

# Nitrogen Fertilizer Sources and Timing before Flooding Dry-Seeded, Delayed-Flood Rice

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Urea is the primary N source used for the large pre-flood N application in delayed-flood rice (*Oryza sativa* L.) production in the southern United States. Urea is prone to substantial  $\text{NH}_3$  volatilization losses, however, if fields are not flooded quickly. Most delayed-flood rice fields require 5 to 10 d to flood. Consequently, a study was conducted to evaluate the use of less  $\text{NH}_3$ -volatile N sources for the pre-flood N application. The objectives were to evaluate the  $\text{NH}_3$  volatilization loss and impact on N uptake and rice yield when urea, urea plus the urease inhibitor *N*-(*n*-butyl)thiophosphoric triamide (NBPT),  $(\text{NH}_4)_2\text{SO}_4$ , or a urea- $(\text{NH}_4)_2\text{SO}_4$  (UAS) blend were applied pre-flood and a flood established 1, 5, or 10 d after N application. When flooding was delayed for 5 or 10 d after N application,  $\text{NH}_3$  volatilization was the least for urea + NBPT (2–10%) and  $(\text{NH}_4)_2\text{SO}_4$  (4–5%) and they produced the highest rice N uptake and yield. The UAS blend that had  $\text{NH}_3$  volatilization losses (11–15%) at 5 and 10 d after application that were intermediate between urea (17–24%) and  $(\text{NH}_4)_2\text{SO}_4$  or urea + NBPT also had N uptake and grain yield intermediate between these N sources. Urea should only be used if ~2 d are required to flood a field. If 3 to 5 d are required to flood a field, then UAS has some merits but it is not as consistent as  $(\text{NH}_4)_2\text{SO}_4$  or urea + NBPT. When >5 d are required to flood,  $(\text{NH}_4)_2\text{SO}_4$  or urea + NBPT should be used.

Abbreviations: NBPT, *N*-(*n*-butyl)thiophosphoric triamide; UAS, urea-ammonium sulfate.

The early N fertilizer application in the dry-seeded, delayed-flood rice culture system should be applied as an  $\text{NH}_4^+$  or  $\text{NH}_4^+$ -forming N source onto dry soil immediately before flooding, termed *pre-flood N application*, at around the four- to five-leaf growth stage (Norman et al., 2003). Once the pre-flood N fertilizer has been applied, flooding should be completed as quickly as possible, preferably within a few days. The floodwater moves the N fertilizer down into the soil profile and thus minimizes losses via  $\text{NH}_3$  volatilization and nitrification-denitrification as long as a flood is maintained (De Datta and Patrick, 1986; Savin et al., 2007). The flood should be maintained for at least 3 to 4 wk to achieve maximum uptake of the pre-flood-applied N fertilizer (Wilson et al., 1989; Norman et al., 1992; Guindo et al., 1994).

Urea (460 g N  $\text{kg}^{-1}$ ) is the primary N source used in the delayed-flood rice cultural system practiced in the southern United States (Norman et al., 2003). This is because of its high N analysis, ease of handling, and lower cost relative to other N sources. Although urea has many fine qualities, it also has the undesirable characteristic in that its rapid hydrolysis to  $\text{NH}_4^+$  can lead to substantial  $\text{NH}_3$  volatilization losses if not soil incorporated within a couple of days after surface application (Mikkelsen et al., 1978; Vlek and Craswell, 1979; Griggs et al., 2007). Most rice farmers cannot flood their fields within a few days following the pre-flood urea fertilizer application. Typically, 5 to 10 d are required to get the floodwater across the field. In a situation where a farmer cannot flood in a timely manner after the pre-flood N application, it would seem prudent to use an N source less prone than urea to  $\text{NH}_3$  volatilization loss.

Ammonium sulfate (210 g N  $\text{kg}^{-1}$ ) is an excellent N source that has slightly acidic properties and thus is less prone to  $\text{NH}_3$  volatilization loss than urea (Vlek and Craswell, 1979). Bufogle et al. (1998) demonstrated that urea was equally effective as  $(\text{NH}_4)_2\text{SO}_4$  as a pre-flood N source in supplying N to delayed-

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flood rice; however, they flooded the study area within 1 or 2 d following the pre-flood N application and did not measure  $\text{NH}_3$  volatilization. Griggs et al. (2007) compared urea to  $(\text{NH}_4)_2\text{SO}_4$  as a pre-flood N fertilizer source for delayed-flood rice and delayed the flood up to 14 d after pre-flood N application. Ammonia volatilization was much greater for urea than  $(\text{NH}_4)_2\text{SO}_4$  during the 14 d before flooding and resulted in significantly less N uptake and grain yield of rice. The drawbacks of  $(\text{NH}_4)_2\text{SO}_4$  are that it typically costs appreciably more than urea, on an N weight basis, and the lower N analysis of  $(\text{NH}_4)_2\text{SO}_4$  compared with urea increases aerial application expense, especially with the large pre-flood N rates (100–150 kg N ha<sup>-1</sup>) required in the southern United States by currently grown rice cultivars. Ammonium sulfate is typically not used as the sole pre-flood N source but is blended with urea to offset some of the costs and still possibly gain some of the beneficial effects of the  $(\text{NH}_4)_2\text{SO}_4$ .

Urease enzyme inhibitors have been reported to be an effective means to minimize  $\text{NH}_3$  volatilization from urea (Bremner and Chai, 1989; McCarty et al., 1989; Watson, 2000). A urease inhibitor minimizes  $\text{NH}_3$  volatilization loss by slowing the rate of urea hydrolysis and conversion to  $\text{NH}_4^+$ . Slowing the urea hydrolysis rate slows the pH and  $\text{NH}_4^+$  concentration increase in the soil surrounding the granule and allows more time for the urea to diffuse into the soil and away from the granule site (Bremner and Chai, 1989; Clay et al., 1990; Watson, 2005). The compound NBPT has been reported to be an effective urease inhibitor and to significantly minimize  $\text{NH}_3$  volatilization loss of urea (Bremner and Chai, 1989; Al-Kanani et al., 1994; Rawluk et al., 2001). Several studies concerning urea applied into the floodwater of transplanted, lowland rice have reported the benefits of NBPT in decreasing  $\text{NH}_3$  volatilization loss and increasing the N uptake of rice (Freney et al., 1995; Chaiwanakupt et al., 1996; Aly et al., 2001) with some measuring a significant grain yield increase (Chaiwanakupt et al., 1996) while others measured no significant yield increase (Buresh et al., 1988; Freney et al., 1995; Aly et al., 2001). None of these rice studies evaluated urea applied with and without NBPT to an unflooded or unsaturated soil surface before flooding such as is practiced in dry-seeded, delayed-flood rice. The only study with some similarities to delayed-flood rice where NBPT has been evaluated was a greenhouse study with transplanted rice (Soliman and Abdel Monem, 1996). Soliman and Abdel Monem (1996) applied urea with and without NBPT to an unsaturated soil surface at an undesignated time before flooding and transplanting rice. They reported significantly greater N uptake by the transplanted rice when urea was applied with NBPT than when it was applied without NBPT.

A review of the refereed literature regarding the  $\text{NH}_3$  volatilization loss of N fertilizer applied pre-flood and the impact on the N uptake and grain yield of dry-seeded, delayed-flood rice found only the field study conducted by Griggs et al. (2007) evaluating urea and  $(\text{NH}_4)_2\text{SO}_4$  applied pre-flood. Griggs et al. (2007) indicated that substantial  $\text{NH}_3$  volatilization loss of urea can occur even if the flood is delayed for just 5 d following urea application and that  $(\text{NH}_4)_2\text{SO}_4$  is a viable substitute for urea when the flood cannot be established in <5 d. The minimal knowledge concerning  $\text{NH}_3$  volatilization loss from the large pre-flood application of urea in dry-seeded, delayed-flood rice coupled with the considerable knowledge of NBPT to mini-

mize  $\text{NH}_3$  volatilization of urea when applied directly to the soil surface necessitates research into the viability of NBPT to increase the efficiency of urea applied pre-flood in delayed-flood rice culture when the flood cannot be established in a timely manner. Consequently, a study was conducted to evaluate and compare the  $\text{NH}_3$  volatilization loss, N uptake, and grain yield of dry-seeded, delayed-flood rice when urea, urea + NBPT,  $(\text{NH}_4)_2\text{SO}_4$ , and a UAS blend were applied to a silt loam soil at various times before flooding.

## MATERIALS AND METHODS

### Site Description

The study was conducted in 2003 and 2004 at the University of Arkansas Pine Tree Branch Experiment Station on a Calloway silt loam (a fine-silty, mixed, active, thermic Aquic Fraglossudalf) in fields that have been in a rice-soybean [*Glycine max* (L.) Merr.] rotation for the past few decades. The experimental site in 2003 had an average soil pH (1:2 soil/water suspension) of 7.3, Mehlich-3-extractable P of 26 mg P kg<sup>-1</sup>, and Mehlich-3-extractable K of 126 mg K kg<sup>-1</sup>, and the experimental site in 2004 had an average soil pH (1:2 soil/water suspension) of 7.6, Mehlich-3-extractable P of 24 mg P kg<sup>-1</sup>, and Mehlich-3-extractable K of 119 mg K kg<sup>-1</sup>. Since soil analyses indicated that soil P and K concentrations were sufficient for optimum rice growth for both experimental sites, no P and K fertilizer was applied (Slaton, 2001). Due to high soil pH, 10 kg Zn ha<sup>-1</sup> as granular  $\text{ZnSO}_4$  was applied to the experimental sites immediately before seeding.

### Yield and Nitrogen Uptake Experiments

The short-statured, long-grain rice cultivar Wells (Moldenhauer et al., 2007) was chosen for use in both years of the study due to its high yield potential, N responsiveness, and widespread use in Arkansas. Rice was seeded at 120 kg ha<sup>-1</sup> in nine-row-wide plots (18-cm spacing) of 4.6 m in length on 16 Apr. 2003 and 26 Apr. 2004. The rice was grown upland until the four- to five-leaf growth stage and then a permanent flood (5–10-cm depth) was established on 4 June 2003 and 13 June 2004 and maintained until maturity. Weed growth was controlled by use of a tank mixture of 0.30 kg ha<sup>-1</sup> clomazone (2-[[[(2-chlorophenyl)methyl]-4,4-dimethyl-3-isoxazolidinone] plus 0.40 kg ha<sup>-1</sup> quinclorac (3,7-dichloro-8-quinolinecarboxylic acid) applied to the soil surface before rice emergence followed by a tank mixture of 4 kg ha<sup>-1</sup> propanil (*N*-(3,4-dichlorophenyl)propanamide) plus 0.04 kg ha<sup>-1</sup> bensulfuron methyl (methyl 2-[[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl]methyl]benzoate) at the four-leaf stage and just before flooding.

Fertilizer N sources were: (i) urea; (ii) urea + NBPT; (iii)  $(\text{NH}_4)_2\text{SO}_4$ ; and (iv) UAS. The UAS was a 1:1 urea- $(\text{NH}_4)_2\text{SO}_4$  blend on an N weight basis. Agrotain solution contains the NBPT urease inhibitor at a concentration of 200 g kg<sup>-1</sup> (Agrotain International, St. Louis, MO). The urea + NBPT source was prepared by blending 1 kg of prilled urea with 4.2 mL of Agrotain solution. Fertilizer N rates applied were 0 (control), 67, and 134 kg N ha<sup>-1</sup>. The application times for the N fertilizers were 10, 5, and 1 d pre-flood. All N fertilizers were applied by hand to a dry soil surface with no mechanical incorporation. The soil gravimetric water content at the time of N application averaged 0.18 and 0.23 kg water kg<sup>-1</sup> soil in 2003 and 2004, respectively.

Plant samples were collected from each plot by hand cutting the total aboveground biomass from a 1-m length of a second inside row at heading for determination of total N uptake. Plant samples were collected at heading for total N uptake because previous research has shown that maximum total N uptake in rice typically occurs at heading

(Norman et al., 1992; Guindo et al., 1994). Plant samples were dried at 60°C to a constant weight, weighed, and ground to pass through a 425- $\mu\text{m}$  sieve. Total N concentration was determined on a 0.1-g subsample of plant tissue by dry combustion (Elementar Vario Max CN, Mount Laurel, NJ; Campbell, 1992). Total N uptake ( $\text{kg N ha}^{-1}$ ) was calculated as the product of plant N concentration ( $\text{kg N kg}^{-1}$ ) and total dry matter accumulation ( $\text{kg ha}^{-1}$ ). At maturity, a 2.6- $\text{m}^2$  area from the center four rows of each plot was harvested for grain yield using a small plot combine. The harvested grain was weighed, analyzed for moisture content and the reported grain yields adjusted to a uniform moisture content of 120 g  $\text{H}_2\text{O kg}^{-1}$  before statistical analysis.

The treatments were arranged as a randomized complete block, 4 (N source)  $\times$  2 (rate)  $\times$  3 (application time) factorial design with four replications plus a no-N control. Analysis of variance was performed on the total N uptake and grain yield data utilizing SAS 9.1 (SAS Institute, Cary, NC). Differences among means were compared using Fisher's protected LSD procedure at a  $P = 0.05$  probability level.

### Ammonia Volatilization Measurements

A semi-open-static system was utilized to monitor  $\text{NH}_3$  volatilization losses, similar to that described by Beyrouy et al. (1988) and Griggs et al. (2007). Clear Plexiglas chambers 13 cm (diameter) by 75 cm (height) were placed in the field between rows of rice and driven 15 cm into the soil. Chambers were protected from rainfall by plastic buckets suspended 5 cm above the top of the chamber by metal rods to allow air circulation. Polyurethane foam sorbers, 2.54 cm thick, were cut to a slightly larger diameter than that of the chambers so that they remained in place when the sorber was expanded against the sides of the chamber. The foam sorbers were washed, impregnated, and extracted with solutions by squeezing with the hands. The foam sorbers were washed with 0.73  $\text{mol L}^{-1}$   $\text{H}_3\text{PO}_4$ , rinsed with deionized water and randomly extracted with 100 mL of 2  $\text{mol L}^{-1}$  KCl solution followed by steam distillation and titration of the distillates to ensure that no  $\text{NH}_4^+-\text{N}$  was present in the sorbers. The washed foam sorbers were impregnated with 20 mL of a 0.73  $\text{mol L}^{-1}$   $\text{H}_3\text{PO}_4$ -33% glycerine (v/v) solution to trap the  $\text{NH}_3$ . This volume was sufficient to saturate the foam sorber evenly but not drip from the sorber or leach down the sides of the chamber. Two foam sorbers were used in each chamber. The first sorber was placed 15 cm below the top of the chamber to trap the  $\text{NH}_3$  volatilized from the soil surface, and the second sorber was placed level with the top of the chamber to eliminate atmospheric interference. The foam sorbers

were stored after washing, impregnating with the  $\text{H}_3\text{PO}_4$ -glycerine solution, and during extraction with the KCl solution in 3.8-L Ziploc (S.C. Johnson & Son, Racine WI) storage bags. A rectangular box was used to organize and file the storage bags containing the foam sorbers.

Ammonia volatilization of each N fertilizer source was measured for 20 d following the 10-d pre-flood N fertilizer application at the 134  $\text{kg N ha}^{-1}$  rate in both years of the study. This allowed monitoring of the  $\text{NH}_3$  volatilization for 10 d prior and 10 d after flooding. Daily maximum and minimum temperatures were measured on site in 2003 and 2004 using a Taylor 5432 thermometer (Forestry Supplies, Jackson, MS) and rainfall amounts were measured for the 20-d period encompassing 10 d before and after flooding. The chambers were flooded, carefully by hand, when the experimental bay was flooded. The foam sorbers were changed 2, 5, 10 (flood established), 15, and 20 d after the fertilizer N sources were applied, and inserted into their original plastic bags. The foam sorbers were extracted by saturating with 100 mL of 2  $\text{mol L}^{-1}$  KCl solution overnight and extracted by hand squeezing each sorber. A 50-mL aliquot of the 2  $\text{mol L}^{-1}$  KCl extract was steam distilled for determination of  $\text{NH}_4^+-\text{N}$  by acidimetric titration according to Mulvaney (1996). The volatilization data were analyzed for each year separately. For each year, the design was a split plot in which the whole plot was a randomized complete block with three blocks and four N sources. The split-plot factor was sampling time. Ammonia volatilization means were separated using a LSD at  $P = 0.05$  following a significant  $F$  test in the analysis of variance. All analyses were performed using SAS 9.1.

### RESULTS AND DISCUSSION

The weather in both years of the study was quite conducive during the 10 d before flooding for measuring and comparing the  $\text{NH}_3$  volatilization potential of N fertilizer sources under field conditions. No measurable precipitation occurred to incorporate the N fertilizers and minimize  $\text{NH}_3$  volatilization during the 10 d before flooding in either year and the air temperature appeared typical. The air temperatures during the 20-d  $\text{NH}_3$  volatilization measurement period in 2003 consisted of lows ranging from 16 to 24°C and highs ranging from 27 to 34°C, which resulted in an average air temperature range of 22 to 29°C. In 2004, the air temperatures during the 20-d measurement period had lows ranging from 13 to 23°C and highs ranging from 24 to 32°C, with an average temperature range of 19 to 27°C.

#### Ammonia Volatilization

The N source  $\times$  sampling time interaction was significant ( $P < 0.0001$ ) in both years of the study (Table 1). Significant amounts of  $\text{NH}_3$  volatilization were measured from all the N sources except urea + NBPT by the first sampling time, 2 d after N fertilization, in both years. Initially, urea and UAS lost similar amounts of  $\text{NH}_3$  and significantly more than urea + NBPT. Generally, hydrolysis of urea when applied without a urease inhibitor requires just a few days to exceed the ability of the soil to buffer the  $\text{NH}_3$  formed through conversion to the stable  $\text{NH}_4^+$  ion (Beyrouy et al., 1988; Clay et al., 1990; Griggs et al., 2007). The use of NBPT has been shown to minimize  $\text{NH}_3$  volatilization of urea for at least a week after application to the soil (Bremner and Chai, 1989;

**Table 1. Cumulative  $\text{NH}_3$  volatilization losses from urea, urea + N-(n-butyl)thio-phosphoric triamide (NBPT),  $(\text{NH}_4)_2\text{SO}_4$  (AS), and a urea-AS (UAS) blend applied to a silt loam soil in 2003 and 2004.**

Time after application	Cumulative $\text{NH}_3$ volatilization losses							
	2003†				2004‡			
	Urea	Urea + NBPT	AS	UAS	Urea	Urea + NBPT	AS	UAS
d	— % of applied N —							
2	8.1	0.1	3.2	6.0	6.1	0.2	2.7	5.1
5	20.7	2.2	4.7	13.2	17.4	1.7	3.9	11.5
10§	24.4	9.8	5.3	15.2	20.5	7.0	4.3	13.1
15	25.6	12.0	5.5	15.7	21.2	8.1	4.5	13.4
20	25.6	12.0	5.6	15.8	21.2	8.2	4.6	13.5

† LSD(0.05) for 2003 to compare means between days within the same N source = 0.7% and to compare means from different N sources = 3.1%.

‡ LSD(0.05) for 2004 to compare means between days within the same N source = 0.9% and to compare means from different N sources = 2.8%.

§ Permanent flood was established.

Zhengping et al., 1991; Rawluk et al., 2001). Within the first 2 d of application,  $(\text{NH}_4)_2\text{SO}_4$  volatilized about one-half of the total  $\text{NH}_3$  lost from this N source during the 20-d sampling period, which agrees with Griggs et al. (2007). Ammonia volatilization from  $(\text{NH}_4)_2\text{SO}_4$  after 2 d was numerically about one-half that of urea and the UAS blend in both years. Unlike urea, which requires a few days to hydrolyze, the reaction of  $(\text{NH}_4)_2\text{SO}_4$  is immediate on dissolution. Thus, it is not unusual for most of the  $\text{NH}_3$  volatilized from  $(\text{NH}_4)_2\text{SO}_4$  to be measured within the first few days after application as the  $(\text{NH}_4)_2\text{SO}_4$  dissolves and acidifies the soil around the granule. Griggs et al. (2007), in a similar study, measured soil surface pH values ranging from 6.6 to 8.4 in the area where urea had been applied, but measured lower soil surface pH values of 5.0 to 5.9 where  $(\text{NH}_4)_2\text{SO}_4$  had been applied.

Ammonia volatilization from urea and the UAS blend increased substantially between 2 and 5 d after application (Table 1). By 5 d after application, urea volatilized about one-third more  $\text{NH}_3$  than the UAS blend, which lost three and six times more than  $(\text{NH}_4)_2\text{SO}_4$  and urea + NBPT, respectively, in both years. Urea + NBPT and  $(\text{NH}_4)_2\text{SO}_4$  lost <5% of the N due to  $\text{NH}_3$  volatilization by 5 d after application. Cumulative  $\text{NH}_3$  losses from  $(\text{NH}_4)_2\text{SO}_4$  5 d after application were not significantly higher than urea + NBPT. Most (81–85% of total volatilized  $\text{NH}_3$ ) of the  $\text{NH}_3$  volatilized from the N sources during the 20-d monitoring period occurred within the first 5 d of application in both years, the only exception being urea + NBPT.

Ammonia volatilization from the N sources essentially ended at 10 d after N fertilizer application due to the establishment of the permanent flood. Griggs et al. (2007) determined that  $\text{NH}_3$  volatilization from urea and  $(\text{NH}_4)_2\text{SO}_4$  applied to a similar silt loam soil was basically over by 10 d after application and ended when the flood was established at 14 d after application. By 10 d after application, urea had cumulative  $\text{NH}_3$  volatilization losses of 24.4% in 2003 and 20.5% in 2004, which were significantly greater than losses from the other N sources (Table 1). The loss of N from the UAS blend was about equidistant between the losses measured from urea and  $(\text{NH}_4)_2\text{SO}_4$ . The addition of NBPT to the urea delayed most of the  $\text{NH}_3$  volatilization loss until 5 to 10 d after application but also resulted in significantly less total N loss via  $\text{NH}_3$  volatilization than urea alone or the UAS blend. Ammonium sulfate lost the least amount of N, with cumulative  $\text{NH}_3$  volatilization losses during the 10 d before flooding of about one-half that of urea + NBPT and one-fifth that of urea. Mikkelsen (1987) reported that  $(\text{NH}_4)_2\text{SO}_4$  was much less susceptible to  $\text{NH}_3$  volatilization than urea. Griggs et al. (2007) measured little loss of  $(\text{NH}_4)_2\text{SO}_4$  and substantial losses of urea via  $\text{NH}_3$  volatilization from a silt loam soil before flooding.

During the 10 d that  $\text{NH}_3$  volatilization was monitored after flooding, no significant increase in loss was measured from  $(\text{NH}_4)_2\text{SO}_4$  or UAS in either year or urea in 2004 (Table 1). The  $\text{NH}_3$  volatilized after flooding from urea + NBPT, however, although significant, was only 2.2 and 1.2% of the applied N in 2003 and 2004, respectively, and 1.2% of the applied N from urea in 2003. Griggs et al. (2007) measured no significant  $\text{NH}_3$  volatilization loss from urea and  $(\text{NH}_4)_2\text{SO}_4$  after the flood was established. Savin et al. (2007) demonstrated, using intact soil cores, that the floodwater could incorporate  $(\text{NH}_4)_2\text{SO}_4$  and especially urea several centimeters below the soil surface and ter-

minate  $\text{NH}_3$  volatilization when the N fertilizers were applied to a dry silt loam soil.

The cumulative  $\text{NH}_3$  volatilization loss during the 20-d monitoring period, 10 d before flooding and 10 d after flooding, from the four N fertilizer sources in decreasing order were: urea > UAS blend > urea + NBPT >  $(\text{NH}_4)_2\text{SO}_4$ . Similarly, Griggs et al. (2007) measured  $\text{NH}_3$  volatilization losses during a 21-d period after pre-flood N application in delayed-flood rice of 14 to 32% from urea and 1.5 to 7% from  $(\text{NH}_4)_2\text{SO}_4$ . Although no research has been conducted in delayed-flood rice on the  $\text{NH}_3$  volatilization of urea + NBPT applied to the soil surface before flooding, studies have been conducted comparing urea + NBPT to urea alone applied to the soil surface in laboratory and field studies with upland crops. Laboratory studies have reported that the addition of NBPT to urea reduced  $\text{NH}_3$  volatilization from 52 to 5% (Bremner and Chai, 1989), 20 to 3% (Zhengping et al., 1991), and 21 to 4% (Al-Kanani et al., 1994) of the applied N. Field studies comparing urea to urea + NBPT applied to the soil surface have shown that the use of NBPT decreased  $\text{NH}_3$  volatilization losses by 93% (Bronson et al., 1989), 99% (Clay et al., 1990), and 28 to 88% (Rawluk et al., 2001). We measured, by 10 d after N application and the onset of the permanent flood, a reduction in cumulative  $\text{NH}_3$  volatilization loss from the use of NBPT of 60% in 2003 and 66% in 2004.

## Nitrogen Uptake

The N rate  $\times$  N source  $\times$  N application time interaction for N uptake by rice was not significant in 2003 ( $P = 0.3030$ ) but was significant in 2004 ( $P = 0.0468$ ). In 2003 for N uptake, however, there were significant two-way interactions of N rate  $\times$  N source ( $P = 0.0003$ ), N rate  $\times$  N application time ( $P = 0.0052$ ), and N source  $\times$  N application time ( $P < 0.0001$ ). Nitrogen uptake by rice increased as N rate increased for all N sources in 2003 (Table 2). Rice N uptake was similar at the 67 kg N ha<sup>-1</sup> rate for urea + NBPT,  $(\text{NH}_4)_2\text{SO}_4$ , and UAS, which were all significantly greater than urea. Urea + NBPT and  $(\text{NH}_4)_2\text{SO}_4$  resulted in the largest N uptake when 134 kg N ha<sup>-1</sup> was applied. The UAS applied at 134 kg N ha<sup>-1</sup> resulted in less N uptake by rice compared with urea + NBPT and  $(\text{NH}_4)_2\text{SO}_4$ , but more than was obtained with urea.

Nitrogen uptake by rice increased as the N rate increased for each of the three N application times (Table 3). No significant decrease in N uptake was measured at the 67 kg N ha<sup>-1</sup> rate when the flood was delayed from 1 to 5 d nor from 5 to 10 d, but there was a decrease in N uptake when the flood was delayed from 1 to 10 d. A significant decrease in N uptake of 9 to

**Table 2. Influence of the N rate and N source<sup>†</sup> interaction, averaged across pre-flood N application time, on N uptake by rice sampled at heading in 2003.**

N rate kg N ha <sup>-1</sup>	N uptake			
	Urea	Urea + NBPT	AS	UAS blend
0	61			
67	98	116	115	114
134	141	164	163	150
LSD(0.05)	9			

<sup>†</sup> NBPT, *N*-(*n*-butyl)thiophosphoric triamide; AS,  $(\text{NH}_4)_2\text{SO}_4$ ; UAS, urea- $(\text{NH}_4)_2\text{SO}_4$ .

**Table 3. Influence of the N rate and pre-flood N application time interaction, averaged across N sources, on N uptake by rice sampled at heading in 2003.**

N rate kg N ha <sup>-1</sup>	N uptake kg N ha <sup>-1</sup>		
	1 d pre-flood	5 d pre-flood	10 d pre-flood
0		61	
67	116	114	108
134	167	158	148
LSD(0.05)		7	

10 kg N ha<sup>-1</sup> was obtained at the 134 kg N ha<sup>-1</sup> rate, however, when the flood was delayed from 1 to 5 d and from 5 to 10 d.

No significant difference in N uptake by rice occurred among the four N sources when they were applied 1 d before flooding (Table 4). When the time between the N application and flooding was increased from 1 to 5 d, a significant decrease in N uptake was measured for urea, but not for urea + NBPT, (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> or UAS. A further delay between N application and flooding from 5 to 10 d caused a significant decrease in N uptake when urea and UAS were the N sources, but not when urea + NBPT or (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> were used.

A significant interaction of N rate × N source × N application time for N uptake by rice was obtained in 2004 (Table 5). Also, a higher native soil N availability in 2004 than 2003 (Tables 2–4), as indicated by N uptake when no N was applied, caused all of the treatments to have numerically higher N uptake in 2004 (Table 5). Similar to 2003, rice N uptake in 2004 increased as the N rate increased for all N sources at each of the three application times. In addition, N uptake was not significantly different among the N sources when they were applied 1 d before flooding at each of the application rates in 2004. When the flood was delayed until 5 d after the N fertilizer application, urea + NBPT and (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> resulted in similar N uptake compared with when the flood was delayed only 1 d after N application at each of the N rates. Urea and the UAS blend, however, had significantly less N uptake when they were applied 5 d before flooding compared with 1 d at the 134 kg N ha<sup>-1</sup> rate, but not at the 67 kg N ha<sup>-1</sup> rate. Urea + NBPT and (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> had greater N uptake than urea when applied 5 d before flooding at each of the N application rates. The UAS blend applied 5 d before flooding resulted in an N uptake by rice not significantly greater than urea or lower than urea + NBPT or (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> when 67 kg N ha<sup>-1</sup> was applied. When 134 kg N ha<sup>-1</sup> was applied 5 d before flooding, the UAS blend resulted in less N uptake than urea + NBPT

**Table 5. Influence of the N source, N rate, and pre-flood N application time interaction on N uptake by rice sampled at heading in 2004.**

N source†	N uptake‡ kg N ha <sup>-1</sup>					
	67 kg N ha <sup>-1</sup>			134 kg N ha <sup>-1</sup>		
	1 d pre-flood	5 d pre-flood	10 d pre-flood	1 d pre-flood	5 d pre-flood	10 d pre-flood
Urea	145	133	125	194	158	153
Urea + NBPT	148	148	144	192	185	172
AS	150	148	146	187	189	177
UAS blend	149	137	132	185	164	161
LSD(0.05)				14		

† NBPT, *N*-(*n*-butyl)thiophosphoric triamide; AS, (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>; UAS, urea-(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>.

‡ N uptake was 105 kg N ha<sup>-1</sup> when no N fertilizer was applied.

**Table 4. Influence of the N source and pre-flood N application time interaction, averaged across N rates, on N uptake by rice sampled at heading in 2003.**

N source†	N uptake kg N ha <sup>-1</sup>		
	1 d pre-flood	5 d pre-flood	10 d pre-flood
Urea	117	97	87
Urea + NBPT	112	115	111
AS	118	114	116
UAS blend	112	109	100
LSD(0.05)		9	

† NBPT, *N*-(*n*-butyl)thiophosphoric triamide; AS, (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>; UAS, urea-(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>.

or (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>. Urea + NBPT and (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> applied at the 67 kg N ha<sup>-1</sup> rate 10 d before flooding maintained rice N uptake similar to when they were applied at 1 and 5 d before flooding. Conversely, urea and UAS experienced gradual, but significant, decreases in N uptake as the flood was delayed from 1 to 10 d. When 134 kg N ha<sup>-1</sup> was applied and the flood delayed for 10 d after N application, all the N sources except (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> had significant decreases in N uptake compared with when they were applied 1 d before flooding, but not when compared with 5 d before flooding.

In general, the total N uptake results (Tables 2–5) for the different N sources during the 2-yr study reflected the NH<sub>3</sub> volatilization results (Table 1). Very little NH<sub>3</sub> volatilization had probably occurred by 1 d after N application and no significant difference in N uptake was measured among the N sources when they were applied 1 d before flooding. Significant NH<sub>3</sub> volatilization loss differences were found among the N sources when applied 5 and 10 d before flooding and significant differences in rice N uptake resulted. Ammonium sulfate and urea + NBPT had the lowest NH<sub>3</sub> volatilization during the 5- and 10-d periods and generally produced the highest rice N uptake when the time between N application and flooding was 5 and 10 d. The UAS blend usually had an intermediate NH<sub>3</sub> volatilization loss compared with the other three N sources and generally resulted in an intermediate N uptake by rice when the flood was delayed for 5 to 10 d. Urea had the most NH<sub>3</sub> volatilized during the 5- and 10-d periods (Table 1) and resulted in rice with numerically the lowest N uptake when the flood was delayed for 5 and 10 d that was always significantly less than (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> or urea + NBPT and significantly less than the UAS blend in 2003 (Table 4) but not in 2004 (Table 5).

## Grain Yield

The N rate × N source × N application time interaction for rice grain yield was significant in 2003 ( $P = 0.0476$ ) and 2004 ( $P = 0.0043$ ). The much larger grain yields in 2004 compared with 2003 (Table 6) can be attributed to the higher native soil N availability in 2004 (Tables 2, 3, and 5). Rice grain yields increased as N fertilizer rate increased for all of the N sources at each application time in both years (Table 6). Grain yield results for the different

**Table 6. Influence of the N source, N rate, and pre-flood N application time interaction on grain yield of rice in 2003 and 2004.**

Year	N source†	Grain yield‡					
		67 kg N ha <sup>-1</sup>			134 kg N ha <sup>-1</sup>		
		1 d pre-flood	5 d pre-flood	10 d pre-flood	1 d pre-flood	5 d pre-flood	10 d pre-flood
		Mg ha <sup>-1</sup>					
2003	Urea	5.41	4.62	3.62	7.34	6.47	5.72
	Urea + NBPT	5.50	5.53	5.65	7.27	7.41	7.21
	AS	5.61	5.63	5.44	7.40	7.55	7.46
	UAS blend	5.38	5.32	4.75	7.10	6.90	6.31
	LSD(0.05)	0.51					
2004	Urea	7.45	6.65	6.42	9.44	8.07	7.75
	Urea + NBPT	7.68	7.87	7.45	9.46	9.18	8.83
	AS	7.87	7.60	7.76	9.14	8.96	8.63
	UAS blend	7.55	7.07	6.84	9.20	8.36	8.13
	LSD(0.05)				0.44		

† NBPT, *N*-(*n*-butyl)thiophosphoric triamide; AS, (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>; UAS, urea-(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>.

‡ The grain yield was 2.32 and 4.86 Mg ha<sup>-1</sup> when no N fertilizer was applied in 2003 and 2004, respectively.

N sources, rates, and application times reflected the total N uptake results (Tables 2–5) quite well. Grain yield was similar for the different N sources within each application rate when the N sources were applied 1 d before flooding (Table 6). Significant grain yield differences were measured between some of the N sources when they were applied 5 and 10 d before flooding, which matched the N uptake differences between the N sources at these application times. Ammonium sulfate and urea + NBPT had the highest grain yield when the flood was delayed for 5 or 10 d and these two N sources almost always resulted in the highest N uptake by rice when the flood was delayed for 5 or 10 d. The UAS blend usually had a grain yield intermediate between urea and (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> or urea + NBPT and typically resulted in an intermediate N uptake by rice that at times could rival the N uptake produced when urea + NBPT was the N source and at times was not significantly better than urea. Urea applied 5 and 10 d before flooding always resulted in rice with significantly lower N uptake and grain yield compared with (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> and urea + NBPT, and was frequently lower than UAS but not always. Similarly, Griggs et al. (2007), working in delayed-flood rice, reported that (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> applied 14 d before flooding resulted in N uptake and grain yield by rice comparable to urea applied 1 d before flooding and significantly greater than urea applied 14 d before flooding. Studies evaluating urea with and without NBPT applied into the floodwater of transplanted, lowland rice have reported measuring a significant grain yield increase when urea was applied with NBPT (Chaiwanakupt et al., 1996), while others measured no significant yield increase (Buresh et al., 1988; Freney et al., 1995; Aly et al., 2001).

## CONCLUSIONS

The N uptake and grain yield of rice were at a maximum and similar among the four N sources when the flood was applied 1 d after N application. This indicates that a flood applied quickly after N application minimizes NH<sub>3</sub> volatilization loss and maximizes the N uptake and grain yield potential of delayed-flood rice. Ammonia volatilization of urea increased substantially between 2 and 5 d after application and usually resulted in significantly less N uptake and grain yield than the less volatile (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> or urea + NBPT when the flood was delayed for 5 d or more. The UAS blend, which had NH<sub>3</sub> volatilization losses

intermediate between urea and (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> or urea + NBPT when the flood was delayed for 5 and 10 d, also had N uptake and grain yield intermediate between these N sources for these flood establishment times. The practical conclusions and recommendations that can be drawn from this study to minimize NH<sub>3</sub> volatilization loss and maximize uptake of N applied pre-flood to delayed-flood rice are: (i) urea is very prone to NH<sub>3</sub> volatilization loss when applied to a silt loam soil and to minimize this loss a permanent flood should be applied in ~2 d after urea application; (ii) if 3 to 5 d are required to flood a field, then the UAS blend has some merits but it is not as consistent as (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> or urea + NBPT; and (iii) if >5 d are required to flood a field, then (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> or urea + NBPT should be used.

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