Fertilizer Source and Tillage Effects on Yield-Scaled Nitrous Oxide Emissions in a Corn Cropping System

Rodney T. Venterea,* Bijesh Maharjan, and Michael S. Dolan

Management practices such as fertilizer or tillage regime may affect nitrous oxide (N_2O) emissions and crop yields, each of which is commonly expressed with respect to area (e.g., kg N ha^{-1} or Mg grain ha^{-1}). Expressing N_2O emissions per unit of yield can account for both of these management impacts and might provide a useful metric for greenhouse gas inventories by relating N_2O emissions to grain production rates. The objective of this study was to examine the effects of long-term (>17 yr) tillage treatments and N fertilizer source on area- and yield-scaled N_2O emissions, soil N intensity, and nitrogen use efficiency for rainfed corn (*Zea mays* L.) in Minnesota over three growing seasons. Two different controlled-release fertilizers (CRFs) and conventional urea (CU) were surface-applied at 146 kg N ha^{-1} several weeks after planting to conventional tillage (CT) and no-till (NT) treatments. Yield-scaled emissions across all treatments represented 0.4 to 1.1% of the N harvested in the grain. Both CRFs reduced soil nitrate intensity, but not N_2O emissions, compared with CU. One CRF, consisting of nitrification and urease inhibitors added to urea, decreased N_2O emissions compared with a polymer-coated urea (PCU). The PCU tended to have lower yields during the drier years of the study, which increased its yield-scaled N_2O emissions. The overall effectiveness of CRFs compared with CU in this study may have been reduced because they were applied several weeks after corn was planted. Across all N treatments, area-scaled N_2O emissions were not significantly affected by tillage. However, when expressed per unit yield of grain, grain N, or total aboveground N, N_2O emissions with NT were 52, 66, and 69% greater, respectively, compared with CT. Thus, in this cropping system and climate regime, production of an equivalent amount of grain using NT would generate substantially more N_2O compared with CT.

Corn production consumes more than 40% of all N fertilizers applied to crops in the United State and therefore represents the largest single source of soil N_2O emissions relative to other crops (ERS, 2011). Although reduction in N fertilizer application rates may be an effective means of reducing N_2O emissions, this may come at the cost of decreased yields depending on the level of fertilizer input before any change (Millar et al., 2010). Alternative practices that could reduce N_2O emissions without necessarily reducing N inputs or crop yields have also been considered, such as optimization of fertilizer source (e.g., Halvorson et al., 2010a) or modification of tillage regime (Omonode et al., 2011). However, the effectiveness of these practices in reducing N_2O emissions may vary depending on local soil and other conditions (Akiyama et al., 2010). Also, alteration of crop yields resulting from any change in management practice needs to be considered. As world demand for agricultural products continues to increase, a focus on reducing area-scaled N_2O emissions without considering emissions per unit of crop yield may simply serve to displace any lost production and its associated emissions to another location or cropping system. To minimize the overall greenhouse gas (GHG) impact of agriculture while increasing crop production, the amount of N_2O emitted per unit of crop production needs to be considered (Van Groenigen et al., 2010). There have been only a few studies that have directly reported yield-scaled emissions in corn or other cropping systems (Gagnon et al., 2011; Halvorson et al., 2010a; Wei et al., 2010).

Modification of tillage regime remains one of the most commonly proposed practices for mitigating the GHG impact of agricultural production due to its potential for sequestering soil carbon and decreasing energy consumption (e.g., Woods et al., 2010). Several studies over the past three decades have addressed the question of whether reduced tillage (RT) increases or decreases N_2O emissions, with highly mixed results (i.e., no till [NT] or RT has been found to increase, decrease, or not affect N_2O emissions compared with conventional tillage [CT]) (reviewed by Rochette et al., 2008c). Similar to its effects on N_2O emissions, RT has been shown to have contrasting effects

J. Environ. Qual. 40:1521–1531 (2011)
doi:10.2134/jeq2011.0039
Posted online 8 July 2011.
Received 7 Feb. 2011.
*Corresponding author (venterea@umn.edu).
© ASA, CSSA, SSSA
5585 Guilford Rd., Madison, WI 53711 USA

R.T. Venterea and M.S. Dolan, USDA–ARS, Soil and Water Management Unit, 1991 Upper Buford Cir., St. Paul, MN 55108; R.T. Venterea and B. Maharjan, Dep. Soil, Water, and Climate Univ. of Minnesota, St. Paul, MN 55108. Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA. Assigned to Associate Editor Martin H. Chantigny.

Abbreviations: CRF, controlled-release fertilizer; CT, conventional tillage; CU, conventional urea; FIEF, fertilizer-induced emissions factor; GHG, greenhouse gas; IU, enzyme inhibitor–impregnated urea; NFRE, nitrogen fertilizer recovery efficiency; NT, no-till; PCU, polymer-coated urea; WFPS, water-filled pore space.

on grain yields depending on soil, climate, or other factors (e.g., Grandy et al., 2006; Vetsch et al., 2007).

A major challenge in managing N for corn production is that soil N availability is not easily synchronized with crop N demand because corn's demand for N is minimal early in the growing season and increases several weeks after emergence (Olson and Kurtz, 1982). Thus, although it may be most convenient or cost-effective to apply N fertilizer before planting or soon after emergence, these practices increase the potential for soil microbial and chemical processes to transform the applied N into N_2O and other highly mobile forms such as NO_3^-. Sidedress fertilizer applications, which are timed to coincide with later plant growth stages, may partly alleviate this problem (Scharf et al., 2002). Improved synchrony may also be achieved with fertilizer products designed to release N more slowly over the course of the season (Halvorson et al., 2010a). The combined use of sidedress timing and controlled-release products may further reduce the potential for N_2O emissions, but there have been few if any studies examining this combination of practices.

The objectives of the current study were (i) to determine area- and yield-scaled N_2O emissions in long-term CT and NT corn plots that received sidedress applications of conventional urea and two different types of controlled-release fertilizers (CRFs) over three consecutive growing seasons and (ii) to examine tillage and fertilizer source effects on soil NH_4^+ and NO_3^- levels, grain and N yields, and nitrogen use efficiency.

Materials and Methods

Site Description and Experimental Design

The site is located at the University of Minnesota's Outreach, Research, and Education Park in Rosemount, MN (44°45′ N, 93°04′ W), where the soil is a naturally drained Waukegan silt loam (fine-silty over skeletal mixed, superactive mesic Typic Hapludoll) with sand, silt, and clay contents of 220, 550, and 230 g kg^{-1}, respectively, and organic carbon of 26 to 30 g C kg^{-1} in the upper 0.2 m. Mean annual precipitation and temperature are 879 mm and 6.4°C, respectively (MCWG, 2011). A long-term study was established in 1990 using a randomized complete block design with crop rotation and tillage intensity as the main treatments in each of three blocks. Previous findings from this site have been reported by Venterea et al. (2005, 2006, 2010). The current study examined the corn phase of the corn–soybean rotation at two levels of tillage intensity. The plots used each year were rotated to follow the corn crop (different sections of the same plots were examined in 2008 and 2010). No measurements were made in the plots while they were planted to soybean. Emissions of N_2O from soybean at this site during 2005 and 2006 were reported by Venterea et al. (2010).

Tillage treatments included (i) CT, which used fall moldboard plowing following corn, fall chisel plowing, or disk-ripping following soybean, with spring pre-plant cultivation before corn and soybean, and (ii) continuous no-till (NT). Chisel plowing historically used 0.2-m deep shanks with 0.3-m spacing and was replaced by disk ripping in 2000, which used 0.3-m deep shanks with 0.76-m spacing and two sets of 0.15-m deep disks.

Corn (37L11; Pioneer, Mankato, MN) was planted in all plots at seeding rates of 79,000 ha^{-1} on 9 May 2008, 5 May 2009, and 6 May 2010 using a John Deere model 7100 MaxEmerge planter. Row cleaning coulters (Yetter Mfg., Colchester, IL) were used in the NT treatments to produce a more desirable seed bed. Liquid starter fertilizer was applied within 5 cm of the seed row at planting at 4.5, 9.0, and 4.5 kg ha^{-1} of urea-N, P, and K, respectively. Additional P and K fertilizers were applied periodically to the entire plot areas (last application in May 2006). After planting in 2008, 2009, and 2010, each of the main plots was subdivided into four 5-m × 5-m subplots for fertilizer treatments, which were assigned randomly within each main plot and consisted of (i) conventional granular urea (CU) (46% N w/w), (ii) polymer-coated urea (PCU) (44% N w/w) (ESN; Agrium Advanced Technologies, Loveland, CO), (iii) urea (46% N w/w) impregnated with the urease inhibitor (IU) N-(n-Butyl)-thiophosphoric triamide and the nitrification inhibitor dicyandiamide, (Super U; Agrotain International, St. Louis, MO), and (iv) a control that received only the starter. Fertilizers were applied on 11 June 2008, 18 June 2009, and 10 June 2010 when the corn was at stage V4 to V6. In each case, fertilizer application was timed to minimize ammonia volatilization losses. In 2008 and 2010, fertilizers were applied before at least 17 mm of precipitation occurring within the next 12 h. In 2009, fertilizers were applied within 6 h after 11 mm of precipitation when the soil surface was very wet. All fertilizer products were hand-applied (broadcast) uniformly on the surface at 146 kg N ha^{-1}. During application, the N_2O flux chamber measurement areas (described below) were initially covered. After the initial application, separately weighed portions of product were applied within the chamber-measurement areas to ensure accurate application rates. One pre-emergence application of metolachlor and two post-emergence applications of glyphosate were made each year. No-till plots received additional glyphosate applications occasionally as needed. During the soybean phase, soybeans were planted in late May or early June and were harvested in mid to late October, with no N fertilizer applied.

Yields and Plant Nitrogen Content

At physiological maturity, corn ears were hand harvested from a total distance of 6.1 m in the middle two rows of each subplot. Grain was dried, shelled, and further dried and weighed to obtain dry grain yields. Stover was obtained by cutting plants just above the crowns for all plants where ears were removed. All stover was weighed, and six plants were subsampled and ground, dried, and weighed for moisture content. Grain and stover samples were further ground with a grinding mill and analyzed with an elemental N analyzer (VarioMax; Elementar, Hanau, Germany) for total N.

Nitrous Oxide Emissions

Soil-to-atmosphere N_2O fluxes were measured once per week starting in April and then twice per week once fertilizers had been applied until October of each year, for a total of 34 to 37 measurement dates each year. Stainless steel chamber anchors (0.50 m × 0.29 m × 0.086 m deep) and tops (0.50 m × 0.29 m × 0.102 m high) were used as described in detail by Venterea et al. (2010). One chamber anchor was installed in each subplot, centered between rows of corn with the short side parallel to the row. Once fertilizers were applied, anchors were not moved for the duration of the growing season. Measurements were generally made during 1000 h to 1200 h local time when soil temperature in the upper 0.10 m was close to its daily mean value. For each measurement, tops were secured to anchors, and samples were collected after 0, 0.5, and 1 h using a 12-mL polypropylene syringe (in 2010, a fourth sample was collected after 1.5 h). Samples were transferred to glass vials sealed with butyl rubber septa (Alltech, Deerfield, IL) and analyzed within 1 wk using a headspace autosampler (Teledyne Tekmar, Mason, OH) connected to a gas chromatograph (model 5890; Agilent/Hewlett-Packard, Santa Clara, CA) equipped with an electron capture detector. The system was calibrated daily using analytical grade standards (Scott Specialty Gases, MI). Chamber gas concentrations were converted from molar mixing ratio units (e.g., ppm) determined by gas chromatography analysis to mass per volume units (μg N m^{-3}) assuming ideal gas relations using air temperatures measured during sampling. Gas fluxes were calculated from the rate of change in N_2O concentration, chamber volume, and surface area using linear regression or the quadratic model of Wagner et al. (1997) and using correction factors to account for suppression of the surface–atmosphere concentration gradient (Venterea 2010). The quadratic model was evaluated using the LINEST function in Excel (v. 2007; Microsoft, Redmond, WA).

Climate and Soil Properties

Air temperature and daily precipitation data were obtained from a weather station l km from the site. Soil temperature was measured during each N_2O flux measurement period using temperature probes (Fisher, Hampton, NH) inserted to the 0.05-m depth within 1 m of the chambers. Soil water content was determined on samples collected to the 0.10-m depth within 1 h of each flux measurement period by drying at 105°C. Additional soil samples were collected for analysis of extractable inorganic N and bulk density on a total of 11 dates in 2008, six dates in 2009, and eight dates in 2010. Soil samples were collected at three to six locations within each subplot from the 0- to 15-cm depth using a 19-mm ID soil core sampler (Oakfield Apparatus, Inc., Oakfield, WI). Sampling locations were randomly selected from within the center 0.38 m of the interrow region, avoiding areas affected by obvious wheel traffic compaction. Cores from each depth were pooled, homogenized, and refrigerated before analysis. Subsamples (~10 g) were extracted in 2 mol L^{-1} KCl, filtered (Whatman no. 42), and stored (–20°C) until analysis for ammonium (NH_4^+)–N and the sum of nitrite (NO_2^-)–N and nitrate (NO_3^-)–N (referred to henceforth as NO_3^-) using a flow-through injection analyzer (Lachat, Loveland, CO). Bulk density was determined from soil mass collected after drying at 105°C. Bulk density values were used together with gravimetric water content to estimate water-filled pore space (WFPS).

Data Analysis and Statistics

Nitrous oxide fluxes measured on each sampling date for each subplot were used to estimate cumulative area-scaled N_2O emissions using trapezoidal integration of flux versus time, which in effect assumes that fluxes changed linearly between measurement dates. Fertilizer-induced emissions factors (FIEFs) were calculated by subtracting the mean growing season N_2O emissions in the control treatments within the corresponding tillage treatment and year from the total cumulative N_2O emissions in each fertilized treatment and expressing the result as a percentage of the fertilizer application rate (146 kg N ha^{-1}). Yields of grain N and total aboveground N were determined from the grain and stover N contents and dry matter yields. Three different indices of yield-scaled N_2O emissions were calculated by dividing cumulative area-scaled emissions by (i) grain yield, (ii) grain N yield, and (iii) total aboveground N yield. Following Van Groenigen et al. (2010), N surplus was calculated as total fertilizer applied minus above-ground N yield. To calculate N surplus for the fertilized treatments, we used the sum of the starter rate (4.5 kg N ha^{-1}) plus the sidedress fertilizer rate (145 kg N ha^{-1}), and for the control treatments, we used the starter rate. Relationships between N surplus and yield-scaled emissions reported by Van Groenigen et al. (2010) were examined using Proc Reg in SAS and SigmaPlot (v. 11, Systat Software Inc., Chicago, IL). Nitrogen fertilizer recovery efficiency (NFRE) was calculated by subtracting the mean aboveground N yield in the control treatment within the corresponding tillage treatment and year from the total aboveground N yield in each fertilized treatment and expressing the result as a percentage of the fertilizer N application rate (Bock, 1984). Soil N intensity was determined by trapezoidal integration of soil concentration versus time (Burton et al., 2008; Engel et al., 2010) separately for NO_3^- and NH_4^+ and for the sum of NO_3^- and NH_4^+. Effects of year, tillage, and fertilizer source were determined using Proc Mixed in SAS with block, block-by-year, and block-by-year-by-tillage treated as random effects (SAS, 2003; Littell et al., 2006). Unless otherwise indicated, means comparisons were applied when any first-order or interaction effect was significant at $P < 0.05$ using least squares means in Proc Mixed. Correlation coefficients (r^2) obtained using linear regression analysis with Proc Reg in SAS are reported ($P < 0.05$).

Results

Weather and Soil Moisture and Temperature

Cumulative precipitation amounts during April through September in 2008 and 2009 were 24 and 30% below the 30-yr average, whereas in 2010 it was 10% above the long-term average (Fig. 1a). In 2010, the mean daily air temperature was considerably higher compared with the other 2 yr (Fig. 1c). Soil WFPS at the time of N_2O flux sampling generally was below 70%, except during periods of high-frequency rainfall events in 2009 and 2010 that resulted in WFPS values above 80% (Fig. 1b). While 2009 had the least amount of total growing season precipitation, it also had the lowest average daily temperature (Fig. 1). This factor, together with a cluster of rainfall events exceeding 20 mm in mid-July through mid-August, resulted in WFPS values at the time of gas flux sampling exceeding 70% for much of this period. Soil moisture content and bulk density tended to be higher under NT than under CT, which resulted in generally higher levels of WFPS. Differences in WFPS by tillage were significant only at the $P < 0.10$ confidence level and only in 2008 and 2009. There were no significant differences

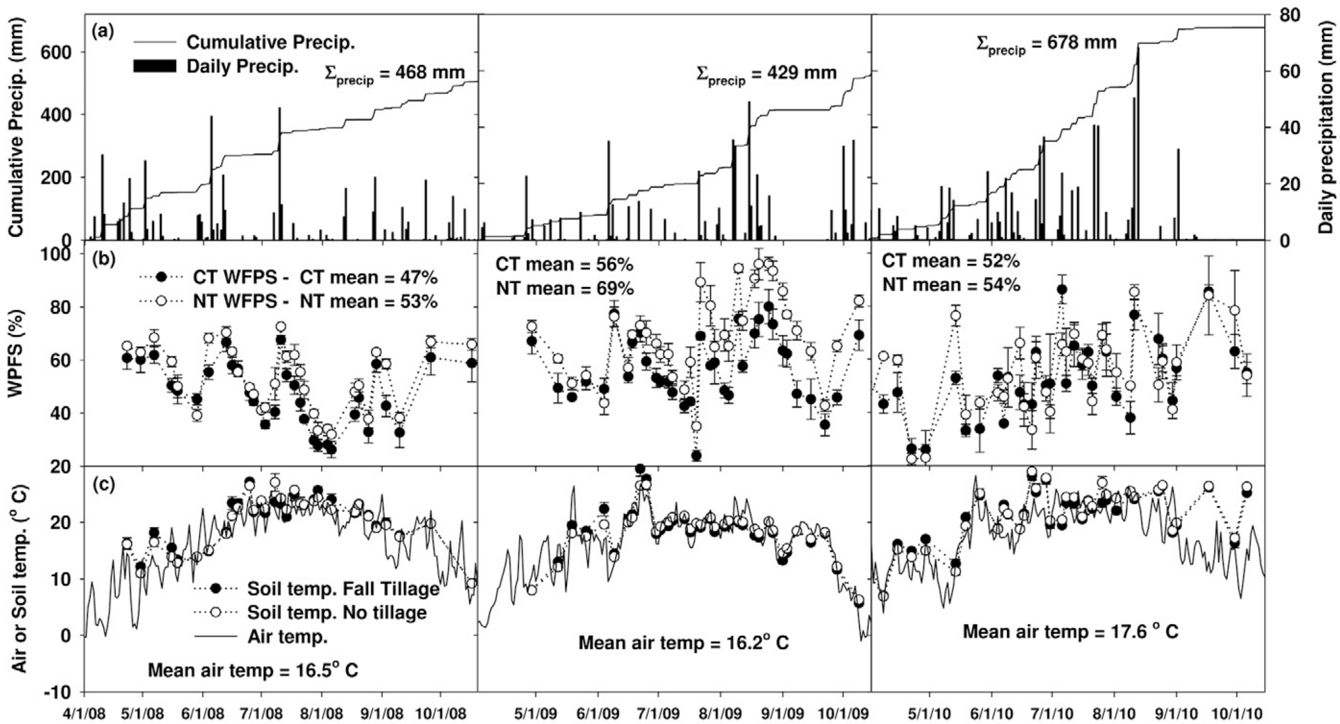


Fig. 1. (a) Daily and cumulative precipitation, (b) mean (and SE) water-filled pore space (WFPS) at the 0- to 0.1-m depth at the time of N_2O sampling, and (c) air temperature and mean (and SE) soil temperature at the 0.05-m depth at the time of N_2O sampling in plots managed under conventional tillage (CT) and no-till (NT) during 2008, 2009, and 2010. The CT and NT means include all of the fertilizer source treatments; there were no differences in soil moisture or temperature due to fertilizer source. Cumulative precipitation and average air temperatures are for the period 1 April through 30 September.

in soil moisture due to fertilizer source or in soil temperature due to tillage or fertilizer source, except that soil temperature tended to be lower in NT than CT early in the growing season (Fig. 1c).

Yields and Nitrogen Use Efficiency

All agronomic variables displayed significant first-order effects of year, tillage, and fertilizer when averaged across each of the other factors (Fig. 2). Yields of grain, grain N, and aboveground N tended to be greatest in the year with the most growing season precipitation (2010), although the year with the least precipitation (2009) had greater grain yields than 2008 (Fig. 2a). The overall NFRE was greater in 2010 than in 2008. Across all years and fertilizer treatments, yields were greater under CT compared with NT, but NFRE was greater under NT (Fig. 2b). Across all years and tillage treatments, yields did not differ among the three fertilized treatments (CU, PCU, or IU), which were all greater than the unfertilized control (Fig. 2c). The NFRE was lower in the PCU compared with CU and IU treatments (Fig. 2c).

Significant year-by-fertilizer treatment interaction effects were found for grain, grain N, and aboveground N yields and for NFRE (Table 1). The data in Table 1 indicate that 2009 was the only year in which any of the fertilizer treatments differed significantly with respect to agronomic variables. In 2009, NFRE and yields of grain and total aboveground N were less in the PCU treatment than in the CU or IU treatments (Table 1). Significant tillage-by-fertilizer treatments interaction effects were found for grain, grain N, and aboveground N yields (Table 2). The NT-control treatment had consistently lower yields across all three yield indices compared with any other treatment. In contrast, yields in the CT-control treatment did not vary from those in any of the fertilized NT treatments (Table 2). The positive correlation between grain yields and growing season cumulative precipitation across the 3 yr was stronger in the NT treatment (r^2 = 0.73) compared with CT (r^2 = 0.20). Similarly, yields were more highly correlated (positively) with average daily air temperature in the NT system (r^2 = 0.68) compared with CT (r^2 = 0.16) across the 3 yr.

Nitrous Oxide Emissions

Daily N_2O fluxes increased within a few days after fertilizer application each year. Increases in N_2O flux also occurred after major precipitation events in July and August of each year (Fig. 3–5). Increased fluxes were observed for several sampling events during August 2009, particularly in the CT treatment, which occurred during the same period in which elevated WFPS was observed (Fig. 1b, 4). In 2009, daily N_2O flux in the CT fertilized treatments (excluding the control) was positively correlated with WFPS (r^2 = 0.30).

On an area basis, N_2O emissions did not differ by year or tillage (Fig. 6a,b). Area-scaled emissions were greater in the CU, PCU, and IU treatments compared with the control, and the PCU treatment had greater area-scaled emissions than IU (Fig. 6c). Area-scaled emissions in NT averaged across all years and fertilizer treatments were 75 mg N m^{-2} (0.75 kg N ha^{-1}) compared with 63 mg N m^{-2} (0.63 kg N ha^{-1}) in CT, although the difference was not significant (P = 0.15). There were no significant year- or tillage-by-fertilizer interaction effects on area-scaled emissions (P > 0.38).

The pattern of significant differences with regard to fertilizer and tillage effects changed when emissions were expressed per unit of grain or grain N yield (Fig. 6b,c; Table 2). Scaled by grain yield, emissions did not vary by fertilizer overall (Fig. 6c) but were significantly greater in NT than CT across years and fertilizer treatments. There was also a significant tillage-by-fertilizer interaction effect, with the CT–PCU treatment having greater emissions than any other CT treatment and the NT–IU treatment having lower emissions than any other NT treatment (Table 2).

Scaled by grain N yield, the overall fertilizer source effect was similar to that for area-scaled emissions, except that the IU treatment had lower emissions than the control (Fig. 6c). Emissions per unit grain N were greater in NT than CT overall (Fig. 6b). Emissions in the NT–control treatment were greater than in all other treatments and were greater in NT–CU and NT–PCU than all CT treatments except CT–PCU (Table 2). The patterns of differences for emissions expressed per unit of aboveground N yield were identical to that for grain N, with NT having 69% greater emissions than CT (data not shown). The mean FIEF averaged across all treatments was greater in 2010 (0.42%) compared with 2008 (0.14%) and 2009 (0.17%). The FIEF in the IU treatment (0.16%) was slightly lower than in the CU (0.26%) and PCU (0.31%) treatments ($P = 0.08$). Values of FIEF did not differ significantly by tillage (data not shown). Linear correlation between N_2O emissions and growing season cumulative precipitation across the 3 yr was stronger in the CT treatment ($r^2 = 0.81$) compared with NT ($r^2 = 0.18$). Similarly, emissions were more highly correlated with average daily air temperature in the CT system ($r^2 = 0.77$) compared with NT ($r^2 = 0.22$) across the 3 yr.

Area-scaled N_2O emissions, averaged by tillage–fertilizer treatment combination within each year, were positively and linearly correlated with N surplus ($r^2 = 0.20$). An exponential rise equation described the yield-scaled emissions data relatively well as a function of N surplus ($r^2 = 0.58$) but only when the NT–control treatment results from 2008 and 2009 were excluded from the analysis (Fig. 7). The NT–control treatments in 2008 and 2009 had higher yield-scaled emissions than predicted by these relationships due to their particularly low grain yields (4.2 and 5.8 Mg ha^{-1}, respectively) and the fact that their area-scaled N_2O emissions (0.71 and 0.57 kg N ha^{-1}, respectively) were not reduced compared with the other treatments. Only the NT–CU and NT–PCU treatments in 2008 and the NT–PCU treatment in 2009 had N surplus values greater than zero (8–20 kg N ha^{-1}), indicating that more N fertilizer was applied than was recovered in the aboveground biomass. The NT–CU and NT–PCU treatments in 2008 also had the greatest yield-scaled emission, with the exception of the two outlier NT–control treatments (Fig. 7).

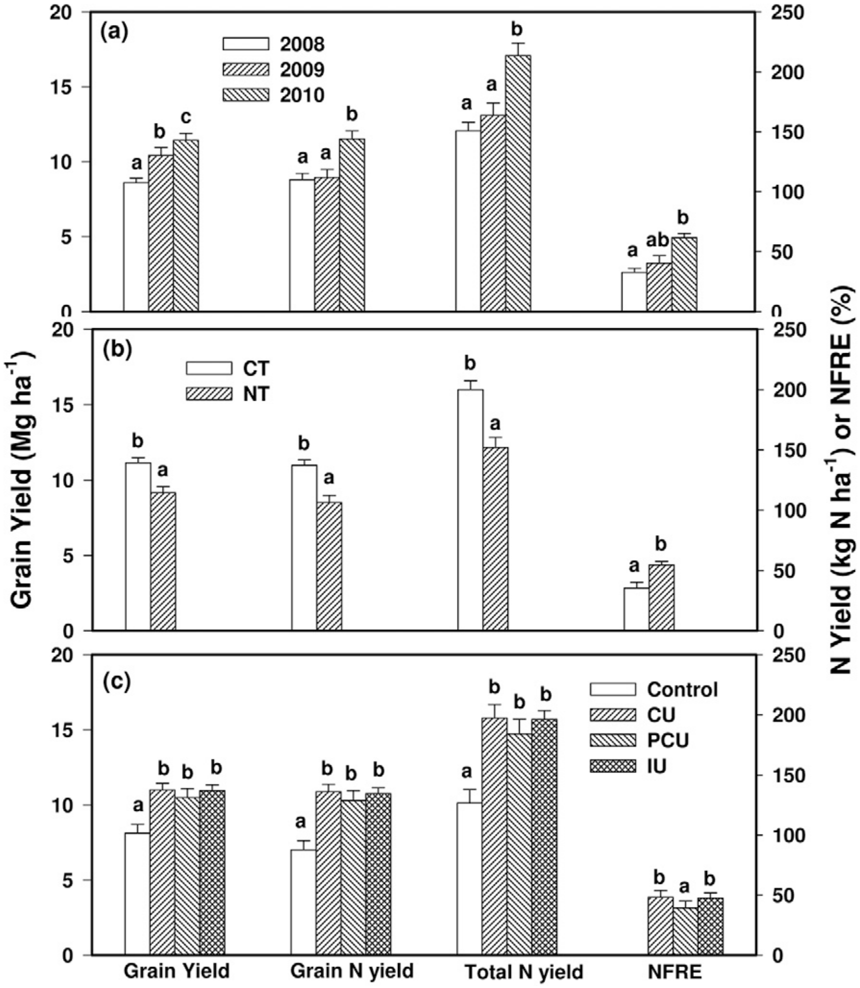


Fig. 2. Mean (and SE) grain yield, grain N yield, total aboveground N yields, and nitrogen fertilizer recovery efficency (NFRE) segregated by (a) year, (b) tillage, and (c) fertilizer source. For each quantity, bars with the same lowercase letter are not significantly different by year (a), by tillage (b), and by fertilizer source (c) ($P < 0.05$). CU, conventional urea; IU, enzyme inhibitor–impregnated urea; PCU, polymer-coated urea.

Soil Inorganic Nitrogen Intensity

Soil NH_4^+ and NO_3^- concentrations in the upper 0.15 m increased after fertilizer application each year (Fig. 8). In 2009 and 2010, inorganic N levels tended to decline to pre-fertilizer levels over the remainder of the growing season, whereas in 2008, elevated soil NO_3^- (and to a lesser extent NH_4^+ concentrations) persisted until at least the mid-September soil sampling event (Fig. 8a). The persistence of soil inorganic N in 2008 may have been due to the persistent dry soil conditions (Fig. 1), which may have inhibited its mobility. This resulted in significantly greater NO_3^- and NO_3^- plus NH_4^+ intensity in 2008 compared with 2009 and 2010 averaged across all fertilizer and tillage treatments (Fig. 6a). Averaged across all years and fertilizer treatments, all three indices of N intensity were greater under CT compared with NT (Fig. 6b), and, averaged across all years and tillage treatments, all three indices of N intensity were greater in the fertilized treatments compared with the control (Fig. 6c). Across all years, NO_3^- intensity increased in the order Control < PCU < IU < CU, and NO_3^-

plus NH_4^+ intensity increased in the order Control < PCU < IU = CU (Fig. 4c). No measure of soil N intensity was significantly correlated with cumulative N_2O emissions.

Table 1. Means (and standard errors) for variables where significant year-by-fertilizer interaction effects were found.

Fertilizer treatments†	2008	2009	2010
	Grain yield (Mg ha^{-1})		
Control	7.3 (0.7) a‡	8.9 (1.4) b	8.2 (0.9) ab
CU	9.3 (0.5) bc	11.5 (0.8) d	12.2 (0.4) d
PCU	8.6 (0.3) bc	10.0 (1.2) c	12.9 (0.5) d
IU	9.2 (0.5) bc	11.4 (0.5) d	12.3 (0.1) d
	Grain N yield (Mg N ha^{-1})		
Control	83 (13) a	84 (16) a	97 (13) ab
CU	123 (8) bc	129 (12) c	157 (7) d
PCU	111 (6) b	110 (14) b	166 (8) d
IU	123 (7) bc	125 (7) bc	156 (2) d
	Aboveground N yield (kg N ha^{-1})		
Control	115 (16) a	119 (24) b	146 (19) cd
CU	167 (11) de	184 (19) e	241 (15) f
PCU	152 (9) cd	158 (16) c	242 (14) f
IU	170 (9) de	193 (12) e	225 (4) f
	Nitrogen fertilizer recovery efficiency (%)		
CU	36 (4.0) abc	44 (12.8) bc	65 (7.2) de
PCU	25 (6.3) ab	27 (8.6) a	66 (5.2) de
IU	38 (6.5) bc	51 (9.6) cde	54 (5.4) cde

† CU, conventional urea; IU, impregnated urea; PCU, polymer-coated urea.

‡ For each variable, values with same letter are not significantly different ($P < 0.05$).

Table 2. Means (and standard errors) for variables where significant tillage-by-fertilizer interaction effects were found.

Fertilizer treatments†	Tillage treatments	
	Conventional tillage	No-till
	Grain yield (Mg ha^{-1})	
Control	9.9 (0.6) b‡	6.3 (0.6) a
CU	12.0 (0.6) d	10.1 (0.5) bc
PCU	11.3 (0.8) cd	9.7 (0.8) b
IU	11.4 (0.6) d	10.6 (0.5) bc
	Grain N yield (Mg N ha^{-1})	
Control	112 (5) b	63 (8) a
CU	151 (8) d	121 (6) b
PCU	143 (11) cd	114 (10) b
IU	142 (5) d	127 (7) bc
	Aboveground N yield (kg N ha^{-1})	
Control	161 (11) bc	92 (12) a
CU	221 (16) d	173 (12) bc
PCU	207 (16) d	161 (15) b
IU	210 (9) d	182 (10) c
	Grain yield scaled N_2O emissions (g N Mg^{-1})	
Control	46 (7) a	100 (17) d
CU	54 (5) a	91 (14) cd
PCU	73 (4) b	91 (9) cd
IU	58 (10) a	67 (8) ab
	Grain N yield scaled N_2O emissions (g N kg^{-1} N)	
Control	4.0 (0.5) a	10.7 (1.9) c
CU	4.4 (0.5) a	7.4 (1.0) b
PCU	5.8 (0.4) ab	7.7 (0.7) b
IU	4.6 (0.8) a	5.6 (0.7) ab

† CU, conventional urea; IU, impregnated urea; PCU, polymer-coated urea.

‡ For each variable, values with same letter are not significantly different ($P < 0.05$).

Discussion

Tillage Effecs

Averaged across all fertilizer treatments and all years, there was no significant tillage effect on area-scaled N_2O emissions in this study. However, when expressed per unit yield of grain, grain N, or total aboveground N, N_2O emissions were 52, 66, and 69% greater, respectively, in NT compared with CT due to lower yields with NT. Averaged over 3 yr, yields in the fertilized treatments (CU, PCU, and IU) were 13% lower with NT than CT. The yield reductions were similar in 2008 (8.9%) and 2010 (9.5%) and greatest in the driest year, 2009 (18%). Similar corn grain yield deficits under long-term NT have been reported in several studies and have been attributed to cooler soil temperatures in the spring, which may inhibit early-season plant development (e.g., Kaspar et al., 1987; Vyn and Raimbault, 1993; Vetsch and Randall, 2004; Vetsch et al., 2007; Halvorson et al., 2006). In spite of yield deficits, NT may be economically feasible because of decreased production costs (Archer et al., 2008). In some cases, NT results in yield increases compared with CT (e.g., Grandy et al., 2006; Ismail et al., 1994). In cases of yield increases, expressing emissions per unit yield would provide additional information to consider in evaluating overall GHG impacts. For example, Almaraz et al. (2009) found in 1 yr that N_2O emissions were 35% greater with NT compared with CT in a clay loam in eastern Canada. However, because yields were also greater (by 17%) with NT in that study, the percentage increase in N_2O emissions under NT would be only 15% expressed on a yield-scaled basis and may not have been significantly different than CT.

In the current study, there was no significant tillage effect on area-scaled emissions, but the trend ($P = 0.15$) was for greater emissions with NT. Although not statistically significant, this trend is consistent with previous findings showing greater area-scaled N_2O emissions in NT compared with CT soils when N fertilizer is applied on or close to the surface (e.g., Venterea et al., 2005; Baggs et al., 2003; Ball et al., 1999). In contrast, other

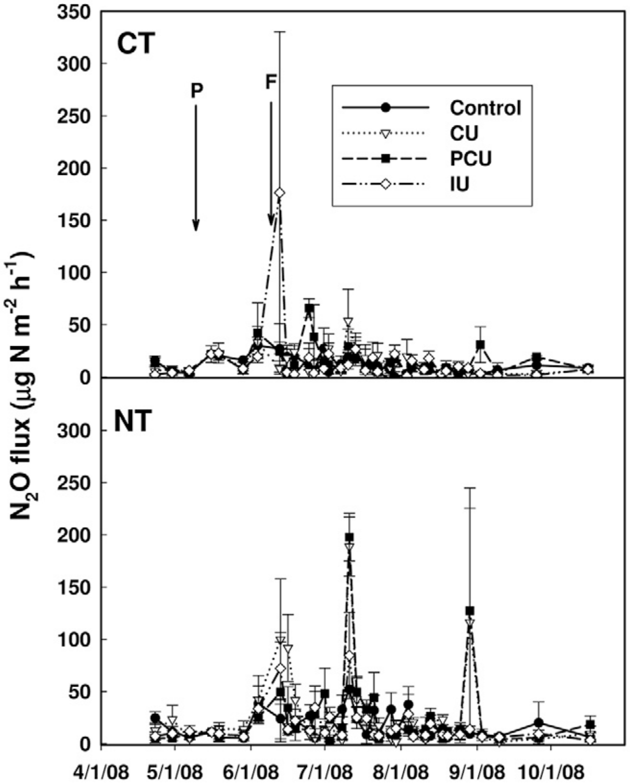


Fig. 3. Mean (SD) N_2O emissions in plots managed under conventional tillage (CT, upper plates) and no-till (NT, lower plates) that were fertilized with conventional urea (CU), polymer-coated urea (PCU), or enzyme inhibitor-impregnated urea (IU) and in a control treatment during 2008. Downward-pointing arrows indicate dates of planting (P) and fertilizer application (F).

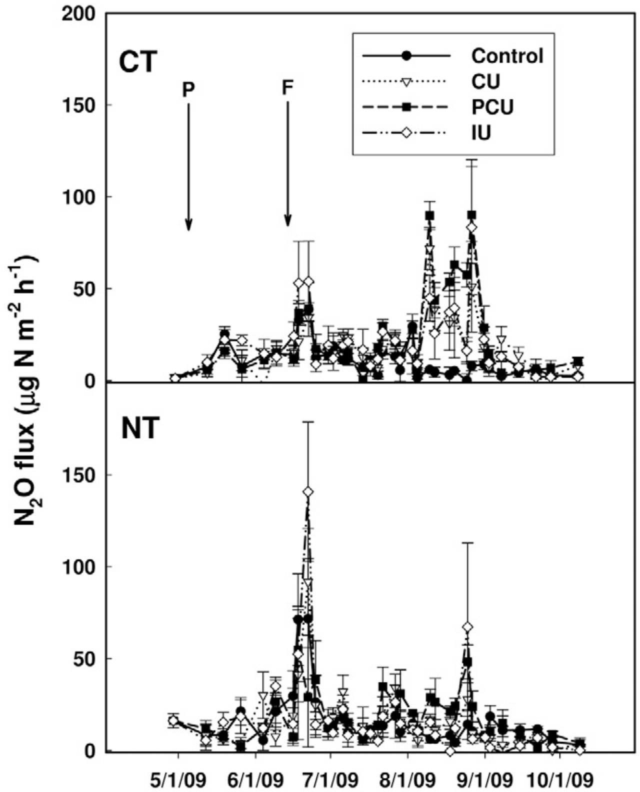


Fig. 4. Mean (SD) N_2O emissions in plots managed under conventional tillage (CT, upper plates) and no-till (NT, lower plates) that were fertilized with conventional urea (CU), polymer-coated urea (PCU), or enzyme inhibitor-impregnated urea (IU) and in a control treatment during 2009. Downward-pointing arrows indicate dates of planting (P) and fertilizer application (F).

studies in soils receiving subsurface-applied N fertilizers have shown lower N_2O emissions under NT (e.g., Venterea et al., 2005; Omonode et al., 2011; Ussiri et al., 2009; Jacinthe and Dick, 1997). Venterea and Stanenas (2008) used soil enzyme data and process modeling to explain this apparent fertilizer placement-by-tillage interaction as being due to greater potential N_2O production in the upper 0.05 m and lower potential N_2O production below 0.10 m in soil profiles of NT versus CT systems. However, not all studies have conformed to this trend of higher emissions with NT compared with CT when N was surface applied. For example, Halvorson et al. (2010b) found greater emissions from CT than NT when N fertilizer was surface banded and watered in after emergence. Other proposed explanations for contrasting results of previous studies have included interactions between soil and climate factors (Rochette et al., 2008a,c; Gregorich et al., 2005) and precipitation regime and/or duration of adoption (Six et al., 2004).

Fertilizer Source Effects

The PCU and IU fertilizer products did not reduce area-scaled N_2O emissions compared with CU when all sources were applied as a single sidedress application several weeks after planting. Bronson et al. (1992) reported that urea with nitrification inhibitors reduced N_2O emissions compared with urea when fertilizers were subsurface applied 7 wk after planting corn. Most other studies showing less N_2O emissions with CRFs compared with CU have used fertilizers applied earlier in the season (i.e., closer to planting or emergence) (Halvorson et al., 2010a,b; Delgado and Mosier, 1996) or using split applications with some applied at planting or emergence and additional amounts applied later in the seasons (Halvorson et al., 2008; Jumadi et al., 2008; Hadi et al., 2008). In the current study, there may have been less opportunity for microbial transformation of fertilizer N before the onset of significant plant N uptake, and this factor may have decreased the potential benefit of the CRFs to reduce N_2O emissions.

The PCU did not perform as well as urea impregnated with nitrification and IU. Polymer-coated urea had significantly lower grain and N yields than CU or IU in 2009 and slightly lower yields in 2008, both of which were drier than normal years. This combined with the greater area-scaled emissions translated into greater yield-scaled N_2O emissions in PCU compared with IU and resulted in lower NFRE in 2009 and overall compared with CU and IU. Climate factors, including the timing of rainfall events in relation to plant N demand, are likely to be important in regulating the agronomic performance of PCUs because water is required for N release (Shaviv, 2000).

We observed FIEFs in the range of 0.14 to 0.42% of the applied N, which is lower than most studies, which tend to average close to 1% (Stehfest and Bouwman, 2006). Although the current study did not directly compare pre-plant versus post-plant N application timing effects, the timing of application may have helped to reduce N_2O emissions. The mean growing season area-scaled N_2O emissions during 2008–2010 with sidedress N application were 0.69 and 0.81 kg N ha^{-1} in

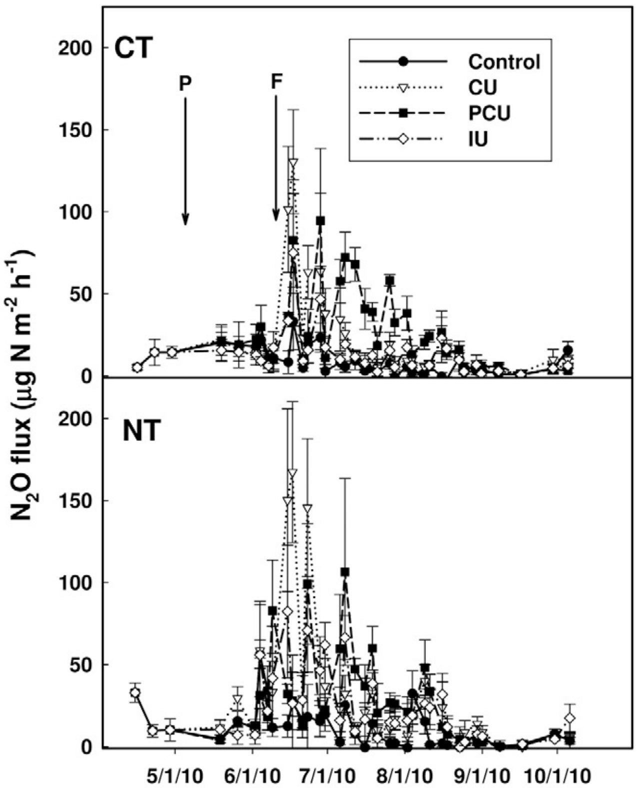


Fig. 5. Mean (SD) N_2O emissions in plots managed under conventional tillage (CT, upper plates) and no-till (NT, lower plates) that were fertilized with conventional urea (CU), polymer-coated urea (PCU), or enzyme inhibitor–impregnated urea (IU) and in a control treatment during 2010. Downward-pointing arrows indicate dates of planting (P) and fertilizer application (F).

the CT and NT, respectively. In a previous 3-yr study at the same site during 2005–2007 where urea was applied before planting at the same rate, mean emissions were 28 to 50% greater (1.04 kg N ha^{-1}) under a tillage regime that was intermediate in intensity between CT and NT (Venterea et al., 2010). Total precipitation amounts during the two 3-yr periods were within 1%.

Nitrogen Use Efficiency

Aboveground N yields were greatly reduced in the NT–control treatment, particularly in the drier years of 2008 (80 kg N ha^{-1}) and 2009 (75 kg N ha^{-1}). Because the NFRE calculation is based on the difference between the fertilized and control treatments, these low N yields skewed the NFRE calculation in favor of NT compared with CT. This suggests that the NT treatments used fertilizer N more efficiently compared with CT, even though NT had lower grain and N yields. It is likely that lower rates of soil organic matter mineralization in the NT soils resulted in a greater dependency on fertilizer N compared with CT soils and in the particularly low yields in the NT–control treatments. This idea is supported by the greater soil N intensity found in CT, which is consistent with a previous study that found greater soil NO_3^- concentrations in CT compared with NT (Grandy et al., 2006). The low N yields in the NT–control treatments in 2008 and 2009 also resulted in these data not conforming to the exponential rise functions relating N surplus to yield-scaled emissions (Fig. 7). Without these data points, our results are consistent with the meta-analysis findings of Van Groenigen et al. (2010) and similarly suggest that as N surplus exceeds zero, yield-scaled N_2O emissions increase exponentially. Our data showed lower emissions than Van Groenigen et al. (2010) at a given level of N surplus. This difference could have resulted from the conservative N management practices (i.e., sidedress application timing) used in the current study. However, other model parameters (i.e., the two coefficients in the exponential term [Fig. 7]) were similar to those found by Van Groenigen et al. (2010).

Yield-scaled Emissions

The few studies directly reporting yield-scaled N_2O emissions in grain production systems report a range of values varying over approximately one order of magnitude. Our yield-scaled emissions were in the range of 46 to 100 g N Mg^{-1} grain (Table 2), which is similar to the range (31–67 g N Mg^{-1}) reported by Halvorson et al. (2010a) in a study of CRFs in irrigated corn in Colorado. These values are more than 10 times less than values (1.3–2.0 kg N Mg^{-1}) reported by Gagnon et al. (2011) in a clay soil receiving sidedress N applications for rainfed corn in eastern Canada. In a rainfed wheat system in China, grain yields of 2 to 6 Mg ha^{-1} combined with area-scaled N_2O emissions of 2 to 4 kg N ha^{-1} resulted in yield-scaled emissions of 1.0 to 2.5 kg N Mg^{-1} (Wei et al., 2010). Even fewer studies have reported N_2O emissions per unit of grain N yield. The range found here (4–11 g N kg^{-1} N) (Table 2) is about 10 times less than the range (50–150 g N kg^{-1} N) reported by Wei et al. (2010).

Expressing N_2O emissions on a yield-scaled basis provides additional information for evaluating overall GHG impacts. For example, based on the current findings, if the same amount of grain were produced using NT and CT, then the NT system would emit 53% more N_2O compared with CT under the same fertilizer regime and would require additional land area to produce the same amount of grain. The same considerations would apply to cases of yield increases or to practices besides tillage that can potentially affect yields and N_2O emissions. For example, Rochette et al. (2008b) noted that using manure as a fertilizer N source decreased silage corn yields and increased area-scaled N_2O emissions compared with synthetic fertilizer, although yield-scaled emissions were not directly reported.

Conclusions

Neither of two CRFs decreased N_2O emissions compared with CU, but they reduced soil NO_3^- even when all sources were applied several weeks after planting. Therefore, these CRFs could have water quality and GHG benefits because leached NO_3^- can be converted to N_2O. However, the PCU results show that the effectiveness of certain CRFs to reduce N_2O emissions may have limits depending on timing of application and climate factors. Area-scaled N_2O emissions were not significantly affected by tillage. However, when expressed per unit yield of grain, grain N, or total aboveground N, N_2O emissions with NT were 52, 66, and 69% greater, respectively, compared with CT. Thus, in this cropping system and climate regime, production of an equivalent amount of grain using NT would generate significantly more N_2O compared with CT. Across all treatments, yield-scaled emissions in this study were equivalent to 0.4 to 1.1% of the N harvested in the grain. Additional data of this type could help in making

Fig. 6. Mean (and SE) cumulative growing season N_2O emissions expressed per unit of area (right-hand axis), grain yield (right-hand axis), and grain N yield (left-hand axis) and soil N intensity (left-hand axis) for nitrate (NO_3^-), ammonium (NH_4^+), and the sum of NO_3^- plus NH_4^+ segregated by (a) year, (b) tillage, and (c) fertilizer source. For each quantity, bars with the same lowercase letter are not significantly different by year (a), by tillage (b), and by fertilizer source (c) ($P < 0.05$).

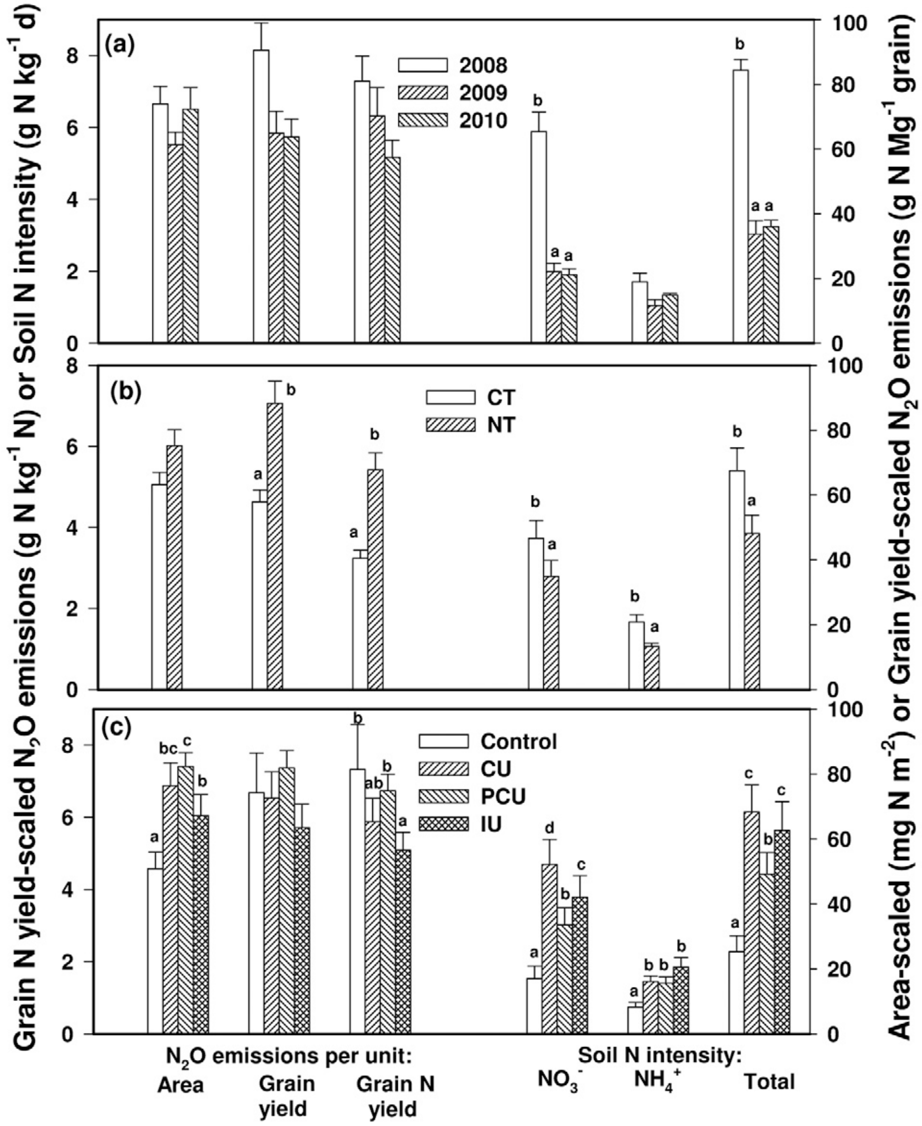
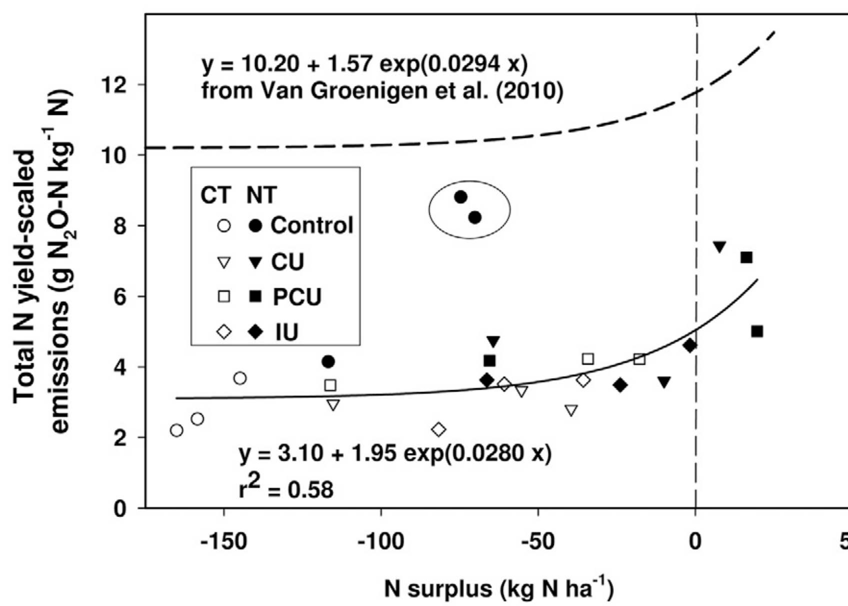


Fig. 7. Relationship between N surplus and N_2O emissions scaled by total aboveground N yield. Symbols designate means of each treatment combination for of three seasons, for conventional tillage (CT, open symbols), no-till (NT, closed symbols), control, conventional urea (CU), polymer-coated urea (PCU), and enzyme inhibitor–impregnated urea (IU). Circled treatments were treated as outliers and were not included in the regression analyses.



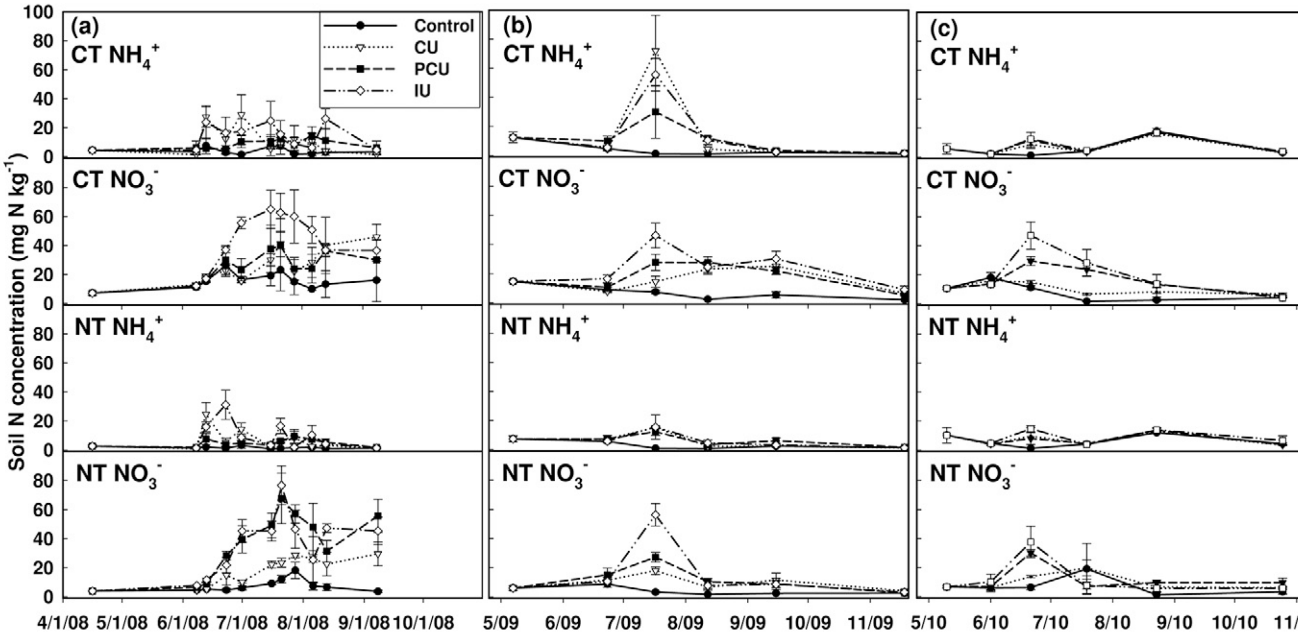


Fig. 8. Mean (and SE) soil concentrations of ammonium (NH_4^+) and nitrate (NO_3^-) in the upper 0- to 0.15-m depth in plots managed under conventional tillage (CT, upper two plates) and no-till (NT, lower two plates) that were fertilized with conventional urea (CU), polymer-coated urea (PCU), or enzyme inhibitor–impregnated urea (IU) and in a control treatment during (a) 2008, (b) 2009, and (c) 2010.

larger-scale GHG emissions assessments by relating N_2O emissions to current and projected grain production rates.

Acknowledgments

The authors acknowledge the assistance of S. Baldivins, C. Clayton, A. Dwinnell, L. Endo, S. Ewert, R. Fujinuma, S. Johnson, J. Leonard, S. Olson, J. Rowe, W. Shanley, L. Watson, M. Watson, K. Wendt, and three anonymous reviewers. This work was supported by the National Research Initiative Competitive Grant no. 2009-55112-05216 from the USDA CSREES/NIFA Air Quality Program, the International Plant Nutrition Institute's Foundation for Agronomic Research (with support from Agrium Advanced Technologies and Agrotain International), and the Agricultural Research Service of the USDA as part of the GRACEnet Project.

References

Akiyama, H., X.Y. Yan, and K. Yagi. 2010. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O and NO emissions from agricultural soils: Meta-analysis. Glob. Change Biol. 16:1837–1846. doi:10.1111/j.1365-2486.2009.02031.x

Almaraz, J.J., F. Mabood, X. Zhou, C. Madramootoo, P. Rochette, B. Ma, and D.L. Smith. 2009. Carbon dioxide and nitrous oxide fluxes in corn grown under two tillage systems in southwestern Quebec. Soil Sci. Soc. Am. J. 73:113–119.

Archer, D.W., A.D. Halvorson, and C.A. Reule. 2008. Economics of irrigated continuous corn under conventional-till and no-till in northern Colorado. Agron. J. 100:1166–1172. doi:10.2134/agronj2007.0291

Baggs, E.M., M. Stevenson, M. Pihlatie, A. Regar, H. Cook, and G. Cadisch. 2003. Nitrous oxide emissions following application of residues and fertilizer under zero and conventional tillage. Plant Soil 254:361–370. doi:10.1023/A:1025593121839

Ball, B.C., A. Scott, and J.P. Parker. 1999. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Tillage Res. 53:29–39. doi:10.1016/S0167-1987(99)00074-4

Bock, B.R. 1984. Efficient use of nitrogen in cropping systems. p. 273–294. *In* R.D. Hauck (ed.) Nitrogen in crop production. ASA, CSSA, SSSA, Madison, WI.

Bronson, K.F., A.R. Mosier, and S.R. Bishnoi. 1992. Nitrous oxide emissions in irrigated corn as affected by nitrification inhibitors. Soil Sci. Soc. Am. J. 56:161–165. doi:10.2136/sssaj1992.03615995005600010025x

Burton, D.L., X. Li, and C.A. Grant. 2008. Influence of fertilizer nitrogen source and management practice on N_2O emissions from two Black Chernozemic soils. Can. J. Soil Sci. 88:219–227. doi:10.4141/CJSS06020

Delgado, J.A., and A.R. Mosier. 1996. Mitigation alternatives to decrease nitrous oxides emissions and urea-nitrogen loss and their effect on methane flux. J. Environ. Qual. 25:1105–1111. doi:10.2134/jeq1996.00472425002500050025x

Engel, R., D.L. Liang, R. Wallander, and A. Bembenek. 2010. Influence of urea fertilizer placement on nitrous oxide production from a silt loam soil. J. Environ. Qual. 39:115–125. doi:10.2134/jeq2009.0130

ERS. 2011. U.S. fertilizer use and price. Produced by USDA Economic Research Service. Available at http://www.ers.usda.gov/Data/FertilizerUse/ (verified 20 June 2011).

Gagnon, B., N. Ziadi, P. Rochette, M.H. Chantigny, and D.A. Angers. 2011. Fertilizer source influenced nitrous oxide emissions from a clay soil under corn. Soil Sci. Soc. Am. J. 75:595–604.

Grandy, A.S., T.D. Loecke, S. Parr, and G.P. Robertson. 2006. Long-term trends in nitrous oxide emissions, soil nitrogen, and crop yields of till and no-till cropping systems. J. Environ. Qual. 35:1487–1495. doi:10.2134/jeq2005.0166

Gregorich, E.G., P. Rochette, A.J. VandenBygaart, and D.A. Angers. 2005. Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. Soil Tillage Res. 83:53–72. doi:10.1016/j.still.2005.02.009

Hadi, A., O. Jumadi, K. Inubushi, and K. Yagi. 2008. Mitigation options for N_2O emission from a corn field in Kalimantan, Indonesia. Soil Sci. Plant Nutr. 54:644–649. doi:10.1111/j.1747-0765.2008.00280.x

Halvorson, A.D., S.J. Del Grosso, and C.A. Reule. 2008. Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. J. Environ. Qual. 37:1337–1344. doi:10.2134/jeq2007.0268

Halvorson, A.D., S.J. Del Grosso, and F. Alluvione. 2010a. Nitrogen source effects on nitrous oxide emissions from irrigated no-till corn. J. Environ. Qual. 39:1554–1562. doi:10.2134/jeq2010.0041

Halvorson, A.D., S.J. Del Grosso, and F. Alluvione. 2010b. Tillage and inorganic nitrogen source effects on nitrous oxide emissions from irrigated cropping systems. Soil Sci. Soc. Am. J. 74:436–445. doi:10.2136/sssaj2009.0072

Halvorson, A.D., A.R. Mosier, C.A. Reule, and W.C. Bausch. 2006. Nitrogen and tillage effects on irrigated continuous corn yields. Agron. J. 98:63–71. doi:10.2134/agronj2005.0174

Ismail, I., R.L. Blevins, and W.W. Frye. 1994. Long-term no-tillage effects on soil properties and continuous corn yields. Soil Sci. Soc. Am. J. 58:193–198. doi:10.2136/sssaj1994.03615995005800010028x

Jacinthe, P.-A., and W.A. Dick. 1997. Soil management and nitrous oxide emissions from cultivated fields in southern Ohio. Soil Tillage Res.

41:221–235. doi:10.1016/S0167-1987(96)01094-X

Jumadi, O., Y. Hala, A. Muis, A. Ali, M. Palennari, K. Yagi, and K. Inubushi. 2008. Influences of chemical fertilizers and a nitrification inhibitor on greenhouse gas fluxes in a corn (*Zea mays* L.) field in Indonesia. Microbes Environ. 23:29–34. doi:10.1264/jsme2.23.29

Kaspar, T.C., T.M. Crosbie, R.M. Cruse, D.C. Erbach, D.R. Timmons, and K.N. Potter. 1987. Growth and productivity of four corn hybrids as affected by tillage. Agron. J. 19:411–481.

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS for mixed models. 2nd ed. SAS Inst., Cary, NC.

MCWG. 2011. Minnesota Climatology Working Group. Available at http://climate.umn.edu/ (verified 2011).

Millar, N., G.P. Robertson, P.R. Grace, R.J. Gehl, and J.P. Hoben. 2010. Nitrogen fertilizer management for nitrous oxide (N_2O) mitigation in intensive corn (Maize) production: An emissions reduction protocol for US Midwest agriculture. Mitig. Adapt. Strateg. Global Change. 15:185–204. doi:10.1007/s11027–010–9212–7.

Olson, R.A., and L.T. Kurtz. 1982. Crop nitrogen requirements, utilization and fertilization. p. 567–604. *In* F.J. Stevenson (ed.) Nitrogen in agricultural soils. Agron. Monogr. 22. ASA, CSSA, and SSSA, Madison, WI.

Omonode, R.A., D.R. Smith, A. Gál, and T.J. Vyn. 2011. Soil nitrous oxide emissions in corn following three decades of tillage and rotation treatments. 2011. Soil Sci. Soc. Am. J. 75:152–163. doi:10.2136/sssaj2009.0147

Rochette, P., D.A. Angers, M.H. Chantigny, and N. Bertrand. 2008a. Nitrous oxide emissions respond differently to no-till in a loam and a heavy clay soil. Soil Sci. Soc. Am. J. 72:1363–1369. doi:10.2136/sssaj2007.0371

Rochette, P., D.A. Angers, M.H. Chantigny, B. Gagnon, and N. Bertrand. 2008b. N_2O fluxes in soils of contrasting textures fertilized with liquid and solid dairy cattle manures. Can. J. Soil Sci. 88:175–187. doi:10.4141/CJSS06016

Rochette, P., D.E. Worth, R.L. Lemke, B.G. McConkey, D.J. Pennock, C. Wagner-Riddle, and R.L. Desjardins. 2008c. Estimation of N_2O emissions from agricultural soils in Canada. I. Development of a country-specific methodology. Can. J. Soil Sci. 88:641–654. doi:10.4141/CJSS07025

SAS. 2003. SAS system for Windows. Release 9.1. SAS Inst., Cary, NC.

Scharf, P.C., W.J. Wiebold, and J.A. Lory. 2002. Corn yield response to nitrogen fertilizer timing and deficiency level. Agron. J. 94:435–441. doi:10.2134/agronj2002.0435

Shaviv, A. 2000. Advances in controlled release of fertilizers. Adv. Agron. 71:1–49. doi:10.1016/S0065-2113(01)71011-5

Six, J., S.M. Ogle, J. Breidtz, R.T. Conant, A.R. Mosier, and K. Paustian. 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Glob. Change Biol. 10:155–160. doi:10.1111/j.1529-8817.2003.00730.x

Stehfest, E., and L. Bouwman. 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: Summarizing available measurement data and modeling of global annual emissions. Nutr. Cycling Agroecosyst. 74:207–228. doi:10.1007/s10705-006-9000-7

Ussiri, D.A.N., R. Lal, and M.K. Jarecki. 2009. Nitrous oxide and methane emissions from long-term tillage under a continuous corn cropping system in Ohio. Soil Tillage Res. 104:247–255. doi:10.1016/j.still.2009.03.001

Van Groenigen, J.W., G.L. Velthof, O. Oenema, K.J. Van Groenigen, and C. Van Kessel. 2010. Towards an agronomic assessment of N_2O emissions: A case study for arable crops. Eur. J. Soil Sci. 61:903–913. doi:10.1111/j.1365-2389.2009.01217.x

Venterea, R.T. 2010. Simplified method for quantifying theoretical underestimation of chamber-based trace gas fluxes. J. Environ. Qual. 39:126–135. doi:10.2134/jeq2009.0231

Venterea, R.T., J.M. Baker, M.S. Dolan, and K.A. Spokas. 2006. Soil carbon and nitrogen storage are greater under biennial tillage in a Minnesota corn–soybean rotation. Soil Sci. Soc. Am. J. 70:1752–1762. doi:10.2136/sssaj2006.0010

Venterea, R.T., M. Burger, and K.A. Spokas. 2005. Nitrogen oxide and methane emissions under varying tillage and fertilizer management. J. Environ. Qual. 34:1467–1477. doi:10.2134/jeq2005.0018

Venterea, R.T., M.S. Dolan, and T.E. Ochsner. 2010. Urea decreases N_2O emissions compared with anhydrous ammonia in a Minnesota corn cropping system. Soil Sci. Soc. Am. J. 74:407–418. doi:10.2136/sssaj2009.0078

Venterea, R.T., and A.J. Stanenas. 2008. Profile analysis and modeling of reduced tillage effects on soil nitrous oxide flux. J. Environ. Qual. 37:1360–1367. doi:10.2134/jeq2007.0283

Vetsch, J.A., G.W. Randall, and J.A. Lamb. 2007. Corn and soybean production as affected by tillage systems. Agron. J. 99:952–959. doi:10.2134/agronj2006.0149

Vetsch, J.A., and G.W. Randall. 2004. Corn production as affected by nitrogen application timing and tillage. Agron. J. 96:502–509. doi:10.2134/agronj2004.0502

Vyn, T.J., and B.A. Raimbault. 1993. Long-term effect of five tillage systems on corn response and soil structure. Agron. J. 85:1074–1079. doi:10.2134/agronj1993.00021962008500050022x

Wagner, S.W., D.C. Reicosky, and R.S. Alessi. 1997. Regression models for calculating gas fluxes measured with a closed chamber. Agron. J. 89:279–284. doi:10.2134/agronj1997.00021962008900020021x

Wei, X.R., M.D. Hao, X.H. Xue, P. Shi, R. Horton, A. Wang, and Y.F. Zang. 2010. Nitrous oxide emission from highland winter wheat field after long-term fertilization. Biogeosciences 10.5194/bg-7–3301–2010.

Woods, J., A. Williams, and J.K. Hughes. 2010. Energy and the food system. Philos. Trans. R. Soc. Ser. B 365:2991–3006. doi:10.1098/rstb.2010.0172