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Enhanced ammonium sources to reduce nitrate leaching

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Abstract

One approach to reduce NO_3 movement to groundwater is increasing the proportion of N supplied to the crop as NH_4–N. Nitrification inhibitors (NI's) can be used to enhance NH_4–N supply, but most studies have focused on yield response, with little attention given to environmental impacts. To determine the effect of enhanced NH_4 sources on corn grain yield, N uptake and NO_3 movement to groundwater, three sidedress materials were compared during three different growing seasons. Application of anhydrous ammonia (AA) and addition of the NI, dicyandiamide (DCD) to urea-ammonium nitrate (UAN) both reduced NO_3 leaching losses relative to that incurred with UAN. With AA and UAN + DCD (as compared with UAN) subsoil solution NO_3 concentrations were reduced by an average of: 1.1 mg NO_3–N kg^{-1} soil following (fall 1993) a dry growing season; 2.4 mg NO_3–N kg^{-1} soil during (spring and summer 1994) and 1.4 mg NO_3–N kg^{-1} soil after (fall 1994) a wet growing season; and 0.5 mg NO_3–N kg^{-1} soil following (fall 1995) a growing season with intermediate rainfall. Based on average solution NO_3 concentrations and approximate drainage after harvest, estimated N losses between harvest and freeze-up were 43, 22 and 19 kg N ha^{-1} with UAN, UAN + DCD and AA, respectively (average of 3 years). Grain yields and aboveground N uptake were greater with AA and UAN + DCD than with UAN, and residual fertilizer N (applied N less aboveground N uptake) was 18, 6 and -2 kg N ha^{-1} with UAN, UAN + DCD and AA, respectively (average of 3 years). As is often observed, the trend for greater yield with addition of the NI was not large or consistent enough to meet registration criteria. Data demonstrating reduced NO_3 leaching are also relevant, and positive environmental impacts should be a criterion for registration. For growers who are reluctant to use AA, this would provide an alternative source to maximize yield while minimizing NO_3 movement to groundwater.

Introduction

To combat the problem of contamination of groundwater by NO_3–N, which is particularly acute below coarse-textured soils (Agriculture Canada, 1993), some areas have guidelines that restrict the time, form and rate of N fertilizer application (Buerkert et al., 1995). Supplying a greater proportion of the plant's N requirements as NH_4–N (vs. NO_3–N) is one approach used to reduce NO_3 leaching. To this end, use of nitrification inhibitors (NI's) applied with NH_4–N fertilizer sources was proposed for the Nitrate Sensitive Areas scheme in the UK (Davies and Williams, 1994). Enhancing the supply of NH_4 can also increase yields (Alexander et al., 1991; Below and Gentry, 1987) because NH_4 assimilation is less energy costly than NO_3 assimilation. Yield improvements with enhanced NH_4 nutrition (EAN), however, are not always reproducible under field conditions (Barber et al., 1992). Some short-season corn hybrids, for example, may not produce a higher yield when nitrification is inhibited (Tsai and Huber, 1996). Greatest yield responses to the addition of NI's occur on coarse-textured soils, soils with low N fertility or at low N application rates (Frye et al., 1989; Malzer et al., 1989), and in situations where excessive soil water leads to heavy N leaching (Prasad and Power, 1995), usually 300 mm or greater annual water surplus in the case of dicyandiamide (DCD) application in the same growing season (Scharf and Alley, 1988). In view of these field results, yield gains with the use of NI's appear to be more related to N conservation within the system than to a physiological response to EAN.

Most research with NI's has emphasized yield response, and studies of their effects on NO_3 leaching are rather limited (Prasad and Power, 1995). With the aim of maximizing yield while minimizing NO_3 movement to groundwater, we compared urea-ammonium nitrate (UAN), anhydrous ammonia (AA) (which are widely used materials, Biederbeck et al., 1996; Anonymous, 1995), and UAN plus DCD in terms of effects on corn yield, N uptake and NO_3 movement to groundwater.

Materials and methods

Field techniques

The study site was located on Fox loamy sand (Typic Hapludalf) not previously cropped with corn. Corn was conventionally tilled in 1993, and no-tilled in 1994 and 1995. Pioneer hybrid 3751 was planted 12 May 1993 with 33 L ha^{-1} 6-24-6, and hybrid 3752 was planted 18 May 1994 and 15 May 1995 with 150 kg ha^{-1} 13-7-20 3%Mg 2%Zn, in 0.9 m rows at a rate of 61,000 seeds per hectare. The remainder of the fertilizer N requirement was knife-injected (with coulters in 1994 and 1995) mid-way between rows on 24–25 June 1993 (Day 175), 23 June 1994 (Day 174) and 13–14 June 1995 (Day 164) to bring the total N applied to 150 kg N ha^{-1}, which is approximately maximum economic N rate (Ball-Coelho and Roy, 1997). For high-use crops such as corn, on coarse-textured soils it is prudent to split-apply N, with the majority sidedressed, when plant demand is greater. Sidedress N source treatments: UAN; UAN plus 5% by volume DCD (IMC-Agrico Company, Henderson, KY) and AA; were arranged in a randomized block design with four replications. Treatments were applied to the same plots (12 rows wide by 25 m long) each year for three years. Weeds were controlled using a pre-emergent tank-mix (metolachlor plus cyanazine). Aboveground corn phytomass was determined in October from 10 randomly selected plants (per plot) cut at the soil surface. Corn grain yield was determined from combined weights of two rows by 20 m on 2 November 1993, and four rows by 18 m on 31 October 1994 and 18 October 1995.

All plots were irrigated with 25 mm of water on 21 July 1993 to facilitate installation of solution samplers in the dry soil. Solution samplers, consisting of a ceramic cup (100 kPa air entry) glued on a PVC tube with internal Teflon micro tubing for the application of a vacuum and sample extraction, were installed at 1 m (two per plot) July–August 1993, according to the method of Lord and Shepherd (1993). One additional lysimeter per plot was installed at 1.5 m in 1994, following observations of corn roots at 1 m, but few roots at 1.5 m. Solutions were collected when subsoil volumetric moisture contents (θv) exceeded approximately 8%. No solution samples were collected during the summer of 1993 due to low θv. Each time solutions were collected, θv was determined by neutron scattering at 0.3, 0.7, 1.0, and 1.2 m (and 1.4 m in 1994 and 1995) in an access tube in each plot.

Soil samples, comprised of a bulk of three, 0.03 m diameter cores per plot, were taken 0.2 m from the row to 1 m on 18 October and 30 November 1993, and to 1.5 m on 27 July and 16 November 1994, and 14 August and 12 October 1995. Cores were divided into 0 – 0.075, 0.075 – 0.15, 0.15 – 0.3, 0.3 – 0 0.5, 0.5 – 0.75, 0.75 – 1.0, 1.0 – 1.25, and 1.25 – 1.5 m depth increments.

Analytical and Statistical

Soil NO_3 and NH_4 concentrations were determined from a filtered 2*N* KCl extract (Maynard and Kalra, 1993) with correction for soil moisture content. Nitrate and NH_4 concentrations in soil extracts and solutions were determined by continuous flow colorimetry (Tel and Rao, 1981ab). Grain and stover samples were oven-dried at 65 °C, then total N was determined by sulfuric peroxide digestion and continuous flow colorimetry in 1993 (Tel and Rao, 1981c) and by combustion analysis in 1994 and 1995 (LECO Corp., St. Joseph, MI).

Grain yield and N uptake (grain + stover) of corn grown with UAN was compared to that grown with the enhanced NH_4 sources (UAN + DCD and AA) using contrasts (with source and year as factors in the ANOVA). Soil NO_3 and NH_4 concentrations were analysed according to a split plot design with N source as the main plot and depth as the sub-plot. θv was analysed using repeated measures with time as the repeated factor, N source as the main plot and depth as the sub-plot. Solution NO_3 concentration data (mg NO_3–N l^{-1}) were analysed separately for each depth, with day as a continuous variable. For comparison to soil NO_3 concentrations, soil solution NO_3 concentrations were converted to a soil weight basis from

$$\text{mg NO}_3\text{–N kg}^{-1}\text{ soil} = \text{NO}_3\ (\text{mg m}^{-3}) \times \theta v_i\ (\text{m}^3\text{m}^{-3}) \div \text{bulk density}_i\ (\text{kg m}^{-3})$$

where θv = experiment mean (1993 and 1995 data) or treatment mean (1994 data) at sample collection, and i = depth of the solution sampler cup. Treatment mean θv were used in 1994 because that fall, soil was often drier in AA plots (by 0.01 m^3 m^{-3}) than with the other N sources. 1994 and 1995 solution data were grouped by spring and summer vs. fall for averaging.

Results

Corn grain yield and N uptake

Corn grain yields did not differ significantly between N sources when compared within years, other than in 1994 when AA-fed corn out-yielded UAN-fed corn (Table 1). When the 3 years of data were combined, yields were greater with AA (7.5 mg ha $^{-1}$) and UAN + DCD (7.4 mg ha $^{-1}$) than with UAN (6.9 mg ha $^{-1}$). Differences in N uptake (particularly stover N uptake) with N source were more pronounced than yield effects (Table 1). Averaged over 3 years, aboveground N uptake was greater with AA (152 kg N ha^{-1}) and UAN + DCD (144 kg N ha^{-1}) than with UAN (132 kg N ha $^{-1}$).

Soil solution NO_3 concentrations

During the fall of 1993, NO_3 concentrations in the soil solution at 1 m were lower with AA and UAN + DCD than with UAN on most sampling dates (18, 20 and 26 October; 1 and 8 November, Figure 1a). Average fall concentration was reduced from 29 mg NO_3–N l^{-1} with UAN to near the drinking water standard of 10 mg NO_3–N l^{-1} with UAN + DCD (12 mg NO_3–N l^{-1}) and AA (11 mg NO_3–N l^{-1}). In 1994, solution NO_3 concentrations were variable at 1 m with few significant source differences. At 1.5 m, NO_3 concentrations were greater with UAN than with AA and UAN + DCD on several sampling dates (Figure 1b). In 1995, NO_3 concentrations at 1 m were greater with UAN than with AA and UAN + DCD in the fall, but at 1.5 m concentrations did not vary with N source (Figure 1c).

Soil profile NO_3 and NH_4 concentrations

Results from soil sampling often corroborated results from solution samplers. On 18 October 1993 soil NO_3 concentrations tended to be greater between 0.3 and 1 m with UAN than with AA and UAN + DCD (Figure 2), similar to trends in solution concentrations at 1 m October through December 1993 (Figure 1a). On 16 November 1994 soil NO_3 concentrations were greater with AA than UAN or UAN + DCD between 1 and 1.5 m (Figure 2), mirroring trends in solution concentrations at 1 m earlier in the season (Figure 1b). Soil profile NO_3 concentrations to 1.5 m were low ($<$ 1 mg kg^{-1}, Figure 2) in the fall of 1994, however, probably due to greater N uptake by corn in 1994 than 1993 or 1995 (Table 1). On 14 August 1995, soil NO_3 concentrations were greater with UAN (5.8 mg kg^{-1}) than AA (0.7 mg kg^{-1}) or UAN + DCD (1.2 mg kg^{-1}) between 0.075 and 0.15 m deep (data not shown). This pulse of NO_3 (with UAN between 0.075 and 0.15 m) was detected deeper that fall in solutions at 1 m (Figure 1c) and in soil between 0.5 and 1.0 m (Figure 2). 1993 and 1995 fall average solution concentrations at 1 m converted to a soil weight basis (Table 2) were similar to fall soil concentrations (18 October 1993 and 12 October 1995, Figure 2).

Greater soil NO_3 between 0.075 and 0.15 m deep with UAN than with AA or UAN + DCD on 14 August 1995 may have been the result of greater nitrification with UAN (although nearly 9 wks after application). In support of this suggestion, on 14 August 1995 soil NH_4 concentration was less with UAN (1.8 mg kg^{-1}) than with AA (5.0 mg kg^{-1}) between 0.15 and 0.3 m (data not shown), and DCD inhibits nitrification for at least 8 weeks in the Fox sand under controlled conditions (Ball-Coelho, 1997). Soil profile NH_4 concentrations did not vary with N source on most sample dates, but on some other occasions soil NH_4 was also greater with AA and UAN + DCD than with UAN. Soil NH_4 was greater: on 18 October 1993 with AA (2.3 mg kg^{-1}) than UAN + DCD (0.5 mg kg^{-1}) or UAN (0.9 mg kg^{-1}) in the top 0.075 m; on 30 November 1993 with AA (1.7 mg kg^{-1}) than UAN (1.1 mg kg^{-1}) between 0.075 and 0.15 m, with AA (2.0 mg kg^{-1}) than UAN + DCD (1.3 mg kg^{-1}) or UAN (0.9 mg kg^{-1}) between 0.15 and 0.3 m, and with AA (1.6 mg kg^{-1}) and UAN + DCD (1.2 mg kg^{-1}) than UAN (0.4 mg kg^{-1}) between 0.3 and 0.5 m; and on 12 October 1995 with AA (4.2 mg kg^{-1}) than UAN (1.2 mg kg^{-1}) between 0.3 and 0.5 m.

Table 1. Corn grain yield and grain and stover N uptake as influenced by sidedress source of N

Source	1993	1994	1995	3 yr Contrast
Grain Yield (Mg ha^{-1} 15.5%)				**UAN vs. AA & UAN + DCD**
UAN	6.7a	8.3b	5.9a	*
UAN + DCD	7.0a	8.8ab	6.4a	
AA	7.0a	9.5a	6.1a	
Grain Uptake (kg N ha^{-1})				
UAN	95a	98b	91a	**
UAN + DCD	102a	107b	96a	
AA	100a	121a	99a	
Stover Uptake (kg N ha^{-1})				
UAN	43b	32b	38b	***
UAN + DCD	52a	35ab	37b	
AA	46ab	41a	49a	

Means in the same column followed by the same letter are not significantly different at $p \leq 0.05$.

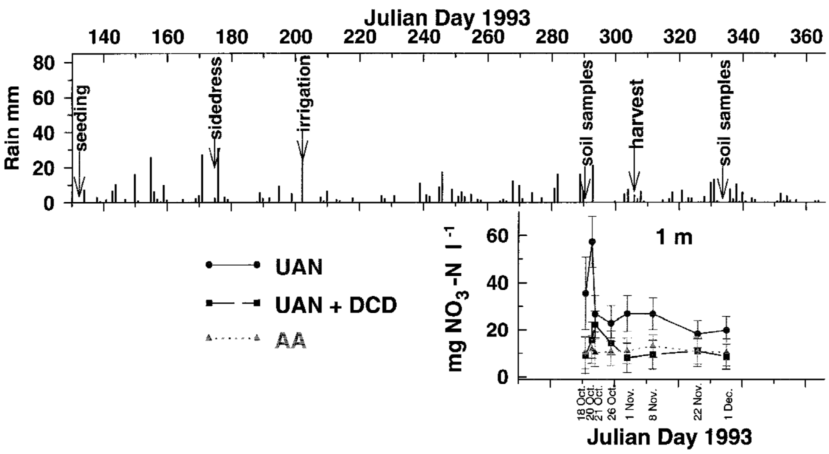

Figure 1a.

Discussion

During the wet 1994 growing season, leaching was reduced by AA and UAN + DCD, and so N was conserved within the system. In 1993 and 1995, however, leaching losses during the growing season were negligible, so increased N uptake and yield with AA and UAN + DCD were not due to N conservation, and may have been physiological responses to EAN. AA often increases corn yields and N uptake relative to other N sources (Malzer and Randall, 1985; Stehouwer and Johnson, 1990; Stevenson, 1992; Hanson et al., 1986), particularly in dry growing seasons (Kampfe and Ansorge, 1972). The AA response could be to EAN, since nearly all AA-N is converted to NH_4, and its subsequent conversion to NO_3 is inhibited by free NH_3-induced death of nitrifiers (Kiehl and Netto, 1974). No response to the addition of NI's to AA, or less response than to NI's added with UAN (Rogers et al., 1981; Malzer and Randall, 1985; Hanson et al., 1986) may in fact be due to this inherent inhibition of nitrification by AA.

Reduction in NO_3 leaching with AA and UAN + DCD (relative to UAN) during the summer of 1994 (by 2.4 mg NO_3–N kg^{-1}soil or 67% at 1.5 m) was probably related to inhibition of nitrification at the time of heavy rains (Figure 1b). In the fall, reductions in solution NO_3 concentrations with AA and UAN + DCD were shallower (at 1 m) following dry growing seasons (by 1 mg NO_3–N kg^{-1}soil or 58% fall 1993 and 0.5 mg NO_3–N kg^{-1}soil or 29% fall 1995) than following the wet growing season (at 1.5 m by 1.4 mg

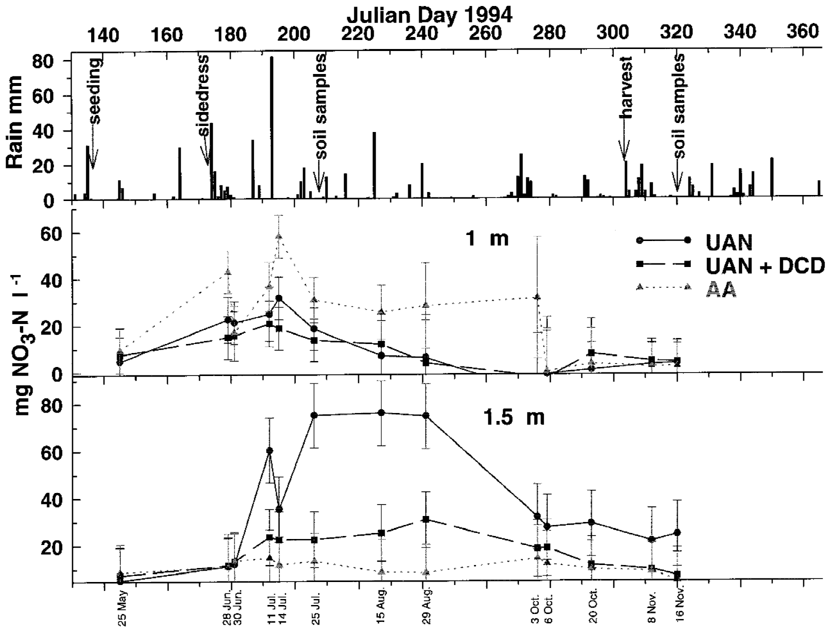

Figure 1b.

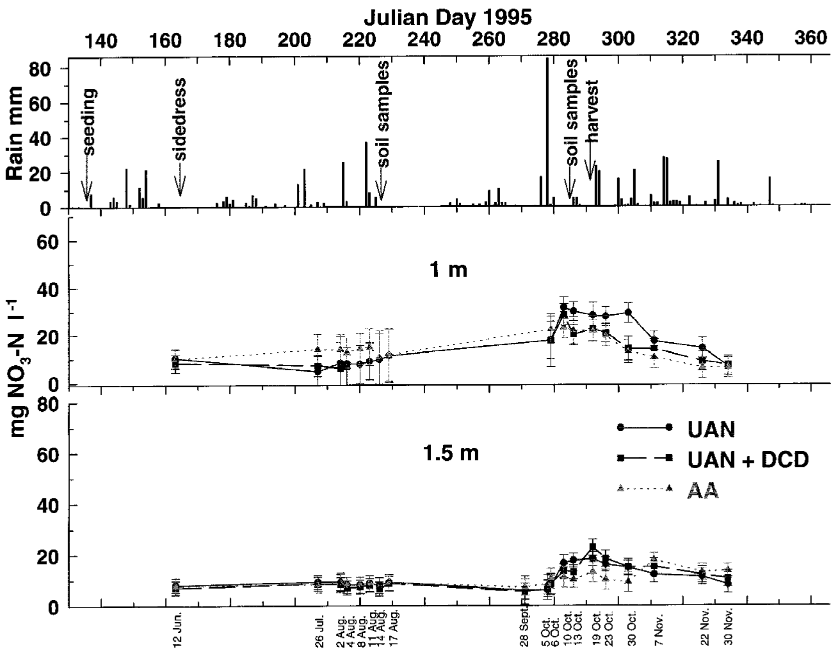

Figure 1c. Soil solution NO_3–N concentrations (at 1 and 1.5 m deep) as influenced by sidedress N source in (a) 1993, (b) 1994 and (c) 1995. Bars denote standard error.

Table 2. Average NO_3 concentration in the soil solution (expressed on a soil weight basis) as influenced by sidedress source of N

Source	1993	1994		1995	
	18 October – 1 December	25 May – 29 August	3 October – 17 November	12 June – 17 August	28 September – 20 November
		(mg NO_3–N kg^{-1} soil)			
		1 m			
UAN	1.9 (0.22)[a]	1.4 (0.34)	0.2 (0.09)	0.5 (0.04)	1.7 (0.13)
UAN + DCD	0.9 (0.16)	1.3 (0.33)	0.4 (0.09)	0.4 (0.04)	1.3 (0.13)
AA	0.8 (0.16)	2.3 (0.33)	0.4 (0.09)	0.7 (0.04)	1.1 (0.13)
p ≥F[b]	0.0001	0.06	0.4	0.0009	0.004
		1.5 m			
UAN		3.6 (0.46)	2.1 (0.18)	0.6 (0.02)	1.1 (0.11)
UAN + DCD		1.5 (0.38)	0.8 (0.15)	0.5 (0.02)	1.0 (0.12)
AA		0.9 (0.38)	0.7 (0.16)	0.5 (0.03)	0.9 (0.13)
p ≥F		0.0001	0.0001	0.080	0.6

[a]Numbers in parentheses are SE.
[b]Probability of a greater F value if there is no source effect.

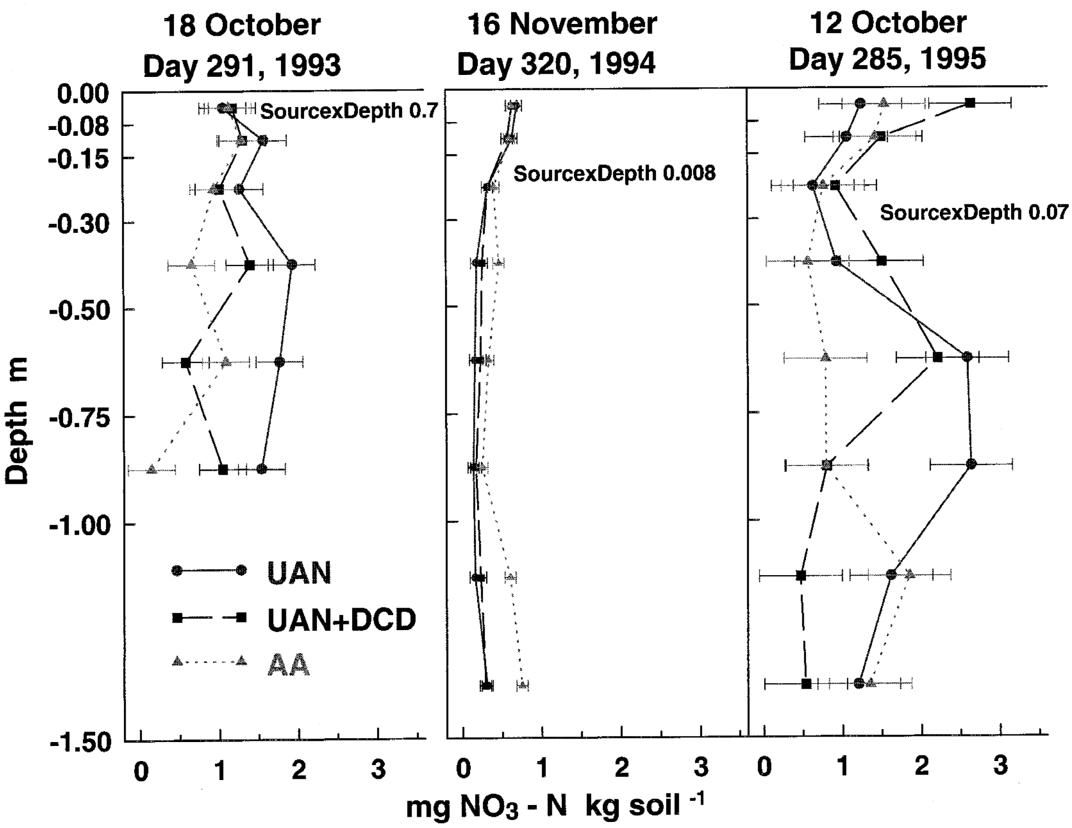

Figure 2. Soil profile NO_3–N concentrations in the fall of 1993, 1994 and 1995 as influenced by sidedress N source. Probability of a source by depth interaction is indicated for each sample date and bars denote standard error.

NO_3–N kg^{-1} soil or 67% fall 1994). This is probably the result of N movement down the profile during the wet summer (Figure 1b), and greater root development and N uptake at 1 m with the larger 1994 crop (than in 1993 or 1995). Pulses of NO_3 at 1 m under AA which did not appear at 1.5 m (Figure 1b) may reflect uptake from that layer in 1994. Kampfe and Ansorge (1972) observed greater root development in the subsoil with AA-fed corn than with NH_4NO_3-fed corn, and in our study the subsoil was drier under AA than under the other sources during the fall of 1994 (data not shown) implicating more deep root development with AA.

Greater topsoil NH_4 concentrations with AA and UAN + DCD than with UAN in the fall of 1993 and 1995 would not be due to inhibition of nitrification until fall, but could be due to greater immobilization following application (as often is found where NI's are used, Wilson et al., 1990; Martin et al., 1997), and subsequent mineralization of this organic N in the fall. Residual N thus conserved during the growing season, can be recycled for the next season by overseeding a winter rye cover crop into corn (Ball-Coelho and Roy, 1997). Reduced leaching losses in the fall with AA and UAN + DCD may also be related to greater above-ground N uptake (by 12 kg ha^{-1} or 9% in 1993, 23 kg ha^{-1} or 18% in 1994, and 8 kg ha^{-1} or 6% in 1995) than with UAN, and hence less residual fertilizer N available for leaching. Estimated leaching losses of N in the fall were: 32, 14 and 12 kg N ha^{-1} in 1993; 48, 18 and 16 kg N ha^{-1} in 1994; and 49, 34 and 30 kg N ha^{-1} in 1995 with UAN, UAN + DCD and AA, respectively (based on the assumption that drainage was equal to rainfall from harvest until December and had the same average NO_3 concentration as measured in solutions at 1, 1.5 and 1 m in 1993, 1994 and 1995, respectively). Average (3 years combined data) reduction in N leaching with AA and UAN + DCD was 53%. Reductions in NO_3 leaching with NI's in other corn systems range: zero (ammonium sulphate + DCD on a loess-derived Luvisol, Buerkert et al., 1995); 10% from planting to silking (urea + nitrapyrin on sandy loam, Walters and Malzer, 1990); 27% (urea + nitrapyrin on silt loam, Owens 1987); and 12 to 17% during the growing season, and 35% after one growing season (urea + nitrapyrin on sandy loam, Timmons, 1984). Impact on leaching appears to be mainly driven by soil texture and whether there is a yield response.

In the present study, NH_4 supply was enhanced by using AA or by adding DCD to UAN. Greatest benefit in terms of both increased N uptake and reduced NO_3 leaching occurred in the wettest year. The trend for increased yield with the addition of DCD was not large or consistent enough to meet registration criteria for fertilizer supplements in Canada, as is commonly observed with NI's. Data demonstrating some reduction of NO_3 movement to groundwater by NI's are as relevant, and registration criteria should reflect water quality concerns. Where AA is not available or growers are reluctant to use AA due to safety concerns, another source would then be available for maximizing yield while minimizing NO_3 leaching.

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