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NOTES & UNIQUE PHENOMENA

Performance of Two Nitrification Inhibitors Over a Winter with Exceptionally Heavy Snowfall

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ABSTRACT

Fall application of NH_3 for spring wheat (*Triticum aestivum* L.) is common in the northern Great Plains. Two field sites were established in eastern North Dakota, with the objective of measuring the relative rate of fall and overwinter nitrification as influenced by two nitrification inhibitors, nitrapyrin and ammonium thiosulfate (ATS). Aqua ammonia was injected into the soil in early October 1996, alone, with nitrapyrin (0.56 and 1.68 kg ha^{-1}), or with ATS (17 kg S ha^{-1}). The N rate was 84 kg ha^{-1}. The winter of 1996–1997 was very unusual, with about 3 m of snowfall—three times the average snowfall in southeastern North Dakota. Nitrapyrin and ATS were effective in slowing nitrification in the fall and both inhibitors increased the amount of mineral N found in the fertilizer bands in the spring at both sites. One site was planted to 'Pioneer 2375' spring wheat. Overwinter N loss, presumably by denitrification, was severe. Amending the ammonia with nitrapyrin or ATS greatly increased wheat growth, N uptake, and grain yield. The apparent N uptake efficiency into the grain + straw was 24% for the unamended aqua ammonia, but was 50 to 56% when nitrapyrin or ATS was used. These results probably define a worst-case scenario regarding the performance of fall-applied ammonia in this area, and suggest that both nitrapyrin and ATS have value as nitrification inhibitors with fall-banded N.

FALL APPLICATION of anhydrous ammonia is a common practice for small-grain production in the northern Great Plains. Fall-applied N in this region is subject to overwinter losses, primarily by denitrification during the spring thaw (Nyborg et al., 1997; Lemke et al., 1998), when water-saturated soil lies over frost deeper in the soil. These losses are reduced by banding (or other localization methods) of the N in the fall, the use of nitrification inhibitors, delay of N application to as late as possible in the fall, and deep placement of the N (Aulakh and Rennie, 1984; Malhi and Nyborg, 1984, 1985, 1990, 1992; Nyborg and Malhi, 1986, 1992; Yadvinder-Singh et al., 1994).

The standard nitrification inhibitor for U.S. agriculture is nitrapyrin [2-chloro-6-(trichloromethyl)pyridine]. Use of nitrapyrin with fall-applied N can increase crop yield in areas where spring thaw denitrification is severe (Malhi and Nyborg, 1985). Ammonium thiosulfate [$(NH_4)_2S_2O_3$] (12–0–0–26 N–P–K–S), a widely used liquid fertilizer, has also been shown to inhibit nitrification. Goos and Johnson (1992) found that, when blended with urea–ammonium nitrate (UAN) [$CO(NH_2)_2$–NH_4NO_3] and banded in the soil in the spring, ATS slowed nitrification for about 4 wk, while the effects of nitrapyrin were observed through 8 wk under field conditions. Graziano (1990) compared UAN and UAN + ATS mixtures broadcast and tilled into the soil in the spring, and found that including ATS slowed nitrification for more than two months (8 or 9 wk) under field conditions. There are only limited data, from microplot experiments, on the value of ATS as a nitrification inhibitor with fall-applied N (Goos and Johnson, 1992).

Two simple experiments were established in the fall of 1996, with the objective of comparing the effects of ATS and nitrapyrin on the rate of nitrification of fall-applied aqua ammonia ($NH_4OH{\cdot}H_2O$). However, the winter of 1996–1997 was unusually severe, with about 2 to 3 m of snow falling in eastern North Dakota. The snow pack reached a 1-m depth in much of this region, and the melting of this snowpack culminated in extensive flooding of Grand Forks, ND. After such an unusual amount of snowfall, one site was planted to spring wheat to determine if the inhibitors helped *conserve* N in the soil.

MATERIALS AND METHODS

Two field experiments were established on soils of lacustrine origin, one on a Fargo silty clay (fine, smectitic, frigid Typic Epiaquerts) at the North Dakota State University Main Experiment Station at Fargo, ND, and one on a Gardena loam (coarse-silty, mixed, superactive, frigid Pachic Hapludolls)

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Abbreviations: ATS, ammonium thiosulfate; UAN, urea–ammonium nitrate.

Table 1. Soil tests from the experimental sites. Soil samples taken in the spring of 1997.

Parameter†	Fargo (0–15 cm)	Buffalo (0–15 cm)	Buffalo (15–60 cm)
pH	7.1	6.9	—
Organic matter, g kg^{-1}	63	27	—
Nitrate N, kg ha^{-1}	25	20	19
Avail. P, mg kg^{-1}	29	18	—
Avail. K, mg kg^{-1}	370	170	—
Sulfate S, kg ha^{-1}	51	>150‡	>450‡
Salinity, dS m^{-1}	0.83	0.72	0.85

† pH of 1:1 soil:water suspension; nitrate by salicylic acid method; available P by Olsen (sodium bicarbonate) extraction; available K by ammonium acetate extraction; sulfate by monocalcium phosphate extraction; salinity by the electrical conductivity of a 1:1 soil:water suspension.
‡ Extractable sulfate-S levels > 150 kg ha^{-1} in the 0- to 15-cm layer or > 450 kg ha^{-1} in the 15- to 60-cm layer are simply noted as *very high* and are not quantified further.

near the town of Buffalo, ND, 60 km west of Fargo. The Gardena soil had a glacial till substratum. Both sites were somewhat poorly drained. The Fargo soil typically has a temporary water table at a 0.3- to 1-m depth in the spring, and the Gardena soil typically has a temporary water table at a 1.5- to 2-m depth in the spring (Prochnow et al., 1985). The previous crop was wheat or barley (*Hordeum vulgare* L.). The sites were rototilled in September before treatments were applied. The fertilizer treatments were knifed into the soil on 30-cm centers at a depth of 10 cm on 3 Oct. 1996. The treatments consisted of a control (no N), aqua ammonia applied alone, aqua ammonia applied along with 0.56 or 1.68 kg ha^{-1} of nitrapyrin, and aqua ammonia applied with 17 kg ha^{-1} of S as ATS. The N rate for all treatments except the control was 84 kg ha^{-1}, accounting for the N contained in the ATS. The fertilizer solutions were injected into the soil using thin-profile anhydrous ammonia knives fed by a John Blue (Huntsville, AL) ground-driven fertilizer pump and flow divider. Aqua ammonia was used in this experiment because it is more easily handled and more accurately applied than anhydrous ammonia. Immediately after fertilizer application, flags were placed in the center three application rows to mark locations for subsequent soil sampling. Individual plot size was 2 by 10 m at the Fargo site and 2 by 15 m at the Buffalo site. At both sites, the design was a randomized complete block with four replications.

Soil cores were taken through the fertilizer bands on 23 and 24 Oct. 1996 and on 12 and 14 May 1997 for the Fargo and Buffalo sites, respectively, to monitor relative rates of nitrification. At each sampling time, six cores per plot were taken through the fertilizer bands with a bucket auger (8.5 cm i.d.). The entire soil mass from each plot was air-dried, ground to pass a 2-mm sieve, mixed well, subsampled, and analyzed for KCl-extractable NH_4^+ and NO_3^- (Keeney and Nelson, 1982).

The Buffalo site was planted to 'Pioneer 2375' spring wheat on 15 May 1997. The seeding rate was 100 kg ha^{-1}, and 60 kg ha^{-1} of monoammonium phosphate ($NH_4H_2PO_4$) was banded with the seed as a starter fertilizer. At the 6- to 7-leaf stage of the main stem, approximately 40 random plants were gently dug up from each plot, according to a predetermined sampling plan. The plants were separated and counted. Twenty random plants from within this sampling were evaluated for the relative chlorophyll content of the uppermost fully developed leaf, using a Minolta SPAD 502 meter (Piekielek et al., 1995). All tillers present on these 20 plants were identified by the Klepper system (Klepper et al., 1982). All 40 plants were excised at the chlorophyll line and the roots were discarded. The tops were dried (60°C), weighed, ground finely (<0.1 mm), and analyzed for total N to include NO_3^- (Bremner and Mulvaney, 1982). At maturity, the center two rows of each plot were harvested with a bundle cutter. Straw and grain yields were determined, and samples of the straw and grain were analyzed for the total N. The N uptake in the grain and straw were calculated. The apparent N uptake efficiency (NUE, %) was calculated as

$$[(A - B)/C] \times 100$$

where A is the N uptake in the grain + straw in treatments receiving N fertilizer, B is the N uptake in the grain + straw in the control, and C is the N rate (84 kg ha^{-1}). Analysis of variance was performed using a microcomputer statistical package (Abacus Concepts, 1989). If the F-test for treatment was significant ($P \leq 0.1$), the least significant difference was calculated.

Table 2. Effect of aqua ammonia (Aqua), nitrapyrin, and ammonium thiosulfate (ATS) on KCl-extractable NH_4^+ and NO_3^- found in fertilizer bands in late fall and spring (Fargo, ND).

Fertilizer treatment†	Fall sampling (23 Oct. 1996) NH$_4$	NO$_3$	Sum	Spring sampling (12 May 1997) NH$_4$	NO$_3$	Sum
	mg N kg^{-1}					
Control	0	6	6	3	0	3
Aqua	54	41	95	2	5	7
Aqua + nitrapyrin, 0.56 kg ha^{-1}	80	32	112	9	13	22
Aqua + nitrapyrin, 1.68 kg ha^{-1}	88	24	112	26	11	37
Aqua + ATS, 17 kg S ha^{-1}	76	21	97	9	20	29
LSD (0.1)	23	7	27	7	6	12

† Fertilizers were applied at 84 kg N ha^{-1} on 3 Oct. 1996.

RESULTS

The results of routine soil tests from the experiment sites are shown in Table 1. Both sites had topsoils that were near neutral in pH. The Buffalo site was very high in available sulfate throughout the entire soil profile. The snowpack reached a maximum depth in early March of about 1 m. The snow had totally melted by mid-April. Surface drainage to ditches occurred at both sites, but was slow, given the nearly level surface conditions. The sites remained too wet for foot traffic and soil sampling until early May. The conditions seemed ideal for a spring-thaw denitrification event, as described in several papers by Nyborg and associates, where the topsoil remains saturated for 7 to 14 d after the melting of the snow pack.

The effect of nitrapyrin and ATS on NH_4^+ and NO_3^- in the fertilizer bands at the Fargo site is shown in Table 2. At the time of the late fall sampling, 20 d after fertilizer application, at least a third of the unamended aqua ammonia had been converted to NO_3^-. Both nitrapyrin and ATS were effective in slowing nitri-

Table 3. Effect of aqua ammonia (Aqua), nitrapyrin, and ammonium thiosulfate (ATS) on KCl-extractable NH_4^+ and NO_3^- found in fertilizer bands in late fall and spring (Buffalo, ND).

Fertilizer treatment†	Fall sampling (24 Oct. 1996) NH$_4$	NO$_3$	Sum	Spring sampling (14 May 1997) NH$_4$	NO$_3$	Sum
	mg N kg^{-1}					
Control	3	1	4	2	2	4
Aqua	32	21	53	0	9	9
Aqua + nitrapyrin, 0.56 kg ha^{-1}	63	16	79	19	12	31
Aqua + nitrapyrin, 1.68 kg ha^{-1}	68	10	78	32	9	41
Aqua + ATS, 17 kg S ha^{-1}	54	17	72	13	23	36
LSD (0.1)	10	6	14	11	3	11

† Fertilizers were applied at 84 kg N ha^{-1} on 3 Oct. 1996.

Table 4. Effect of aqua ammonia (Aqua), nitrapyrin, and ammonium thiosulfate (ATS) on spring wheat at the 6- to 7-leaf stage of the main stem (Buffalo, ND).

Fertilizer treatment†	Leaf chlorophyll	T1 + T2 tillers	Total tillers	Plant DM	Total N	Plant N uptake
	SPAD‡	no. plant^{-1}		mg plant^{-1}	g kg^{-1}	mg plant^{-1}
Control	33.5	1.16	1.21	332	24.6	8.2
Aqua	38.5	1.55	1.93	433	30.0	13.1
Aqua + nitrapyrin, 0.56 kg ha^{-1}	41.5	1.80	2.35	513	34.9	17.9
Aqua + nitrapyrin, 1.68 kg ha^{-1}	42.6	1.88	2.56	544	33.9	18.5
Aqua + ATS, 17 kg S ha^{-1}	44.5	1.91	2.96	529	37.6	19.9
LSD (0.1)	1.8	0.14	0.35	30	3.3	1.9

† Fertilizers were applied at 84 kg N ha^{-1} on 3 Oct. 1996.
‡ SPAD units: relative chlorophyll reading using a Minolta SPAD-502 meter.

fication, leading to increased soil NH_4^+ and decreased soil NO_3^- levels in the soil samples. By the time of the May sampling, 6.5 months later, the amount of mineral N remaining in the fertilizer bands was about the same for the control as for the unamended aqua ammonia, indicating substantial movement or loss. When the ammonia was amended with nitrapyrin or ATS, there was a measurable increase in both NH_4^+ and NO_3^- in the bands. The effects of the low rate of nitrapyrin and ATS were about the same with regards to residual NH_4^+ in the bands, but more NO_3^- was observed with ATS. The highest levels of NH_4^+ in the bands were observed with the high rate of nitrapyrin.

Nitrification in the fall was also active at the Buffalo site (Table 3). Based on residual NH_4^+ in the band samples, nitrification was at least half-complete by late October with the unamended aqua ammonia treatment. Adding nitrapyrin or ATS to the ammonia slowed nitrification, as at the Fargo site. The level of NH_4^+ in the band samples receiving unamended aqua ammonia was 32 mg N kg^{-1}, increasing to 54 to 68 mg N kg^{-1} when ATS or nitrapyrin was used. By mid-May, levels of mineral N in the fertilizer band samples were about the same for the control and unamended aqua ammonia treatments, indicating substantial loss or movement. There was significantly more NH_4^+ and NO_3^- in the band samples where the ammonia had been amended with nitrapyrin or ATS, showing that both inhibitors were effective in slowing nitrification.

For the entire growing season, the control plots and the plots receiving unamended aqua ammonia had visually poorer color and growth than the other treatments. These differences were quantified at the 6- to 7-leaf stage of the main stem (Table 4) and at maturity (Table 5). Relative leaf chlorophyll levels, using a Minolta SPAD meter, show that the unamended aqua ammonia treatment gave greener plants than the control, but leaf greenness was greater when nitrapyrin or ATS were used.

Nearly complete tillering at the T1 and T2 position is critical for high wheat yields in this region. It has been estimated that 95 to 100% of the yield of spring wheat plants in eastern North Dakota is given by the combined contributions of the main stem, T1, and T2 tillers (Goos and Johnson, 1996). The same paper suggested that ≥90% initiation of T1 and T2 tillers indicates good attention to seedbed preparation and the fertility needs of young wheat plants. In this present study, tillering at the T1 and T2 positions was very poor with the control, and reached 90% initiation (1.8 T1 + T2 tillers per plant) only when ATS or nitrapyrin was used. Total tiller numbers, plant dry matter, N concentration, and N uptake all followed the same trends, with a positive response to both nitrification inhibitors. It is unlikely that the response of wheat to the ATS was due to the sulfur in the ATS, as the level of available sulfate was very high throughout the soil profile.

The treatment effects observed at the 6- to 7-leaf stage were also apparent at harvest, with the unamended aqua ammonia treatment being better than the control, and with a further increase in all parameters when ATS or nitrapyrin was added to the ammonia. The control treatment remained chlorotic for the whole growing season. The unamended aqua ammonia treatment remained chlorotic also, and did not green-up later in the season. Thus, it seems that a considerable N loss event did occur, not just a temporary lack of availability due to NO_3^- movement to the lower root zone. Grain yields increased by about 900 kg ha^{-1} with unamended ammonia, with an additional increase of 600 kg ha^{-1} when amended with a nitrification inhibitor. Apparent N uptake efficiency into the grain and straw was increased

Table 5. Effect of aqua ammonia (Aqua), nitrapyrin, and ammonium thiosulfate (ATS) on spring wheat at maturity (Buffalo, ND).

Fertilizer treatment†	Straw yield	Grain yield	Straw N uptake	Grain N uptake	Total N uptake	Apparent NUE‡
	kg ha^{-1}					%
Control	2686	1579	10.6	28.2	38.8	—
Aqua	4511	2486	13.9	45.4	59.3	24
Aqua + nitrapyrin, 0.56 kg ha^{-1}	4701	3024	19.2	61.7	80.9	50
Aqua + nitrapyrin, 1.68 kg ha^{-1}	5131	3084	18.8	62.4	81.2	50
Aqua + ATS, 17 kg S ha^{-1}	4969	3179	20.9	65.3	86.2	56
LSD (0.1)	406	291	2.7	6.4	6.8	9

† Fertilizers were applied at 84 kg N ha^{-1} on 3 Oct. 1996.
‡ NUE, nitrogen uptake efficiency.

from 24% for unamended ammonia to 50 to 56% with ATS or nitrapyrin. Given the unprecedented amount of snow received in the winter of 1996–1997 (about three times the average snowfall), these results probably define a worst-case scenario for the performance of fall-applied ammonia in eastern North Dakota.

Previous field studies have shown that ATS is a weaker nitrification inhibitor than nitrapyrin (Goos and Johnson, 1992), and nitrapyrin would be preferred over ATS when a strong nitrification inhibitor is needed. However, our results suggest that, with band application, ATS may also have value as a nitrification inhibitor with fall-applied N. The major advantage of ATS over nitrapyrin is that it is a useful carrier of both N and S. Unlike nitrapyrin, ATS is not thought to be compatible with anhydrous ammonia. Further research is warranted, to develop methods of co-injection of ATS with anhydrous ammonia that allow for maximum nitrification inhibition by the ATS.

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