide; HD, heading; NBPT, N-(n-butlyl) thiophosphoric triamide; TDM, total dry matter; TNU, total nitrogen uptake; UAS, urea + ammonium sulfate.

Table 1. Soil chemical properties for each study location in 2009 and 2010.

Year	Location	Texture classification†	Organic matter	Sum of bases	pH	Extractable nutrient levels‡						
						P	K	Ca	Mg	Zn	S	Na
			%	$\text{mol}_c\ \text{kg}^{-1}$					mg kg^{-1}			
2009	Stoneville, MS	Silty clay loam	1.1	20	7.2	62	138	2929	533	3	80	74
2010	Stoneville, MS	Silty clay loam	1.2	28	8.2	87	190	3950	912	2	87	76
2009	Crowley, LA	Silt loam	1.3	8	7.0	21	61	1286	215	7	15	80
2010	Crowley, LA	Silt loam	1.0	9	7.7	4	54	1303	231	4	5	77

† Lancaster soil test extractant was used for Mississippi soils (Cox, 2001) and Mehlich-3 (Mehlich, 1984) soil test extractant was used for Louisiana soils.

‡ Particle-size analysis was determined using the hydrometer method for all locations (Gee and Bauder, 1986).

losses from urea (Buresh et al., 1988; Bremner and Chai, 1989; Clay et al., 1990; Al-Kanani et al., 1994; Rawluk et al., 2001; Norman et al., 2009). Agrotain (Agrotain International, St. Louis, MO) contains NBPT (26% w/w) as its active ingredient and is extensively used as a surface coating on granular urea to minimize ammonia volatilization in delayed flood rice. In addition to reducing NH_3 volatilization, NBPT has been shown to increase the N uptake of rice (Freney et al., 1995; Chaiwanakupt et al., 1996; Aly et al., 2001). Grain yield with NBPT results have varied; Chaiwanakupt et al. (1996) and Norman et al. (2009) observed an increase in grain yield with NBPT, whereas others have not (Buresh et al., 1988; Freney et al., 1995; Aly et al., 2001).

There is demand for higher rice production per unit of land area to meet the needs of an increasing population. Therefore, it is critical to ensure potential N losses are minimized in every possible extent. Factors affecting N losses due to NH_3 volatilization have been extensively studied; however, only three field experiments have been conducted that examined different N sources and application timing and measured subsequent NH_3 volatilization through the use of the semi-open static chamber method (Beyrouty et al., 1988; Griggs et al., 2007; Norman et al., 2009). Only one has evaluated the urease inhibitor NBPT (Norman et al., 2009) and it was only on one soil type. Griggs et al. (2007) and Norman et al. (2009) reported grain yield limiting N losses due to NH_3 volatilization on silt loam and clay soils. Previous research conducted by Walker (unpublished data, 2009) on clay soils in Mississippi, has shown a consistent decrease in grain yield as the time from application to permanent flood increases; however, it is uncertain to what extent the yield loss can be explained by NH_3 volatilization losses. Therefore, the objectives of this study were to quantify N loss via NH_3 volatilization for different N sources and N-fertilizer application timings on southern U.S. rice growing environments and determine the apparent N recovery efficiency and grain yield as it was affected by NH_3 volatilization losses.

MATERIALS AND METHODS

Field experiments were established in Mississippi and Louisiana during the 2009 and 2010 seasons. Fields in Mississippi were located at the Mississippi State University–Delta Research and Extension Center, in Stoneville while the Louisiana fields were located at the Louisiana State University Agricultural Center–Rice Research Station, in Crowley. The two environments in Mississippi will be identified by DREC09 and DREC10 for studies conducted in the years 2009 and 2010, respectively. Likewise, the studies conducted in Louisiana will be identified as RRS09 and RRS10. The soils for DREC09 and DREC10 were classified as Tunica clay (clayey over loamy, smectitic over mixed, superactive, nonacid, thermic Vertic Epiaquerts) while RRS09 and RRS10 were classified as Crowley silt loam (fine, smectitic, thermic Typic Albaqualfs). Selected chemical and physical properties of the soils can be found in Table 1.

Five N sources and four pre-flood N-fertilizer application timings were evaluated. Nitrogen sources included: urea (46–0–0), Agrotain-treated urea [a.i. NBPT at 4.17 mL kg^{-1}], Super-U [combination of a.i. DCD and a.i. NBPT both at proprietary rates], ammonium sulfate (21–0–0–24S), and a 1:1 blend of ammonium sulfate plus urea. Pre-flood N fertilizer application timings were 10, 7, 4, and 1 dbf. In addition, a check treatment (0 N) was also included. A factorial arrangement of treatments in a randomized complete block design with four replications was used for each trial.

'Cocodrie,' a semi-dwarf, long-grain cultivar (Linscombe et al., 2000), was drill seeded on 17 May and 28 April at 90 kg ha^{-1} for DREC09 and DREC10, respectively (Table 2). 'Cheniere,' a high-yielding, early maturing, semidwarf long-grain

Table 2. Dates of important agronomic management, fertilizer treatment, and rainfall events for all study locations in 2009 and 2010.

Event	DREC09	DREC10	RRS09	RRS10
Seeding	17 May	28 Apr.	23 Mar.	14 Mar.
Seedling emergence	26 May	6 May	5 Apr.	1 Apr.
Fertilization timing:				
10 dbf†	9 June	18 May	3 May	20 Apr.
7 dbf	11 June	21 May	6 May	23 Apr.
4 dbf	15 June	24 May	9 May	26 Apr.
1 dbf	18 June	27 May	12 May	29 Apr.
Flood established	19 June	28 May	13 May	30 Apr.
Rainfall event(s) during 10 dbf	none	21 May (6 mm) 22 May (0.2 mm) 25 May (1 mm) 27 May (5 mm)	3 May (14 mm) 4 May (18 mm) 12 May (8 mm)	27 Apr. (2 mm)
50% Heading‡	13 Aug.	21 July	na§	7 July
Harvest	21 Sept.	17 Aug.	13 Aug.	8 Aug.

† dbf, days before flood establishment.

‡ 50% Heading, date when 50% of the panicles emerged from sheath.

§ na, not applicable.

cultivar (Linscombe et al., 2006) was drill seeded on 23 March and 14 March for RRS09 and RRS10, respectively. In all trials, rice was seeded to a depth of 4 cm. Experimental plots consisted of seven (RRS09 and RRS10) or eight (DREC09 and DREC10) drill rows spaced 20 cm apart and measuring 4.6 m in length. Rice was grown in a delayed-flood culture and flood was established at the five-leaf growth stage and maintained throughout the remainder of the growing season until it was drained approximately 2 wk before harvest. Phosphorus, K, S, and Zn were applied according to state soil test recommendations. All trials were managed throughout the season according to individual state recommendations (Saichuk, 2009; Buehring, 2008). Rice plots were harvested when grain moisture ranged from 150 to 180 g kg^{-1} with a Wintersteiger Delta Combine (Wintersteiger, Inc., Salt Lake City, UT) equipped with a Harvest Master Grain Gauge (Juniper Systems, Inc., Logan, UT). Grain yields were standardized to 120 g kg^{-1} moisture content. Pertinent dates for agronomic practices and precipitation events are listed in Table 2.

Total aboveground biomass from 0.9 m of row from the second inside row was hand harvested at 50% heading (HD) from each plot. The biomass samples were oven-dried at 60°C until a constant weight was obtained (48–72 h) and weighed to determine total dry matter (TDM). Samples were ground through a Wiley Mill with a no. 40 screen. Total N concentration was determined using a LECO TruSpec series combustion analyzer (LECO Corp., St. Joseph, MI) according to procedures outlined by Campbell (1992) using a 0.10-g sample. Total N uptake (TNU) was calculated by multiplying TDM by N concentration. Apparent N recovery efficiency, an estimate of fertilizer N efficiency, was calculated according to Ye et al. (2007) where, ANRE = (Total plant N uptake with N application – total plant N uptake without N application)/N application × 100. Due to a late-season off-target drift of glyphosate onto the rice plots, grain yield and ANRE were not used in the analyses for RRS09.

Separate field experiments designed to measure NH_3 volatilization from five N sources over an 18 d period were established adjacent to the yield trials described above. The five N fertilizer sources were identical to the sources used in the field trials described above and were applied at a rate of 168 kg N ha^{-1}. The fertilizer was allowed to sit on the soil surface until a flood was established 10 d after application. A semi open-static system was used to monitor NH_3 volatilization losses, similar to that described by Beyrouty et al. (1988), Griggs et al. (2007), and Norman et al. (2009). Clear plexiglass chambers 13 cm in diameter, 75 cm tall were driven 15- cm deep into the soil. Two polyurethane foam sorbers (2.54 cm thick), impregnated with 20 mL of a 0.73 M H_3PO_4–33% glycerine (v/v) solution, were installed in each chamber to trap volatilized NH_3. Before use, each sorber was initially washed with 0.73 M H_3PO_4, rinsed with deionized water, placed into labeled Ziploc bags. The sorbers were randomly extracted with 100 mL of 2 M KCl solution to ensure minimal NH_4–N contamination. The first sorber was placed 15 cm below the top of the chamber to trap the NH_3 volatilized from the soil surface, and the second sorber was placed level with the top of the chamber to eliminate atmospheric interference. Sorbers were protected from rainfall by plastic buckets. The buckets were suspended 5 cm above the top of the chamber by either metal rods (MS) or by a cross-section of 6.4 mm pvc pipe (LA) placed between the top of the cylinder and the bottom of the bucket, allowing air circulation. The first sorbers were installed immediately after N fertilizer application and were removed and replaced with new sorbers 3, 6, 9, 12, 15, and 18 d thereafter (Table 2). The upper sorbers were discarded after removal while the lower sorbers were placed into their original corresponding labeled Ziploc bags. The sorbers were then treated with 100 mL of 2 M KCl solution, allowed to equilibrate for 24 h, and extracted by physically squeezing the sorbers. An automated segmented flow analyzer (Perstorp Analytical Flow III Analyzer, Wilsonville, OR) was then used to determine the concentration of NH_4–N in each sample.

Apparent NRE and rice grain yield data were analyzed as a split-split-plot with environment treated as the whole plot. Nitrogen source defined the subplot, while N application time defined the sub-subplot. Each trial included four replications. Apparent NRE and rice grain yield data were submitted to PROC MIXED in SAS 9.2 (SAS Institute, 2008).

For ammonia volatilization data, the experimental design was a split-split plot where the whole plot was environment, the subplot was fertilizer N source, arranged in a randomized block with four replications. The sub subplot factor was sampling time (sorber removal). Statistical analysis for ammonia volatilization was conducted in SAS 9.2 using PROC MIXED (SAS Institute, 2008). Least square means at the $P < 0.05$ was used for mean separation. When a sampling time interaction was present, as was N source by sampling time, cumulative ammonia volatilization was fitted to Eq. [1] and 95% confidence intervals for fitted values were generated using PROC NLIN:

$$Y = a \times \exp\{-\exp[-(t - t_0)/k]\} \qquad [1]$$

where a is the plateau representing the maximum ammonia volatilized (% of N applied); t_0, is the abscissa of the inflection point representing the lag phase (d); k is the Gompertz rate constant (d^{-1}); and t is time (d).

RESULTS AND DISCUSSION

Volatilization Chambers

Ammonia volatilization was influenced by two, two-way interactions. First, ammonia volatilization was affected by an interaction of environment and N source ($P < 0.0001$, Table 3). In general, loss of N via ammonia volatilization was greater

Table 3. Influence of the interaction of environment and N source, pooled over sampling time on percent ammonia volatilization loss for RRS09, RRS10, DREC09, and DREC10.

	Cumulative ammonia volatilization losses			
Inhibitor	DREC09	DREC10	RRS09	RRS10
	% of applied N			
Urea	7	7	33	19
UAS blend	8	6	21	13
AS	3	5	5	4
Urea + NBPT + DCD	2	4	3	3
Urea + NBPT	2	2	4	2
LSD (0.05)†		5		

† LSD = least significant difference for environment × N source interaction for cumulative ammonia volatilization loss at the 0.05 probability level.

for RRS09 and RRS10 compared to DREC09 and DREC10. The greatest amount of ammonia volatilization occurred when urea was applied at RRS09 (33%). In the same environment, the UAS blend resulted in less volatilization compared to urea. The least volatilization (2–5%) occurred with AS, urea + NBPT, and urea + NBPT + DCD regardless of the environment. Though ammonia losses at RRS10 were not as high as RRS09, the same trend was present. Similar to RRS09 and RRS10, the greatest losses for DREC09 and DREC10 occurred for urea and UAS; however, urea only experienced an approximate 7% loss to ammonia volatilization. Unlike RRS09 and RRS10, the UAS lost similar amounts to urea at DREC09 and DREC10. These data clearly suggest that urea + NBPT, urea + NBPT + DCD, and AS are effective in minimizing N loss via ammonia volatilization. Furthermore, when compared to urea + NBPT, the blend of UAS was not as effective in minimizing volatilization loss in any of the four environments. Experiments conducted in 2003 and 2004 on a Calloway (fine-silty, mixed, active, thermic Aquic Fraglossudalf) silt loam by Norman et al. (2009) and on a Dewitt (fine, smectitic, thermic Typic Albaqualf) silt loam by Griggs et al. (2007) showed similar findings for ammonia volatilization loss from urea. Loss of ammonia ranged from 20 to 30% in these two reports. Norman et al. (2009) showed that AS decreased ammonia loss to 5% whereas urea+NBPT resulted in ammonia loss of 10%. This is different than what was found in our study as numerical, but not significant differences were always greater for AS compared to urea+NBPT, and urea+NBPT+DCD. Griggs also showed that volatilization loss was less from urea on a Perry (very-fine, smectitic, thermic Chromic Epiaquert) clay relative to the Dewitt silt loam reaching a maximum of 10 to 15% from 10 to 20 d after application. Our findings of greater ammonia loss with urea on the Crowley series compared to the Tunica series is substantiated by those of Griggs et al. (2007). Furthermore, Boswell et al. (1985) demonstrated that the cation exchange capacity (CEC) of the soil influences NH_3 volatilization by acting as a temporary sink for NH_4^+, which reduces the aqueous NH_4^+ concentration and the NH_3 concentration (Boswell et al., 1985).

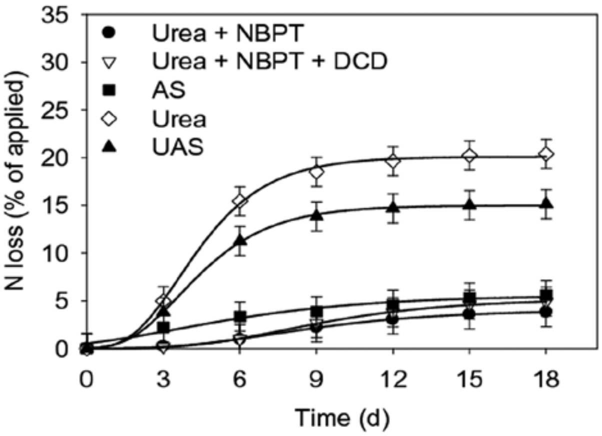

Fig. 1. Cumultive ammonia volatilization for sampling time (d) from semi-open, static chamber method for urea + N-(n-butyl) thiophosphoric triamide (NBPT), urea + NBPT + dicyandiamide (DCD), ammonium sulfate (AS), urea, and 1:1 urea + AS blend (UAS). Symbols represent the mean of two environments from Louisiana and Mississippi each replicated four times ($n = 16$). Error bars denote the standard error of the mean. Fitted values, indicated by the smooth line, are the best fit of the Gompertz model $Y = a \times \exp(-\exp(-(t - t_0)/k))$ where a is the plateau representing the maximum ammonia volatilized (% of N applied); t_0, is the abscissa of the inflection point representing the lag phase (d); k is the Gompertz rate constant (d^{-1}); and t is time (d).

Ammonia volatilization was also affected by an interaction of N source and sampling time ($P < 0.0001$, Fig. 1, Table 4). In general,ammonia volatilization increased with increasing days after application (daa). Volatilization reached a plateau for all sources once the permanent flood was established (10 daa). When pooled over environment, maximum volatilization was greatest for urea (20%), UAS (15%), followed by AS, Urea+NBPT+DCD, and urea+NBPT at 6, 5, and 4%, respectively. The lag phase, which is an indication of the kinetics of the reaction indicated that urea, UAS, and AS were similar in that volatilization occurred within approximately 3.5 daa. The major difference in the three sources was the loss of ammonia from AS happened rapidly, but did not continue over many days (maximum of 6% loss), whereas the loss continued to increase at a greater rate for urea and UAS until reaching the plateau at 10 to 12 daa. Norman et al. (2009) reported that unlike urea, which requires a few days to hydrolyze, the reaction of AS is immediate on dissolution; it is not unusual for most of the NH_3 volatilized from AS to be measured within the first few days after application as the AS dissolves and acidifies the soil surrounding the granule. Beyrouty et al. (1988) reported that within the first 7 to 10 d after preflood N application, the majority of the N losses due to NH_3 volatilization were observed; cumulative NH_3 volatilization loss for urea was 30% of applied N. Urea+NBPT and urea+NBPT+DCD had lag phase values of approximately twice as much as urea indicating that NBPT was indeed slowing the rate of hydrolysis.

Table 4. Fitted values for the Gompertz growth model describing cumulative ammonia volatilization as a function of N source by sampling time for the semi-open, static chamber method. Nitrogen sources included urea + N-(n-butyl) thiophosphoric triamide (NBPT), urea + NBPT + dicyandiamide (DCD), ammonium sulfate (AS), urea, and 1:1 urea + AS blend (UAS). The Gompertz model is as follows: $Y = a \times \exp\{-\exp[-(t - t_0)/k]\}$ where a is the plateau representing the maximum ammonia volatilized (% of N applied); t_0, is the abscissa of the inflection point representing the lag phase (d); k is the Gompertz rate constant (d^{-1}); and t is time (d).

N source	A, max evolved	K, inverse rate constant	B, lag phase	R^2	*P* value
	%	d			
urea	20.0916 (± 0.5667)†	1.8822 (± 0.3206)	3.6060 (± 0.2339)	0.9983	0.0001
UAS blend	14.9833 (± 0.2708)	1.9762 (± 0.2119)	3.6000 (± 0.1521)	0.9993	0.0001
AS	5.5848 (± 1.3347)	4.2220 (± 3.2912)	3.5621 (± 2.0570)	0.9664	0.0011
urea + NBPT + DCD	5.2086 (± 0.2519)	3.6032 (± 0.4902)	7.6860 (± 0.3111)	0.9994	0.0001
urea + NBPT	4.0505 (± 0.1138)	3.7500 (± 0.3499)	7.2135 (± 0.2221)	0.9997	0.0001

† Ninety-five percent confidence interval as calculated by SAS NLIN.

Table 5. Test of fixed effects and interactions for rice apparent nitrogen recovery efficiency (ANRE) and grain yield at the LSU AgCenter RRS in 2010 and the MSU DREC in 2009 and 2010.

Source	ANRE	Grain yield
	$P > F$†	
Environment	0.04	<0.0001
Timing	0.44	0.0008
N Source	0.05	0.20
Environment × Timing	0.004	<0.0001
Environment × N source	<0.0001	0.001
Timing × N source	0.93	0.33
Environment × Timing × N source	0.62	0.22

Table 6. Apparent nitrogen recovery efficiency (ANRE) as affected by the interaction of environment and N source pooled across N application timing.

N source†	ANRE‡		
	RRS10	DREC09	DREC10
	%		
urea	59	64	48
urea + NBPT	65	64	43
urea + NBPT + DCD	68	71	49
AS	52	43	55
UAS blend	56	57	44
LSD (0.05)§		11	

† NBPT, *N*-(n-butyl)thiophosphoric triamide; DCD, dicyandiamide; AS, $(NH_4)_2SO_4$; UAS blend, urea-$(NH_4)_2SO_4$. All N sources applied at 168 kg N ha^{-1}.

‡ ANRE, apparent N recovery efficiency, = (total plant N uptake with N application – total plant N uptake without N application)/N application × 100.

§ LSD = least significant difference for environment × N source interaction for ANRE at the 0.05 probability level.

Apparent Nitrogen Recovery Efficiency

Apparent N Recovery Efficiency was affected by an interaction of environment and N source as well as an interaction of environment and application timing (Table 5). Pooled over application timing, %ANRE was similar within each N source for the RRS10 and DREC09 environments (Table 6). Furthermore, each source in these two environments provided greater %ANRE compared to DREC10 except for AS. At RRS10 and DREC09, urea + NBPT + DCD had greater %ANRE compared to AS and UAS. At DREC10, AS proved to be more efficient compared to UAS and urea + NBPT.

Nitrogen application timing in the three environments demonstrated different trends (Table 7). Comparing results within the environments, RRS10 tended to have greater %ANRE the closer the application was to establishing a permanent flood. The ANRE was not significantly different between fertilizer application occurring 1, 7, and 10 dbf at DREC09. DREC10 had the largest %ANRE at 1 dbf, and was greater than 4 and 10 dbf applications but not different than 7 dbf. The lack of improvement in fertilizer efficiency between 7 and 1 dbf can be partially explained by the rainfall events which occurred after fertilizer application on Days 7 and 6 before flood establishment thus, incorporating the fertilizer (Table 2). Comparing results across the environments and N sources, at 1 and 4 dbf, RRS10 produced the greatest %ANRE, whereas at 10 dbf, DREC09 was greatest. Fertilizer use efficiency for ^{15}N (FUE-^{15}N), in tropical lowland rice production has been reported to be approximately 30 to 50% (De Datta et al., 1968; Bronson et al., 2000; Eagle et al., 2001). Research conducted by Wilson et al. (1989) found that dependent on the application time, the rice plant had an observed total recovery of 53 to 74% of the applied N. Guindo et al. (1992) reported FUE-^{15}N values for drill-seeded, delayed-flood rice in the range of 72 to 79% when ^{15}N fertilizer was applied 1 d before flood establishment andinto the flood water at panicle differentiation. Our results show a range of 43 to 71% ANRE for multiple N sources and multiple times between N fertilizer application and flooding across multiple environments.

Table 7. Apparent nitrogen recovery efficiency (ANRE) as affected by the interaction of environment and N application timing pooled across N source.

Preflood N†	ANRE‡		
	RRS10	DREC09	DREC10
	%		
1 d	64	57	54
4 d	64	53	44
7 d	59	61	49
10 d	54	66	44
LSD (0.05)§		9	

† Preflood N, days before flood establishment; application timing rate of 168 kg N ha^{-1}.

‡ ANRE, apparent nitrogen recovery efficiency, = (Total plant N uptake with N application – total plant N uptake without N application)/N application × 100.

§ LSD = least significant difference for environment × N application timing interaction for ANRE at the 0.05 probability level.

Rice Grain Yield

The environment by N source and environment by N application timing affected rice grain yields (Table 8). Regardless of N source, or N application timing, DREC09 produced less grain yields compared to the other environments. Furthermore, no yield differences occurred among N sources within DREC09. Rice grain yield has been shown to decrease as seeding date is delayed due to decrease in the number of days spent in vegetative growth (Slaton et al., 2003). Slaton et al. (2003) optimized rice grain yield in Arkansas when seeding date occurred between 29 March and 26 April. Averaged over recent years, the optimum planting date to achieve 95% or greater relative grain yield based on planting date at the DREC has been from late-March to mid-April (Walker, unpublished data). Due to adverse planting

Table 8. Rice grain yield as affected by an interaction of environment and N source pooled across N timing.

N source†	Environment		
	RRS10	DREC09	DREC10
	Grain yield		
	kg ha^{-1}		
urea	8958	8430	9274
urea + NBPT	9500	8459	9424
urea + NBPT + DCD	9326	8358	9237
AS	8844	8187	9582
UAS	9203	8287	9193
LSD (0.05)‡		290	

† NBPT, *N*-(n-butyl) thiophosphoric triamide; DCD, dicyandiamide; AS, $(NH_4)_2SO_4$; UAS blend, urea-$(NH_4)_2SO_4$. All N sources applied at 168 kg N ha^{-1}.

‡ LSD = least significant difference for environment × N source interaction for grain yield at the 0.05 probability level.

Table 9. Rice grain yield as affected by an interaction of environment and N application timing pooled across N source on grain yield.

Preflood N†	Grain yield RRS10	 DREC09	 DREC10
	kg ha^{-1}		
1 d	9613	8457	9589
4 d	9235	8237	9321
7 d	9072	8243	9474
10 d	8745	8440	8984
LSD (0.05)‡		259	

† Preflood N, days before flood establishment; application timing rate of 168 kg N ha^{-1}.

‡ LSD = least significant difference for environment × N application timing interaction for grain yield at the 0.05 probability level.

conditions in 2009, the experiment could not be planted until 17 May 2009 for DREC09. Weather patterns quickly changed after planting DREC09 and soil conditions were extremely dry when N fertilizer treatments were applied and continued until permanent flood establishment. Results from the ammonia volatilization experiments were clear in that volatilization potential was substantially less for the Tunica clay soil relative to the Crowley silt loam. Dry soil conditions and low volatilization potential are responsible for no source or timing differences for rice grain yield at DREC09. In the DREC10 and RRS10 environments, N sources resulted in different grain yields. At RRS10, urea + NBPT resulted in grain yields that were greater than all sources but urea + NBPT + DCD. At DREC10, AS resulted in greater yields, albeit relatively small differences (<5%), compared to UAS, urea + NBPT + DCD, and urea. Except for urea and AS, which when applied at DREC10 were greater than RRS10, yields were similar for sources when compared across the RRS10 and DREC10 environments. Ammonia volatilization potential was shown to be greater at RRS10 compared to DREC09 and DREC10, with volatilization losses exceeding 20% when urea was the source at RRS10.

Rice grain yields at RRS10 decreased with increasing days of N application before establishing a permanent flood (Table 9). Pooled across N sources approximately 10% yield loss was observed when N was applied 10 d before permanent flood establishment. A similar trend was observed at DREC10; however, the loss was approximately 6%. Within N application timings, rice grain yields were similar across DREC10 and RRS10 except at the 7 d timing where grain yields were greater at DREC10 compared to RRS10. Table 2 provides pertinent precipitation events that provide some clarity on the grain yield results. No precipitation occurred during the application timing window at DREC09, and only 2 mm of rain was received the day after the 4 dbf application timing at RRS10. However, for DREC10, precipitation events occurred on the day of the 7 dbf application, the day after the 4 dbf application, and the day of the 1 dbf application. Similar to ANRE, these rainfall events at DREC10 partially explain the yield responses. Certain timings theoretically would have been more prone to volatilization losses, that is, applications onto damp soil, whereas rain events after application may have minimized volatilization. Sommer et al. (2004) emphasized that soil resistance to NH_3 volatilization is associated with rainfall events. Harper et al. (1983) reported that rainfall dispersed urea which prevented high concentrations of NH_3 and NH_4^+ from building up around urea-prills. Bouwmeester et al. (1985) reported a 4-cm rainfall decreased N losses by approximately 30% regardless of the initial soil moisture content; the highest losses were observed when wet soil conditions were maintained and air humidity was between 80 and 95% with no rainfall (Bouwmeester et al., 1985).

CONCLUSIONS

These results clearly demonstrate differences exist in ammonia volatilization potential from two major rice growing soils in the southern United States. We measured ammonia volatilization losses from the Crowley silt loam in Louisiana similar to those measured from silt loam soils in Arkansas. The Tunica clay soil lost only 30 to 50% of the amount for the silt loam soil in this study and in other studies from Arkansas. Urea + NBPT, Urea + NBPT + DCD, and AS were effective in minimizing N loss to volatilization as compared to urea. A UAS blend provided better control of volatilization at RRS09 and RRS10 as compared with urea; however, it was not different from urea at DREC09 and DREC10. Yield losses were substantial due to volatilization at RRS10. Yield differences occurred at DREC10 but not at DREC09. In general at RRS10 and DREC10, rice grain yields increased as fertilizer application time before permanent flood establishment decreased. The lone exception was 7 dbf at DREC10 which could be partially explained by rainfall events which occurred just after fertilizer application. Results from this study suggest that growers who cannot incorporate urea fertilizer within a few days after application should protect against volatilization loss using the urease-inhibiting compound NBPT. In environments where volatilization losses can be substantial, growers can expect a sizable return on the investment.

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