Published September 9, 2014

Journal of Environmental Quality
TECHNICAL REPORTS
ATMOSPHERIC POLLUTANTS AND TRACE GASES

Anhydrous Ammonia Injection Depth Does Not Affect Nitrous Oxide Emissions in a Silt Loam over Two Growing Seasons

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Abstract

Anhydrous ammonia (AA) is a major fertilizer source in North America that can promote greater emissions of nitrous oxide (N_2O) than other nitrogen (N) fertilizers. Previous studies found that injection of AA at a shallow depth (0.1 m) decreased N_2O in a rainfed clay loam but increased N_2O in an irrigated loamy sand compared with the standard injection depth of 0.2 m. The objective of this study was to evaluate the effects of AA injection depth in a silt loam soil used for corn (*Zea mays* L.) production and managed under two contrasting tillage regimes over two consecutive growing seasons (2010 and 2011) in Minnesota. In contrast with previous studies, AA placement depth did not affect N_2O emissions in either tillage system or in either growing season. Tillage by itself affected N_2O emissions only in the drier of two seasons, during which N_2O emissions under no tillage (NT) exceeded those under conventional tillage (CT) by 55%. Soil moisture content under NT was also greater than under CT only in the drier of the two seasons. Effects of AA placement depth and long-term tillage regime on N_2O emissions exhibit intersite as well as interannual variation, which should be considered when developing N_2O mitigation strategies. Further study is needed to identify specific soil, climate, or other factors that mediate the contrasting responses to management practices across sites.

Anhydrous ammonia (AA) is a major source of N fertilizer in the United States. In 2011, AA accounted for approximately 25% of N fertilizers applied to all crops (ERS, 2013). Use of AA is particularly common in corn (*Zea mays* L.) production systems. For example, AA accounted for 46% of all N fertilizer applied to corn in Minnesota in 2009 (Bierman et al., 2012). Some studies have found that emissions of nitrous oxide (N_2O) from soil were greater following application of AA than other N sources such as urea (Thornton et al., 1996; Venterea et al., 2010; Fujinuma et al., 2011). Hence, improved management of AA may play a significant role in agricultural greenhouse gas mitigation efforts in the United States. However, there are relatively few reports of N_2O emissions following AA application compared with other N fertilizer forms.

Anhydrous ammonia is generally applied by injecting pressurized ammonia (NH_3) into subsurface bands using a series of knife-injectors pulled by a tractor; the applicators also deploy soil closing implements to reduce NH_3 volatilization to the atmosphere. Shallower AA application allows for reduced energy and fuel expenditure and/or faster tractor speeds due to decreased mechanical resistance. So-called high speed/low draft applicators for shallower AA application using enhanced soil closing systems have become commercially available (Model 2501H, John Deere). Initial studies examined effects of these applicators on NH_3 losses (Stamper, 2009) and crop performance (Woli et al., 2014). Two previous studies compared N_2O emissions by AA placement depths with contrasting results. Fujinuma et al. (2011) found that shallow (0.10 m) AA injection resulted in a 100% increase in N_2O emissions compared with conventional application depth (0.20 m) in an excessively well-drained loamy sand managed under irrigation for corn production. An earlier study by Breitenbeck and Bremner (1986) found the opposite effect in a rainfed clay loam soil, that is, increasing N_2O emissions with increasing AA application depth. Currently, these are the

J. Environ. Qual. 43:1527–1535 (2014)
doi:10.2134/jeq2014.07.0292
Received 14 July 2014.
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Abbreviations: AA, anhydrous ammonia; AA-d, deep-applied anhydrous ammonia; AA-s, shallow-applied anhydrous ammonia; CT, conventional tillage; FIEF, fertilizer-induced emission factor; NFRE, nitrogen fertilizer recovery efficiency; NH4, ammonium; NH4I, soil ammonium intensity; NO23, nitrite plus nitrate; NO23I, soil nitrite plus nitrate intensity; NT, no tillage; SMC, soil moisture content; SOC, soluble organic carbon; SOM, soil organic matter; WFPS, water-filled pore space.

only known field studies comparing effects of AA placement depth on N_2O emissions.

Reduced tillage or no tillage (NT) is a common practice in North America (Vetsch and Randall, 2004) which can have a number of agronomic benefits (Holland, 2004). Comparison of conventional tillage (CT) versus NT effects on N_2O emissions have varied widely, with some studies reporting greater N_2O under NT (e.g., Goodroad et al., 1984; Liu et al., 2006) or the reverse effect (e.g., Jacinthe and Dick, 1997; Kessavalou et al., 1998; Omonode et al., 2011). Tillage effects on N_2O emissions are likely to vary with climate, duration of the tillage practice, and N management practices (Six et al., 2004; Van Kessel et al., 2013). Tillage is known to affect the magnitude and vertical distribution of several soil properties that may affect N_2O emissions in contrasting ways, including soil moisture content (SMC), bulk density, temperature, soluble organic carbon (SOC), pH, and microbial enzyme potential (Rochette et al., 2008; Venterea and Stanenas, 2008). Thus, tillage effects on N_2O emissions are not easily predicted for a particular site or growing season. A previous study at the same site as the current study found that N_2O emissions following AA application were greater under CT than NT during a single growing season (Venterea et al., 2005), but impacts of interannual climate variation were not evaluated.

The primary objective of this study was to quantify the effects of AA placement depth and long-term tillage practices on soil N_2O emissions over two consecutive growing seasons in a silt loam soil used for corn production in southeastern Minnesota. Secondary objectives were to quantify these same treatment effects on soil inorganic N dynamics, grain yield, crop N uptake, and N fertilizer recovery efficiency (NFRE).

Materials and Methods

Site Description and Experimental Design

The experiment was conducted on a long-term study site (Venterea et al., 2006) at the University of Minnesota Research Station in Rosemount, MN (44°45′ N, 93°04′ W), where the soil is a naturally drained Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls) containing 220 g kg^{-1} sand, 550 g kg^{-1} silt, and 230 g kg^{-1} clay. The 30-yr mean annual precipitation and temperature are 748 mm and 7.7°C, respectively (calculated for 1984–2013) (Minnesota Climatology Working Group, 2014). A 2-yr study (2010 and 2011) was conducted using a randomized complete block, split-plot design with tillage intensity as the main effect and AA placement depth as the split-plot effect. In this experiment, we studied the corn phase of a corn–soybean [*Glycine max* (Merr.) L.] rotation at two levels of tillage in each of three blocks each year. Tillage treatments included CT consisting of fall disk-ripping and spring preplant cultivation, and continuous NT, both of which had been maintained in the plots since 1991. Each main plot measured 27.4 m (36 rows) wide by 61 m long. Each year, each of three CT and NT plots were subdivided into three 6.1-m-wide (8 rows) by 61-m-long subplots, which were assigned randomly to one of three fertilizer treatments: (i) deep-applied AA (AA-d), consisting of 146 kg N ha^{-1} of AA applied with a target depth of 0.20 m, (ii) shallow-applied AA (AA-s), consisting of 146 kg N ha^{-1} of AA applied with a target depth of 0.10 m, and (iii) a control, which received no AA. All treatments including the control received a liquid starter fertilizer applied 5 cm from the seed row at planting, which contained 4.5, 9.0, and 4.5 kg ha^{-1} of N, P, and K, respectively. The AA was applied on 3 May 2010 and 6 May 2011. Equipment provided by John Deere to apply AA was similar to commercially available shallow and conventional depth AA applicators. Applicators were calibrated to the desired N application rate using trial runs on separate sections of field and verified by load-cell weight measurements. Shallow application was performed using a faster tractor speed (7–8 miles per hour) compared with deep placement (4 miles per hour). Tractors and applicators were operated by personnel familiar with the equipment. Corn was planted at a seeding rate of 79,000 seeds ha^{-1} on 6 May 2010 and on 17 May 2011 using a John Deere model 7100 MaxEmerge planter. Row cleaning coulters (Yetter Mfg.) were used in the NT treatments to produce an improved seed bed. Flags were inserted after AA application so that seeds could be planted approximately midway between AA injection lines.

Yield and Plant Nitrogen Content

At physiological maturity, corn ears were harvested from all plants within 1.5-m sections of the middle two rows of each subplot. Ears were dried at 35°C, shelled, and further dried for 3 d at 65°C and weighed to obtain dry grain and cob yield. Stover was collected in six plants from each subplot that had also been harvested for grain by cutting each plant just above the crown. Stover was partially ground and dried at 35°C until a constant mass was obtained (approximately 1 wk) to determine moisture content. Grain, cob, and stover subsamples were further ground with a grinding mill and analyzed for N content using an elemental analyzer (VarioMax; Elementar). Total N content in aboveground biomass was calculated from the sum of N harvested in grain, cob, and stover, all expressed on a dry mass basis.

Nitrous Oxide Emissions

Soil-to-atmosphere N_2O fluxes were measured using static chamber methods (Venterea et al., 2010) from April through October in 2010 and 2011. Both years, fluxes were measured twice per week after fertilizer application until the end of August and once a week at other times, for a total of 44 sampling dates in 2010 and 40 in 2011. Approximately 46% of the flux sampling events occurred within 24 h of precipitation events both years. In each subplot, two stainless steel chamber anchors (0.50 m by 0.29 m by 0.086 m deep) each equipped with a 20-mm-wide by 5-mm-thick flange around its perimeter were installed so that the flange rested directly on the soil surface. The two anchors were placed adjacent to each other without overlapping, thereby covering ~ 85% of the inter-row width. On each sampling day between 0900 and 1200 local time, insulated and vented chamber tops (0.50 m by 0.29 m by 0.102 m high), each also equipped with a 20-mm-wide by 5-mm-thick flange around their perimeter, were sealed to the anchors by attaching the chamber flange to the anchor flange using binder clips. Gas samples were collected at 0, 0.5, 1, and 1.5 h using a 12-mL polypropylene syringe. Samples were immediately transferred to glass vials sealed with butyl rubber septa (Alltech) and analyzed within 2 wk using a headspace autosampler (Teledyne Tekmar) connected to a gas chromatograph (model 5890, Agilent/Hewlett-Packard) equipped with an electron capture detector. The equipment was calibrated with analytical grade standards (Scott Specialty Gases) each day when samples were analyzed. Gas concentrations in molar mixing ratios determined by the gas chromatograph were converted to mass per volume concentrations using ideal gas law and air temperatures at sampling. Fluxes of N_2O were calculated from the rate of change in chamber N_2O concentration using methods designed to account for suppression of the surface–atmosphere concentration gradient (Venterea, 2010, 2013).

Soil Physical and Chemical Properties

Soil temperature was measured during each N_2O flux measurement using temperature probes (Fisher) inserted to the 0.05-m depth within 1 m of the chambers. Soil samples were collected from midway between the row and midrow positions (referred to as the 1/4-row position) to the 0.05-m depth within 1 h of each flux measurement period using a 19-mm-diameter coring tool (Oakfield Apparatus, Inc.). These samples were used to determine gravimetric water content, bulk density, and water-filled pore space (WFPS) by drying at 105°C. Additional soil core samples were collected from each subplot once per month for analysis of extractable inorganic N and SMC. Two cores from each subplot, one from the midrow position and one from the 1/4-row position, were collected each to a depth of 0.3 m. The cores were separated into two depth intervals (0–0.15 m and 0.15–0.30 m), and then cores from each depth interval collected from the midrow and 1/4-row positions were composited together. Samples were placed in a cooler and delivered to the laboratory where 10-g subsamples were extracted in 2 M KCl, filtered (Whatman no. 42), and analyzed for nitrite (NO_2^-) plus nitrate (NO_3^-) (hereafter referred as NO23) using the Greiss–Ilosvay method with cadmium reduction, and for ammonium (NH4) using the sodium salicylate-nitroprusside method (Mulvaney, 1996) with each method modified for use with a flow-injection analyzer (Lachat).

Data Analysis and Statistics

Daily N_2O fluxes for each sampling date were determined from the average flux measured in two adjacent chambers in each subplot. Cumulative growing-season N_2O emissions were determined by trapezoidal integration of daily fluxes versus time (Leithold, 1976). The fertilizer-induced emissions factor (FIEF) (%) was calculated by subtracting cumulative area-based N_2O emissions in the control treatment from that in each fertilized treatment within the same block and then expressing the result as a percentage of the fertilizer N applied (146 kg N ha^{-1}). Yield-based N_2O emissions (g N Mg^{-1} yield) were calculated by dividing cumulative area-based N_2O emissions by grain yield in each subplot (Venterea et al., 2011). Nitrogen fertilizer recovery efficiency (NFRE) was calculated by subtracting the total aboveground N uptake in the control treatment from that in each fertilized treatment and expressing the result as a percentage of the fertilizer N applied. Soil NO23 intensity (NO23I) and soil NH4 intensity (NH4I) were determined separately for the 0- to 0.15-m and 0.15- to 0.30-m depths for each subplot by trapezoidal integration of the respective soil N concentrations versus time (Burton et al., 2008; Engel et al., 2010). Effects of year, tillage, and AA application depth on cumulative N_2O emissions, FIEF, N intensity, and agronomic variables were determined using Proc Mixed in SAS, with year, tillage, and AA application depth as fixed effects and block and all interactions of block with other terms (year, tillage, and application depth) as random effects (SAS, 2003; Littell et al., 2006). Year was treated as a fixed effect to examine effects of large differences in precipitation patterns between the two growing seasons. When the main effect was significant, means comparisons were conducted using contrasts in SAS. To maintain a balanced design, data from the control treatment (which lacked an application depth) were excluded from the treatment comparisons but were included in regression analyses (conducted using SAS). Paired t tests by block were used to compare treatment effects on soil temperature, SMC, and WFPS using SAS. Significance criteria of $P < 0.05$ are used unless otherwise mentioned.

Results

Climate, Soil Physical Properties, and Crop Responses

Rainfall amounts and temporal patterns differed substantially between years (Table 1, Fig. 1a). Although much less precipitation occurred in April 2010 than in April 2011, ~30% more rainfall occurred in 2010 than in 2011. The months of June, July, and August in 2010 were particularly wet compared with 2011 and with the 30-yr averages (Table 1). Across the whole season, SMC at the 0- to 0.05-m depth interval was significantly greater under NT than CT in 2011 but did not vary by tillage in 2010. Soil WFPS (at 0–0.05 m) ranged from 25 to 80% in 2010 and from 19 to 71% in 2011 and was greater under NT than CT both years. In 2010, the significantly greater WFPS in NT was due to the combination of greater bulk density (1.22 ± 0.005 g cm^{-3}) compared with CT (1.16 ± 0.007) and a nonsignificant trend for greater SMC (0.246 ± 0.004) compared with CT (0.242 ± 0.004). In 2011, the significant difference in WFPS was due entirely to greater SMC in NT (0.235 ± 0.006) than CT (0.213 ± 0.005), as bulk density did not differ by tillage (1.07 ± 0.006 g cm^{-3} in both CT and NT). Soil moisture content, WFPS and bulk density measured across the 0- to 0.15-m depth interval did not vary by tillage or placement either year; differences in SMC at 0.15 to 0.30 m were consistent with the 0.05-m data, that is, wetter under NT only in 2011. Soil moisture content did not differ by AA depth, and soil temperature did not differ by tillage or AA application depth either year. There were no

Table 1. Rainfall patterns by month and growing season.

Period	2010	2011	Difference†	30-yr mean‡
	mm			
Apr.	48	95	−47	71
May	99	100	−1	99
June	169	123	46	103
July	171	136	35	89
Aug.	154	65	89	108
Sept.	37	13	24	72
Total	678	532	146	542

† Calculated as the monthly rainfall in 2010 minus the monthly rainfall in 2011.

‡ Calculated for 1984–2013 using data available at Minnesota Climatology Working Group (2014).

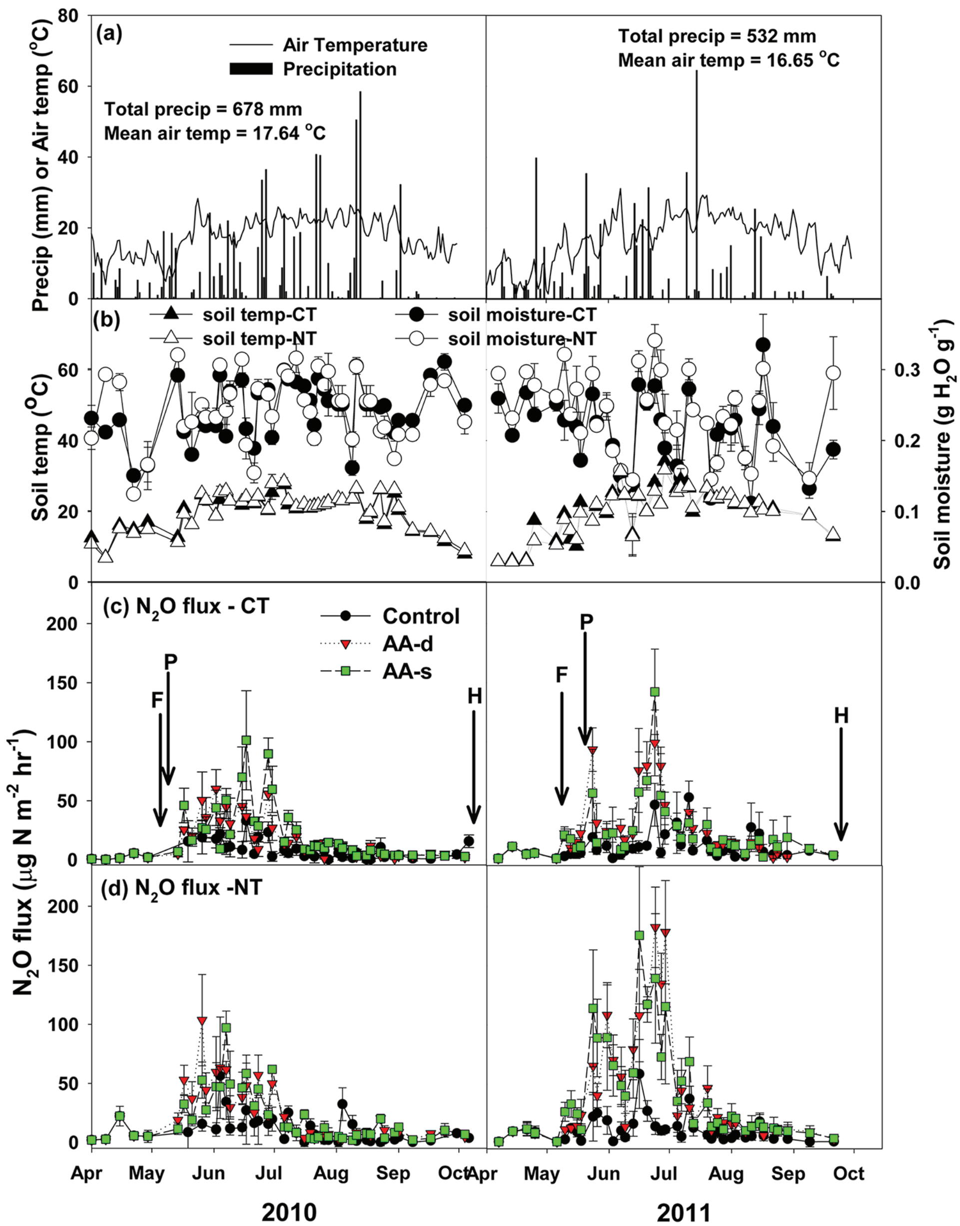

Fig. 1. (a) Weather variables, (b) soil temperature and moisture content, and daily N_2O fluxes in (c) conventional-tillage (CT) and (d) no-tillage (NT) systems that received anhydrous ammonia (AA) applied with target depth of 0.2 m (AA-d) and 0.1 m (AA-s) and in a control that received no AA in 2010 and 2011. Downward-pointing arrows indicate dates of planting (P), fertilizer application (F), and harvest (H).

significant effects of tillage, AA application depth, or year on grain yield, crop N uptake, or NFRE (Table 2).

Nitrous Oxide Emissions

Nitrous oxide fluxes increased after AA application both years (Fig. 1c–d), with maximum fluxes occurring in June each year. In 2011, after the initial increase following fertilizer application, fluxes declined to below 40 μg N m^{-2} h^{-1} in all treatments by 13 June, and then increased again reaching their maximum values on 29 June. This temporal pattern in N_2O fluxes in 2011 appeared to be driven at least in part by fluctuations in SMC. Between 29 May and 13 June 2011, less than 9 mm of rain occurred, resulting in SMC values below 0.15 g H_2O g^{-1} by 13 June, which corresponded to the decline in N_2O fluxes. This was followed by several rainfall events over the next 9 d totaling 111 mm during which soil MC increased to as high as 0.34 and 0.28 g H_2O g^{-1} in the NT and CT treatments, respectively, which corresponded to the second increase in N_2O fluxes. From late May through the end of June 2011, daily N_2O fluxes were significantly and positively correlated with SMC (r^2 = 0.18). However, across the entire growing seasons of 2011 or 2010, daily N_2O fluxes were not significantly correlated with SMC or WFPS. There was a significant correlation between daily N_2O flux and soil temperature each season, but the degree of correlation was relatively low (r^2 = 0.06 and 0.10 in 2010 and 2011, respectively). There was a significant year × tillage interaction effect (Table 2) on area- and yield-based cumulative N_2O emissions and FIEF, both of which were greater under NT than CT in 2011 but not in 2010 (Fig. 2). There were no significant effects of AA application depth on cumulative N_2O emissions, and across all treatments, area-based N_2O emissions and FIEF were greater in 2011 than in 2010 (Table 2).

Table 2. Results of statistical analyses of dependent variables as affected by year, anhydrous ammonia (AA) application depth, tillage, and their interactions.

Sources of effect	Grain yield	Aboveground N uptake	NFRE†	N_2O emissions	Yield-based N_2O emissions	FIEF†
	Mg ha^{-1}	kg N ha^{-1}	%	kg N ha^{-1}	g N Mg^{-1} grain	%
Year (Y)						
2010	11.7 (0.2)	148.7 (7.6)	30.2 (5.2)	0.85 (0.03) b‡	72.7 (3.0)	0.25 (0.03) b
2011	11.7 (0.4)	185.0 (11.3)	45.6 (6.7)	1.17 (0.10) a	101.2 (8.9)	0.43 (0.05) a
Significance	NS§	NS	NS	*	NS	*
Depth¶ (D)						
Control	8.2 (0.5)	98.6 (7.7)	–	0.41 (0.02)	51.6 (4.1)	–
AA-d	11.9 (0.3)	169.6 (11.6)	39.4 (8.4)	1.01 (0.08)	86.9 (8.0)	0.35 (0.04)
AA-s	11.5 (0.3)	164.1 (10.5)	36.4 (6.8)	1.00 (0.09)	83.0 (8.3)	0.33 (0.06)
Significance	NS	NS	NS	NS	NS	NS
Tillage# (T)						
CT	11.7 (3.4)	171.3 (49.4)	33.2 (7.8)	0.85 (0.25) b	73.4 (21.2) b	0.24 (0.07) b
NT	11.7 (3.4)	162.4 (46.9)	42.6 (10.0)	1.17 (0.34) a	100.4 (29.0) a	0.44 (0.13) a
Significance	NS	NS	NS	***	***	***
T × D	NS	NS	NS	NS	NS	NS
Y × D	NS	NS	NS	NS	NS	NS
Y × T	NS	NS	NS	*	*	*
Y × T × D	NS	NS	NS	NS	NS	NS

* Significant at $P < 0.05$.

*** Significant at $P < 0.001$.

† FIEF = fertilizer-induced emission factor; NFRE = nitrogen fertilizer recovery efficiency.

‡ For each variable, means followed by the same letter are not significantly different ($P < 0.05$).

§ NS, not significant.

¶ AA-d = deep-applied AA (0.2 m target depth); AA-s = shallow-applied AA (0.1 m target depth); control was not included in statistical analysis.

CT = conventional tillage; NT = no tillage.

Soil Nitrogen Concentrations and Intensity

Soil NO23 concentrations increased to above 20 μg N g^{-1} after AA application before decreasing to baseline levels in late August of each year (Fig. 3a—b). In 2010, soil NH4 increased in mid August in the AA and control treatments, possibly due to large rainfall events occurring after a dry, warm period (Fig. 1a–b), which may have stimulated N mineralization from soil organic matter. In general, soil NH4 levels did not display a large increase following AA application, indicating that the sample collection did not capture soil from directly within the AA band (see Discussion section). Significant tillage × depth and/or tillage × year interaction effects were observed for soil NH4I and NO23I (Table 3–4). Soil NO23I in the AA-d/NT treatment was consistently greater than in the AA-s/NT, AA-d/CT, and AA-s/CT treatments in both years and for both depth intervals (Table 4). No significant differences in NH4I or NO23I by AA depth occurred within the CT treatment, and all significant differences by AA depth within the NT treatment displayed the same pattern of greater N intensity in the AA-d treatment compared with the AA-s treatment. In 2010, cumulative N_2O emissions were significantly and positively correlated with soil NO23I in the 0- to 0.15-m and 0.15- to 0.30-m depth intervals (r^2 = 0.42 and 0.33, respectively). Cumulative N_2O emissions were not significantly correlated with soil NO23I in 2011 or with NH4I either year.

Discussion

Anhydrous Ammonia Placement Depth

In contrast with two previous studies (Breitenbeck and Bremner, 1986; Fujinuma et al., 2011), no significant difference in N_2O emissions was observed with AA application depth. Fujinuma et al. (2011) reported greater N_2O emissions from AA applied with a target depth of 0.1 m compared with 0.2 m in a loamy sand under irrigation. Breitenbeck and Bremner (1986) observed the reverse effect in a clay loam soil, that is, greater N_2O emissions with AA applied at 0.2 m compared with 0.1 m. This trend in results among the current study, Fujinuma et al. (2011), and Breitenbeck and Bremner (1986) suggests

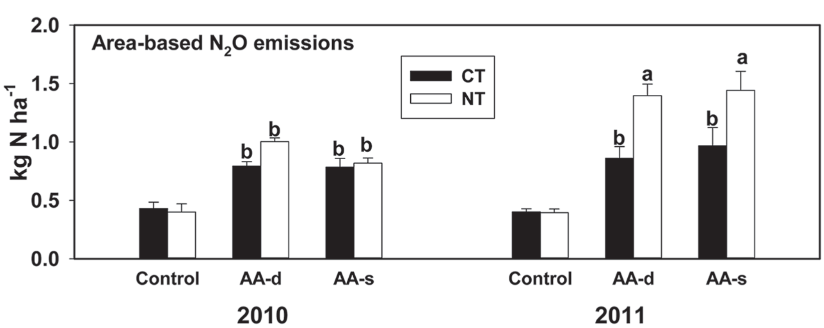

Fig. 2. Cumulative growing season N_2O emissions in plots under conventional-tillage (CT) and no-tillage (NT) systems that received anhydrous ammonia (AA) applied with target depth of 0.2 m (AA-d) and 0.1 m (AA-s) and in a control that received no AA in 2010 and 2011. Data from control were not included in statistical analysis. Bars with same lowercase letters are not significantly different ($P < 0.05$).

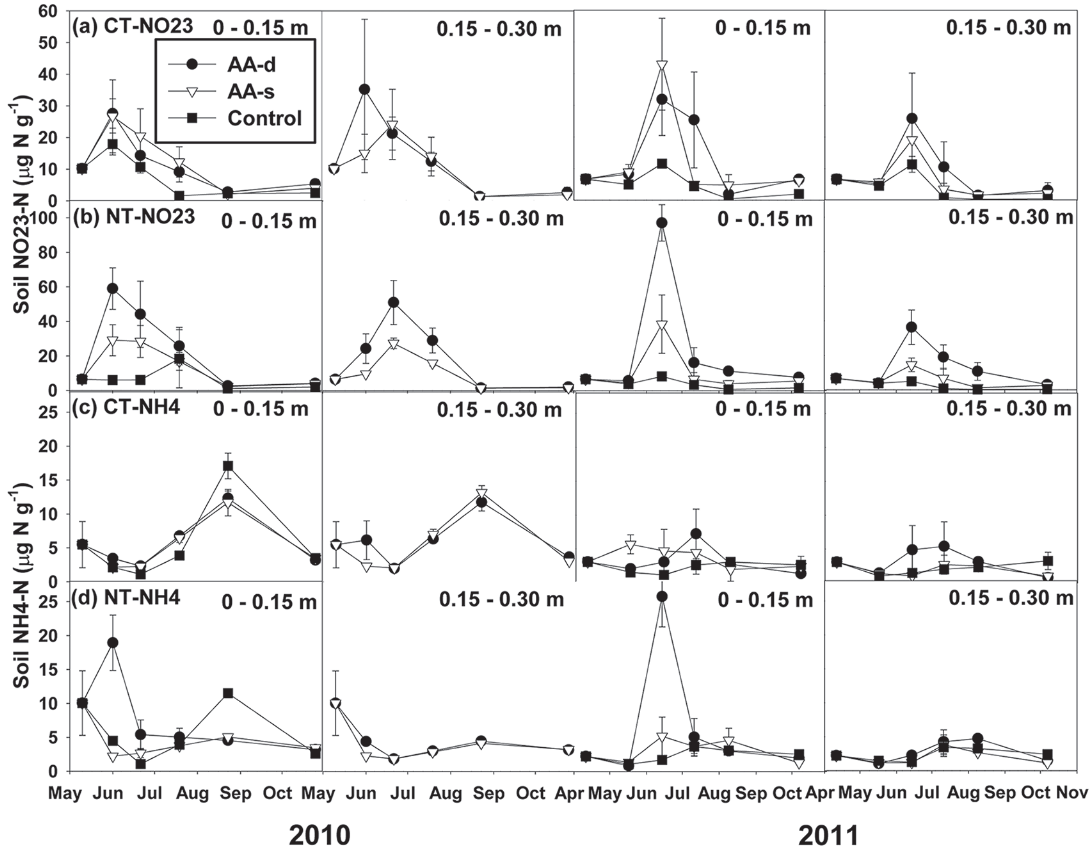

Fig. 3. Soil nitrite plus nitrate (NO23, a–b) and ammonium (NH4, c–d) concentrations in the 0- to 0.15-m and 0.15- to 0.3-m depth intervals in plots under conventional tillage (CT) and no-tillage (NT) systems that received anhydrous ammonia (AA) applied with target depth of 0.2 m (AA-d) and 0.1 m (AA-s) and in a control that received no AA in 2010 and 2011. No data are available for control plots in 0.15- to 0.3-m depth in 2010.

that in finer-grained, poorly drained soils, reductive biological processes (i.e., denitrification, which would be expected to be more important as a source of N_2O as clay content increases) resulted in greater N_2O emissions with deeper AA application; whereas in very coarse, well-drained soils, nitrification as a source of N_2O resulted in greater N_2O emissions with shallower AA application. This latter effect was discussed by Fujinuma et al. (2011), who hypothesized that greater N_2O emissions with shallow AA could have been due to greater soil organic matter (SOM) content in surface versus deeper soil layers giving rise to greater rates of N_2O production from nitrification-driven reactions. Their hypothesis was based on the findings of Venterea (2007), who found that N_2O-producing reactions derived from nitrification increased with increasing SOC, and also on results showing that AA application can solubilize SOM (Tomasiewicz and Henry, 1985; Clay et al., 1995). The current soil under study, of moderate texture, represents a middle-point between the fine- and coarse-textured conditions where increasing denitrification-derived N_2O with deeper placement may have been balanced by increasing nitrification-derived N_2O with shallower placement. Other studies have examined effects of placement depth on N_2O emissions using N fertilizers other than AA and using other application depths. Drury et al. (2006), for example, reported N_2O emissions following ammonium nitrate applied at depths of 2 and 10 cm over three growing seasons in a clay loam. The data from Drury et al. (2006) are consistent with the trend discussed above in that greater N_2O emissions were observed with greater application depth in a fine-grained soil. The effect of fertilizer placement depth on N_2O emissions is likely to be affected by a variety of factors, including N fertilizer source, the actual application depth, climate regime, annual weather variation, drainage class, and soil organic carbon content, some of which may be correlated with soil texture. Thus, more site-level studies across differing soil types as well as intercomparison analyses are required to determine the specific soil, climate, or other factors that mediate the contrasting responses to fertilizer application depth across sites.

We did not measure emissions of other N-containing gases including nitric oxide (NO) or NH_3, although these may have varied by AA placement depth. Stamper (2009) found higher rates of NH_3 loss following shallow versus deep AA application in silty clay loam and silt loam soils for N application rates ≥135 kg N ha^{-1}, but the rates of N loss were generally not of agronomic significance. A more thorough experimental evaluation of AA placement depth effects would need to simultaneously measure multiple N loss pathways.

Tillage Effects

Cumulative N_2O emissions differed by tillage only in the drier of the two growing seasons (2011). While soil WFPS was greater under NT than CT both years, SMC was significantly greater under NT than CT only in the drier year. Thus, the pattern of differences in N_2O emissions was more closely represented by differences in SMC than in WFPS. Although WFPS is commonly cited as a regulator of N_2O, recent studies have shown that WFPS may not be a reliable indicator of potential

N_2O emissions (Balaine et al., 2013). The trend observed here of tillage affecting soil-gas efflux only in the drier growing season is also consistent with Venterea et al. (2006), who found that cumulative soil CO_2 emissions were 40% greater in NT than CT during the drier of two growing seasons. As discussed by Venterea et al. (2006), differences in SMC among tillage systems may be more pronounced during drier periods, when the mulching effects of reduced tillage have a greater impact on soil temperature and evaporation; thus, during drier periods, tillage effects on moisture-dependent microbial activity, including activity that drives N_2O and CO_2 emissions, are also likely to be greater than under wetter conditions.

Table 3. Results of statistical analyses of soil intensities of ammonium (NH4I) and nitrite plus nitrate (NO23I) at different depth intervals as affected by year, anhydrous ammonia (AA) application depth, tillage, and their interactions.

Sources of effect	Soil N intensity (0.00–0.15 m)		Soil N intensity (0.15–0.30 m)	
	NO23I	NH4I	NO23I	NH4I
	——— g N kg^{-1} d ———			
Year (Y)				
2010	2.25 (0.36)	0.99 (0.07)	1.98 (0.25)	0.88 (0.08) a†
2011	2.59 (0.36)	0.72 (0.09)	1.46 (0.24)	0.44 (0.05) b
Significance	NS‡	NS	NS	*
Depth§ (D)				
Control	0.87 (0.14)	0.76 (0.11)	0.77 (0.15)	0.75 (0.11)
AA-d	2.87 (0.42) a	0.97 (0.09) a	2.14 (0.27) a	0.71 (0.09)
AA-s	1.97 (0.24) b	0.74 (0.07) b	1.30 (0.17) b	0.61 (0.10)
Significance	*	*	*	NS
Tillage¶ (T)				
CT	1.95 (0.23) b	0.84 (0.09)	1.51 (0.23)	0.78 (0.11) a
NT	2.89 (0.42) a	0.87 (0.09)	1.93 (0.28)	0.53 (0.04) b
Significance	*	NS	NS	**
T × D	*	**	*	NS
Y × D	NS	NS	NS	NS
T × Y	NS	*	NS	**
Y × T × D	NS	NS	NS	NS

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

† For each variable, means followed by the same letter are not significantly different ($P < 0.05$).

‡ NS, not significant.

§ AA-d = deep-applied AA (0.2 m target depth); AA-s = shallow-applied AA (0.1 m target depth); control was not included in statistical analysis.

¶ CT = conventional tillage; NT = no tillage.

Table 4. Effects of two long-term tillage practices and two anhydrous ammonia (AA) placement depths on soil ammonium intensity (NH4I) and soil nitrite plus nitrate intensity (NO23I) in soil sampled from two depth intervals across two growing seasons.†

Placement depth‡	2010		2011	
	Tillage practice§			
	CT	NT	CT	NT
	——— g N kg^{-1} d ———			
	NH4I			
	0–0.15 m			
AA-d	1.10 (0.12) a	1.12 (0.17) a	0.57 (0.12) b	1.11 (0.10) a
AA-s	1.04 (0.11) a	0.70 (0.03) b	0.65 (0.17) b	0.57 (0.07) b
	0.15–0.30 m			
AA-d	1.13 (0.11) a	0.66 (0.04) b	0.55 (0.18) bcd	0.51 (0.06) bcd
AA-s	1.12 (0.08) a	0.60 (0.06) bc	0.34 (0.02) d	0.37 (0.04) cd
	NO23I			
	0–0.15 m			
AA-d	1.63 (0.31) c	3.44 (1.07) ab	2.25 (0.69) bc	4.15 (0.43) a
AA-s	1.78 (0.59) c	2.13 (0.52) bc	2.12 (0.28) bc	1.85 (0.72) c
	0.15–0.30 m			
AA-d	1.91 (0.53) bc	2.86 (0.49) a	1.46 (0.51) bc	2.33 (0.55) ab
AA-s	1.58 (0.57) bc	1.55 (0.13) bc	1.08 (0.28) c	0.97 (0.29) c

† Within each intensity index and each depth interval, values with the same letter designation are not significantly different ($P < 0.05$).

‡ AA-d = deep-applied AA (0.2 m target depth); AA-s = shallow-applied AA (0.1 m target depth).

§ CT = conventional tillage; NT = no tillage.

In a previous study at the same site, Venterea et al. (2005) observed that N_2O emissions in CT were 40% greater than in NT when AA was applied using a conventional applicator (with a target depth of 0.15–0.20 m) in a single growing season (2004), in contrast to the current findings for 2011 where NT exceeded CT by 55%. Thus, in 3 yr of examining tillage effects on N_2O emissions following AA application at this site, three different trends in N_2O emissions have been observed: NT < CT (2004), NT = CT (2010), NT > CT (2011). These results cannot be explained by differences in total rainfall, as the 2004 growing season was intermediate (597 mm) between 2011 and 2010. Substantially greater rainfall occurred during May 2004 (173 mm) compared with 2010 or 2011 (≤100 mm). Both SMC and N_2O emissions were greater under CT than under NT during May 2004, possibly due to greater drainage capacity in the NT soil under near-saturated conditions (Mahboubi et al., 1993). Thus, rainfall patterns within a particular growing season may be more important than total growing season precipitation in regulating tillage effects on N_2O emissions.

Soil Nitrogen Dynamics

Area-scaled N_2O emissions were positively correlated with NO23I in 2010, consistent with other reports (Burton et al., 2008; Engel et al., 2010; Zebarth et al., 2012), but no significant correlation was observed for 2011. The pattern of differences in NO23 by sampling depth, tillage, and AA application depth (Table 4) are not consistent with and do not appear to explain the observed treatment effects on N_2O emissions (Fig. 2). Maharjan and Venterea (2013) found that measurement of soil NO_2^- separately from NO_3^- provided better explanation of treatment effects on N_2O emissions than measurement of their combined concentrations, as done here and in the vast the majority of similar studies. Application of AA is known to cause substantial NO_2^- accumulation (Chalk et al., 1975). Soil NO_2^- dynamics may have been particularly important in 2011 under drier conditions, where NO_2^- is more likely to generate N_2O than NO_3^- (Venterea, 2007), and this may explain the lack of correlation between N_2O and NO23I in 2011.

We attempted to collect soil samples from within the AA injection zone, but the data suggest that the actual sampling locations were not always within this zone. The paths of the AA injection knives following application were flagged and corn rows were planted at equal spacing such that the highly concentrated AA bands would be centered between planted rows. Soil samples were collected from the midrow position (and mixed with samples from the 1/4-row position). The absence of a large or consistent increase in soil NH4 concentrations after fertilizer addition indicates that these methods were not successful in consistently capturing soil from within the AA injection zone, where soil NH4 concentrations of >500 μg N g^{-1} were expected (Chalk et al., 1975) (after accounting for dilution with samples from the 1/4-row position). This most likely resulted from the narrowness of the injection zone and variation in the lateral positioning of the knives as the tractor moves across the field. The NH4I data therefore may be more indicative of soil processes occurring in the nonfertilized zones due to the lower mobility of NH4 once applied to soil compared with NO_3^-. Greater NH4I in 2010 than 2011 in the CT treatments may have reflected greater amounts of N mineralization occurring in the wetter of the two seasons.

Crop Responses

Depth of AA application did not affect grain yield or NFRE. Fujinuma et al. (2011) found greater NFRE (but not yield) with shallower AA in an irrigated loamy sand with AA placed between corn rows (as in the current study). In a 3-yr multisite study, Woli et al. (2014) found reduced yields with shallow compared with deep placement when AA bands were located directly beneath corn rows before planting in spring, but only when N rates were above 180 kg N ha^{-1}. The yield decline under these conditions was suspected to be the result of AA-induced seedling injury. No significant effect of tillage on grain yield was observed in the treatments receiving AA in the current study. Greater yields with CT compared with NT have been attributed to cooler soil temperatures in NT in spring, which may inhibit plant development (e.g., Kaspar et al., 1987; Vyn and Raimbault 1993; Vetsch and Randall, 2004). No significant differences in soil temperature were observed by tillage, which could explain the lack of a tillage effect on yield during these two growing seasons. The control treatments (no AA applied) in the current study under CT had 40 and 25% greater yields than the NT/control treatments in 2010 and 2011, respectively, suggesting that soil N availability from mineralization was lower in the NT treatment. In 2010, soils were much drier (~0.15 g H_2O g^{-1}) at the time of AA application than in 2011 (~0.26 g H_2O g^{-1}). This result suggests there may have been greater NH_3 volatilization losses in 2010 than 2011(Stanley and Smith, 1956), which may explain why NFRE was lower in 2010 than in 2011.

Conclusions

Modification of agricultural management practices to reduce N_2O emissions is being considered as a strategy for reducing the overall greenhouse gas footprint of cropping systems. This study found that decreasing the depth of AA application in a silt loam soil did not affect N_2O emissions over two growing seasons, in contrast with two previous studies reporting either an increase or a decrease in emissions with shallower AA application. This study also found that the intensity of long-term tillage management affected N_2O emissions only in the drier of two growing seasons. Effects of AA placement depth and long-term tillage regime on N_2O emissions exhibit intersite as well as interannual variation, which should be considered when developing N_2O mitigation strategies. Further study is needed to identify specific soil, climate, or other factors that mediate the contrasting responses to management practices across sites.

Acknowledgments

The authors thank M. Dolan, J. Coulter, J. Leonard, A. Dwinnell, W. Shanley, E. Alms, P. Bradley, N. Meier, A. Hart, D. Olson, and John Deere & Company for their assistance. This work was supported by the National Research Initiative Competitive Grant no. 2009-55112-05216 from the USDA CSREES/NIFA Air Quality Program.

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