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The impact of nitrogen placement and tillage on NO, N_2O, CH_4 and CO_2 fluxes from a clay loam soil

Xuejun J. Liu[1,4], Arvin R. Mosier[2], Ardell D. Halvorson[3] & Fusuo S. Zhang[1]
[1]*College of Resources and Environmental Sciences, China Agricultural University, 100094, Beijing, China.* [2]*Agricultural and Biological Engineering Department, University of Florida, 281 Frazier Rogers Building, Museum Road, 110570, Gainesville, FL, USA.* [3]*USDA-ARS, 2150 Centre Avenue Building D, Suite 100, Fort Collins, CO, USA.* [4]*Corresponding author**

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Abstract

To evaluate the impact of N placement depth and no-till (NT) practice on the emissions of NO, N_2O, CH_4 and CO_2 from soils, we conducted two N placement experiments in a long-term tillage experiment site in northeastern Colorado in 2004. Trace gas flux measurements were made 2–3 times per week, in zero-N fertilizer plots that were cropped continuously to corn (*Zea mays* L.) under conventional-till (CT) and NT. Three N placement depths, replicated four times (5, 10 and 15 cm in Exp. 1 and 0, 5 and 10 cm in Exp. 2, respectively) were used. Liquid urea–ammonium nitrate (UAN, 224 kg N ha^{-1}) was injected to the desired depth in the CT- or NT-soils in each experiment. Mean flux rates of NO, N_2O, CH_4 and CO_2 ranged from 3.9 to 5.2 $\mu g\ N\ m^{-2}\ h^{-1}$, 60.5 to 92.4 $\mu g\ N\ m^{-2}\ h^{-1}$, −0.8 to 0.5 $\mu g\ C\ m^{-2}\ h^{-1}$, and 42.1 to 81.7 $mg\ C\ m^{-2}\ h^{-1}$ in both experiments, respectively. Deep N placement (10 and 15 cm) resulted in lower NO and N_2O emissions compared with shallow N placement (0 and 5 cm) while CH_4 and CO_2 emissions were not affected by N placement in either experiment. Compared with N placement at 5 cm, for instance, averaged N_2O emissions from N placement at 10 cm were reduced by more than 50% in both experiments. Generally, NT decreased NO emission and CH_4 oxidation but increased N_2O emissions compared with CT irrespective of N placement depths. Total net global warming potential (GWP) for N_2O, CH_4 and CO_2 was reduced by deep N placement only in Exp. 1 but was increased by NT in both experiments. The study results suggest that deep N placement (e.g., 10 cm) will be an effective option for reducing N oxide emissions and GWP from both fertilized CT- and NT-soils.

Introduction

Nitric oxide, N_2O, CH_4 and CO_2 emissions from agricultural soils are important sources of anthropogenic trace gas emissions to the atmosphere (Mosier et al., 2004). These trace gases directly or indirectly contribute to the accelerated global warming and/or ozone depletion in the troposphere (IPCC, 2001). NO and N_2O are produced predominantly as by-products of two microbial processes: nitrification and denitrification. Although both oxidative and reductive processes consume NO, the relative consumption by denitrification seems to be higher (Skiba et al., 1993). Therefore, nitrification typically is the main source of NO (Anderson and Levine, 1986). In contrast, denitrification is usually the main source of N_2O especially under condition of high soil water content (Azam et al., 2002). In the soil, CH_4 is produced under anaerobic conditions by microbial decomposition of organic materials whereas CO_2 production results from oxidation

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* E-mail: liu310@cau.edu.cn

of soil organic materials by heterotrophic microorganims and the respiration of plant roots (Yamulki and Jarvis, 2002). However, soils can act as both a source and sink for atmospheric CH_4.

Many studies have examined the contribution of soil to the atmospheric budgets balance of NO, N_2O, CH_4 and CO_2, but uncertainties remain because of the extreme variability of emissions in both space and time (Mosier et al., 2004). Variability of gas emission arises from soil–plant system heterogeneity and from the complex interactions which occur among the physical, chemical and biological variables controlling their generation and emission (Duxbury and McConnaughey, 1986; McTaggart et al., 1994). Banding/injection of N fertilizer and tillage, lead to mechanical soil disturbance and are thought to greatly alter gaseous fluxes in soils (Hansen et al., 1993; Kessavalou et al., 1998). So it becomes a concern on how to mitigate NO, N_2O, CH_4 and CO_2 emissions from soils through proper N management and tillage practice (Maljanen et al., 2001; Shrestha et al., 2004). Therefore, best N management and tillage practices needed to be identified to minimize agricultural emissions of NO, N_2O, CH_4 and CO_2. Deep placement of fertilizer N, due to its higher N utilization efficiency by crops, is presumably one of those methods. On the other hand, conservation tillage or NT has been a common practice in North America (Vetsch and Randall, 2004). The use of NT has shown a number of agronomic benefits (Holland, 2004). Some of these benefits led to reductions in the emission of the greenhouse gas (GHG) CO_2 through less fuel and machinery used than in CT systems. NT also frequently increased the potential to store (sequester) more C in the soil organic matter. Large uncertainties of the NT impact on N_2O fluxes, however remain (Six et al., 2004). In a 5-yr tillage with N fertilization experiment, Liu et al. (2005a) found that N_2O fluxes peaked earlier but generally lasted a shorter period in NT (shallower N placement, 3–5 cm, due to surface residues) than in CT (deeper N placement, 5–10 cm) after N fertilization. This finding suggests that N placement and tillage may affect the emission patterns of N_2O and NO_x. Limited evidence shows that NT is not likely to lead to an increase in N_2O emissions, provided that the N fertilizer is banded, as is the common practice with farmers using NT systems (Liu et al., 2005a). The objectives of this study were to identify (1) the impact of depth of N fertilizer placement on NO, N_2O, CH_4 and CO_2 emissions from CT and NT soils and (2) the potential of decreasing NO_x and N_2O emissions by deep N placement and tillage strategy.

Materials and methods

N placement experiments

The N placement experiments were located within two zero-N plots of the CT and NT treatments in a long-term experiment which was initiated in 1999 at the Agricultural Research, Development, and Education Center (ARDEC) northeastern Colorado (40°39′ N; 104°59′ W), USA. The region has a semi-arid temperate climate with typical mean temperature of 10.6 °C and low rainfall of 382 mm yr^{-1} (the average of 1900–2003). The soil is classified as fine-loamy, mixed, superactive, mesic Aridic Haplustalfs. The detailed information of the field experiment was introduced by Halvorson et al. (2005). Briefly, the CT continuous corn rotation used mechanical tillage (stalk shredder, disk, moldboard plow, mulcher, land leveler, etc.) for seed bed preparation. The NT continuous corn rotation, initiated in 1999, however, left the residues on the soil surface after corn harvest without mechanical tillage. Corn seeds were sown in late April each year. The two N placement experiments were placed at the center of two corn rows within unfertilized CT and NT plots designated as CT-N0 and NT-N0, by inserting a set of 20.4 cm diameter polyvinyl chloride (PVC) 10 cm long cylinders, to establish microplots, 8 cm into the soil. The microplot cylinders also served as gas sampling anchors. Anchors were set between two corn rows so that the measurements could be done with little effect on corn plants in the plots. Liquid urea–ammonium nitrate (UAN, 32% N) was injected at three locations (to simulate banding) using 5, 10 or 15 cm long syringe needles to provide the equivalent of 224 kg N ha^{-1} within each microplot. There were three depths of N placement in both CT-N0 and NT-N0 plots with four replications of each treatment. The depths of

N placement were 5, 10, and 15 cm in Experiment (Exp.) 1. When Exp. 1 ended, anchors were removed and set to nearby positions within the same plots to initiate Exp. 2. Because the NO_x and N_2O fluxes observed from the microplots in which fertilizer was injected 10 or 15 cm into the soil were not detectably different, fertilizer was on or 5, and 10 cm below the soil surface in Exp. 2. Experiment 1 was initiated on May 12, and ended on June 9, 2004 while Exp. 2 started on June 15 and ended on July 14, 2004.

Gas sampling and measurements

Fluxes of NO, N_2O, CH_4, and CO_2 (began in May 2004 and ended in July 2004) were measured two to three times per week, midmorning of each sampling day. Ten-centimeter-high vented round PVC chambers (inner diameter 20.4 cm) were installed on permanently fixed microplot cylinders that served as flux chamber anchors. The chambers were sealed to the anchors using a 5-cm wide rubber band that was cut from a truck tire intertube. Gas samples from the chamber headspace were collected by syringe (size: 35 ml with scale) at 0, 15 and 30 min after installation. Twenty-five milliliter of each sample in syringe was injected into 12 ml evacuated tubes (to insure over pressure of sample in the tubes) that were sealed with butyl rubber septa and transported to the laboratory for analysis by gas chromatography (GC) within 24 h. The GC used was a fully automated instrument Varian 3800 (Varian Inc., Walnut Creek, CA, USA) equipped with thermoconductivity, flame ionization and electron capture detectors to quantify CO_2, CH_4 and N_2O, respectively. The fluxes of the three gases were calculated from the change in concentration in the chamber headspace with time (Liu et al., 2005a).

Nitric oxide emissions were measured on each anchor, 30–60 min after N_2O, CH_4, and CO_2 flux measurements had been made, using a dynamic chamber technique in conjunction with a commercial NO–NO_2–NO_x analyzer (model 42C; Thermo Environmental Instruments, Franklin, MA, USA). The size of dynamic chamber used in the study is 20.4 cm (inner diameter) by 15 cm (height). In this method, NO-, NO_2-, and O_3-free air with a flow rate of about 1.8 L min^{-1} was generated with a pump attached to activated charcoal and Purifil filters and was introduced to each chamber via an entry port. A portion of the outlet air stream from each chamber was sampled consecutively via a quarter-inch outer-diameter polytetrafluoroethylene (PTFE) tube (covered with a PTFE film 'Tygaflor' on the inside walls) for NO analysis. NO fluxes were calculated from the differences in respective concentrations at the inlet and outlet air, the flow rate of air through the chamber, and the surface area covered by the chamber. Total emissions of NO, N_2O, CH_4 and CO_2 during each experiment were calculated from the averaged daily-based fluxes multiplied by the time interval between measurements. Using the same methods, background flux rates of NO, N_2O, CH_4 and CO_2 from the unfertilized CT and NT plots were measured for the same time period (Liu et al., 2005a).

Other measurements

Soil water content (0–15 cm) and soil (5 cm) and air temperature were measured in CT-N0 and NT-N0 plots at each trace gas-sampling event by a soil dielectric constant probe (Decagon Devices, Inc., Pullman, WA, USA) and a hand-held digital thermometer (Omega Engineering, Stamford, CT, USA), respectively. Mean bulk densities (B_d) were 1.38 and 1.44 g cm^{-3} for CT and NT soils, respectively. Soil water content (v/v) was then expressed as water filled pore space (WFPS) values according to bulk density [WFPS (%) = Soil water content $\times$ $1/(1\text{-}B_d/2.65) \times 100\%$]. Soil samples (0–30 cm) were collected at the beginning and end of each N placement experiment and were analyzed for ammonium N and nitrate N using a continuous flow analyzer (Lachat QickChem FIA + 8000 Series, Hach Company, Loveland, CO, USA) after the extraction by 1 mol L^{-1} KCl solution. The date and amount of precipitation and irrigation were recorded during the study period.

Statistical analysis

Determination of differences in NO, N_2O, CH_4 and CO_2 emissions in both experiments by N

Mention of trade names or proprietary products does not indicate endorsement by USDA and does not imply its approval to the exclusion of other products that may be suitable placement and tillage as well as soil mineral N affected by N placement and tillage was determined statistically (ANOVA and GLM regressions) using a MINITAB statistical software (release 13 for windows, Minitab Inc., USA). Significant differences are expressed at $P < 0.05$, unless otherwise stated.

Results

Temperature and water conditions

Daily air temperature, precipitation and irrigation are illustrated in Figure 1(a–d). Average air temperature was about 2.6 °C higher in Exp. 2 than in Exp. 1 although air temperature showed much more variation in Exp. 1 (Figure 1a) compared with that in Exp. 2 (Figure 1b). Soil temperature in CT (average 17.3 °C) was generally higher than in NT (average 16.0 °C) in Exp. 1 (Figure 1a, $P = 0.193$) but no differences between CT (average 19.8 °C) and NT (average 19.4 °C) were observed in Exp. 2 (Figure 1b, $P = 0.659$). Rainfall and irrigation amounts in Exp. 2 (165 mm) were greater than those in Exp. 1 (97 mm). Water filled pore space (WFPS) was 10–25% higher in NT than that in CT in both experiments (Figure 1c,d, $P < 0.001$ for Exp. 1 and Exp. 2). So the soil conditions in Exp. 2 may have favored denitrification loss especially under NT condition compared with Exp. 1.

NO and N_2O emissions

The fluxes of NO and N_2O in both experiments are illustrated in Figure 2 (a–d). In Exp. 1, NO fluxes remained at very low level (−1.3–4.7 μg N m^{-2} h^{-1}) within the first several days (13–17 May) after N fertilization, peaked on 18–20 May (10.9–42.1 μg N m^{-2} h^{-1}), then dropped to background level quickly since 21 May, after that a unique peak flux of NO was observed only in CT 5 cm on 1 June (Figure 2a). The average NO fluxes of were 5.9 and 2.0 μg N m^{-2} h^{-1} for CT and NT irrespective of the depths of N placement, which were slightly higher than the background NO fluxes of 4.6 (CT) and 1.1 (NT) μg N m^{-2} h^{-1} from the same non-fertilized plots during the same time period (calculated from Liu et al., 2005a). The corresponding N_2O fluxes were much higher, with mean fluxes of 26.7 μg N m^{-2} h^{-1} for CT and 94.2 μg N m^{-2} h^{-1} for NT across N placement (Figure 2c), compared with the mean N_2O fluxes of 5.0 (CT) and 2.9 (NT) μg N m^{-2} h^{-1} from the same non-fertilized plots

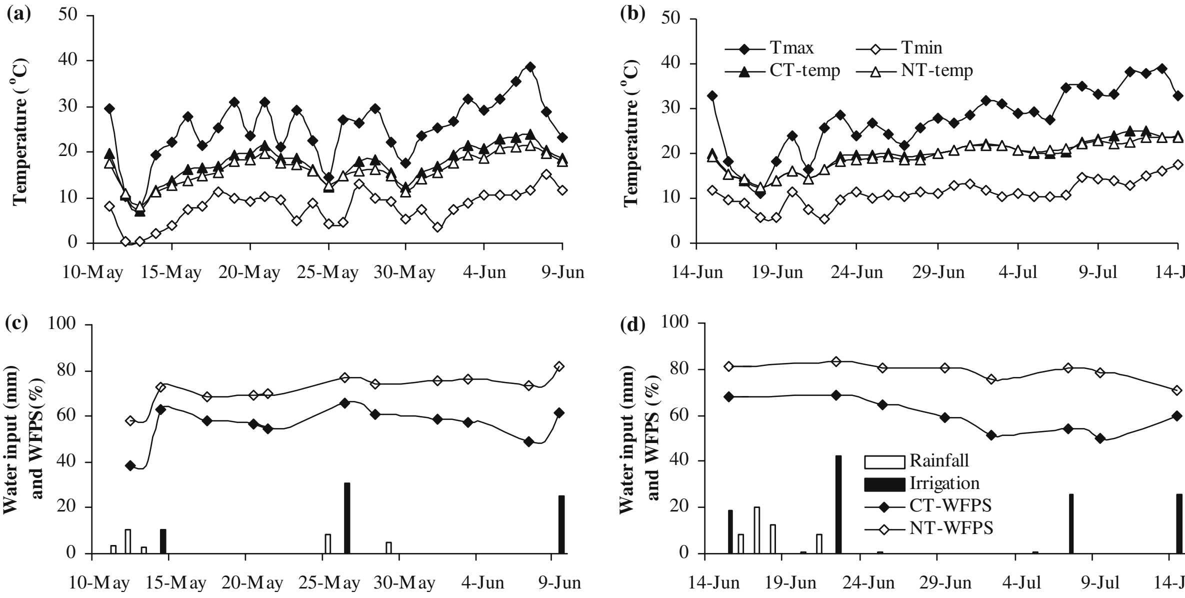

Figure 1. Maximum/minimum air temperature and daily mean soil temperature (a,b), and rainfall/irrigation and soil water filled pore space (c,d) in Exp. 1 (left) and Exp. 2 (right) during the study periods.

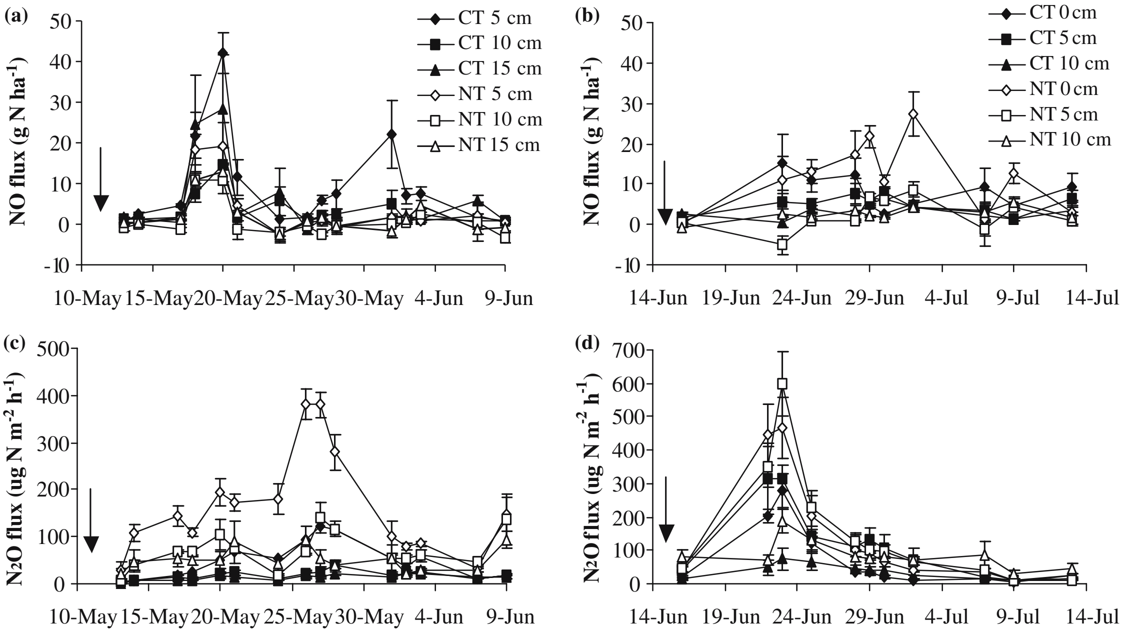

Figure 2. Effect of N placement and tillage on the fluxes of NO (a,b) and N_2O (c,d) from soils in Exp. 1 (left) and Exp. 2 (right) during the study periods. Bars denote standard error of means (SEM). Arrows denote fertilization.

(calculated from Liu et al., 2005a). N_2O fluxes, in contrast to those of NO, increased steadily and peaked several times after N fertilization during the study period (12 May to 9 June). The highest N_2O flux (about 380 μg N m^{-2} h^{-1}) was observed in NT 5 cm on May 26 and 27, which corresponded to a rainfall (8.1 mm) with a moderate irrigation (30.7 mm). Compared with CT, NT generally led to lower NO fluxes but greater N_2O fluxes at all placement depths in Exp. 1.

In Exp. 2, mean NO fluxes were 5.3 and 5.1 μg N m^{-2} h^{-1} for CT and NT (Figure 2b) compared with the mean fluxes of 7.6 and 2.5 μg N m^{-2} h^{-1} for CT and NT non-fertilized plots (calculated from Liu et al., 2005a), respectively. The small NO fluxes observed were relatively constant in both NT and CT except where fertilizer was applied to the soil surface. This was likely due to the 40 mm of rain that fell during the week after applying the fertilizer (Figure 1d) which moved the surface application into the soil. In contrast, N_2O fluxes increased quickly and peaked about 1 week after N application then dropped dramatically to the background level (Figure 2d). The peak fluxes of N_2O always followed rainfall and irrigation events while those of NO were reversed in the two experiments (Figures 1 and 2). Deep N placement (10 and 15 cm) reduced both NO and N_2O fluxes compared with shallow N placement (5 cm in Exp. 1 and 0 and/or 5 cm in Exp. 2) under both CT and NT conditions. NT usually caused lower NO fluxes but much greater N_2O fluxes than CT at the same depth of N placement in both experiments.

Total cumulative N_2O fluxes were significantly greater in NT than in CT while the situation was reversed for total cumulative NO fluxes in Exp. 1 (Table 1). Total cumulative emissions of NO and N_2O were significantly higher in the shallow placement (5 cm) than from the deeper placement. However, the NO and N_2O emissions were not significantly different between the 10 and 15 cm N placements. Total cumulative emissions of N_2O (100–300 g N ha^{-1} for CT and 350–1020 g N ha^{-1} for NT) were much higher than those of NO (30–60 g N ha^{-1} for CT and 5–20 g N ha^{-1} for NT). In Exp. 2, the cumulative emissions of both N gases followed the same trends as those in Exp. 1 (Table 2). But N_2O emissions from CT (230–726 g N ha^{-1}) were greater than those in Exp. 1 (125–385 g N ha^{-1}), probably due to higher WFPS in Exp. 2 (Figure 2c, d). Surface N application (0 cm) and

Table 1. Total emissions of NO, N_2O, CH_4 (g N or C ha^{-1}) and CO_2 (kg C ha^{-1}) from soils as affected by N placement and tillage in Exp. 1

Treatment	CT 5 cm	CT 10 cm	CT 15 cm	NT 5 cm	NT 10 cm	NT 15 cm
NO	61.9	21.3	34.9	21.5	5.9	13.5
N_2O	385	174	125	1005	405	316
CH_4	−1.4	7.0	3.8	3.7	2.0	4.3
CO_2	250	168	211	349	354	365
Statistical analysis						
	Tillage (T)		Placement (P)		Interaction (T × P)	
NO	***		**		NS	
N_2O	***		***		***	
CH_4	NS		NS		NS	
CO_2	***		NS		NS	

NS, ** and *** represent not significant, significant at 0.01 and 0.001 levels, respectively.

shallow N placement (5 cm) resulted in significantly smaller emissions of N_2O compared with deep N placement (10 cm, Table 2). The only significant interaction between N placement and tillage occurred for N_2O emission in Exp. 1 (Table 1).

CH_4 and CO_2 emissions

The dynamics of CH_4 and CO_2 fluxes as affected by N placement and tillage in both experiments are shown in Figure 3(a–d). In Exp. 1, N application caused a quick CH_4 flux (a net result of methane production and oxidation, up to 8.5 μg C m^{-2} h^{-1}) from CT and NT soils then CH_4 production and oxidation were in equilibrium and no net CH_4 fluxes occurred. No significant effects of N placement and tillage on CH_4 fluxes were found in the Exp. 1 (Figure 3a). Carbon dioxide fluxes followed emission patterns that were similar to N_2O. NT led to several higher emission peaks of CO_2 compared with CT but N placement did not affect CO_2 fluxes from either CT or NT soils (Figure 3c). In Exp. 2, CH_4 uptake (negative emission) was observed in most cases (Figure 3b) while CO_2 fluxes tended to increase, coinciding with the increase in soil temperature during the study period (Figures 3d and 1b).

Table 2. Total emissions of NO, N_2O, CH_4 (g N or C ha^{-1}) and CO_2 (kg C ha^{-1}) from soils as affected by N placement and tillage in Exp. 2

Treatment	CT 0 cm	CT 5 cm	CT 10 cm	NT 0 cm	NT 5 cm	NT 10 cm
NO	51.5	33.1	21.7	74.0	14.0	15.9
N_2O	438	726	230	897	939	531
CH_4	−5.9	−8.6	−12.2	0.2	−1.8	−2.0
CO_2	516	476	510	622	584	592
Statistical analysis						
	Tillage (T)		Placement (P)		Interaction (T × P)	
NO	NS		***		NS	
N_2O	**		**		NS	
CH_4	*		NS		NS	
CO_2	*		NS		NS	

NS, *, ** and *** reresent not significant, significant at 0.05, 0.01 and 0.001 levels, respectively.

Total cumulative fluxes of CH_4 and CO_2 were illustrated in Tables 1 and 2. In contrast to N oxides, N placement did not affect either CO_2 or CH_4 flux in either experiment. Higher cumulative CO_2 emissions were observed in NT plot than in CT plot in Exp. 1 (Table 1) and Exp. 2 (Table 2). Methane consumption was small but generally lower in NT than in CT during the study periods (Tables 1 and 2). The interactions between N placement and tillage for CH_4 and CO_2 were not significant in the two experiments.

Global warming potential (GWP)

GWP (kg CO_2-equivalents ha^{-1}) for (N_2O, CH_4 and CO_2) were estimated using values of 296, 23 and 1, respectively for a 100-year time frame on a per molecule basis (IPCC, 2001) for the gas in each experiment period (~4 weeks) in Figure 4. In Exp. 1, deep N placement (10 and 15 cm depths) significantly reduced the total GWP compared with shallow N placement (5 cm depth). In contrast, NT led to greater total GWP for N_2O, CH_4 and CO_2 than CT. In Exp. 2, similar effect of tillage on the GWP was observed although the GWP for all the three gases was much greater in Exp. 2 than in Exp. 1 (Figure 4). However, N placement did not show obvious effect on the GWP in Exp. 2. The three greenhouse gases contributed to 73–95% (CO_2), 5–27% (N_2O) and −0.02–0.03% (CH_4) of the total GWP, respectively.

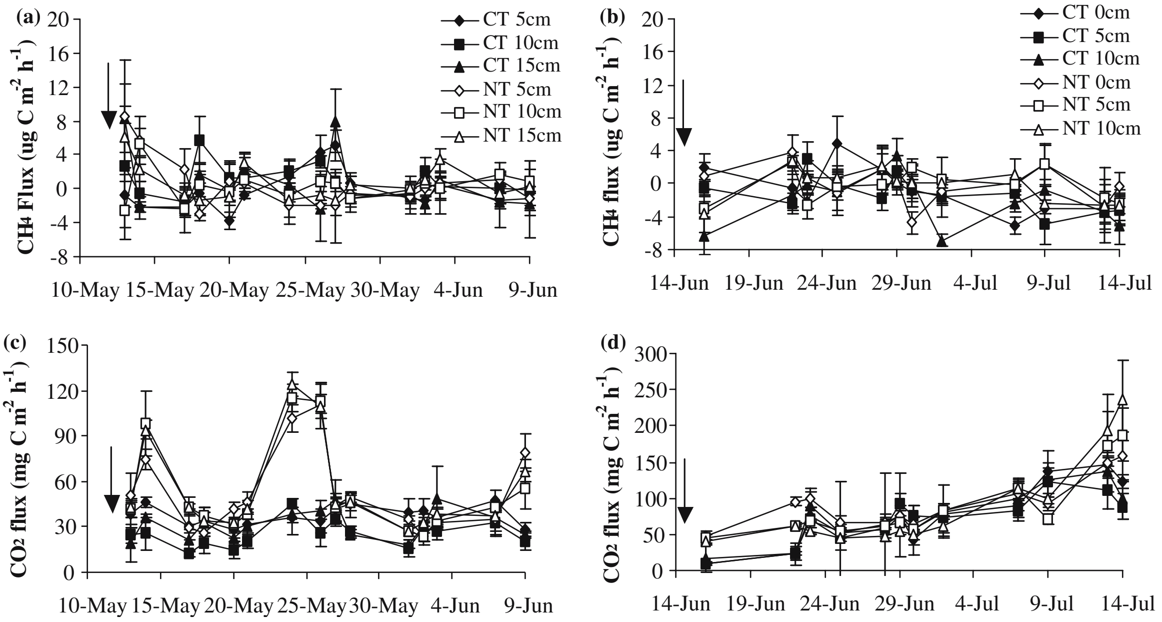

Figure 3. Effect of N placement and tillage on the fluxes of CH_4 (a,b) and CO_2 (c,d) from soils in Exp.1 (left) and Exp.2 (right) during the study periods. Bars denote standard error of means (SEM). Arrows denote fertilization.

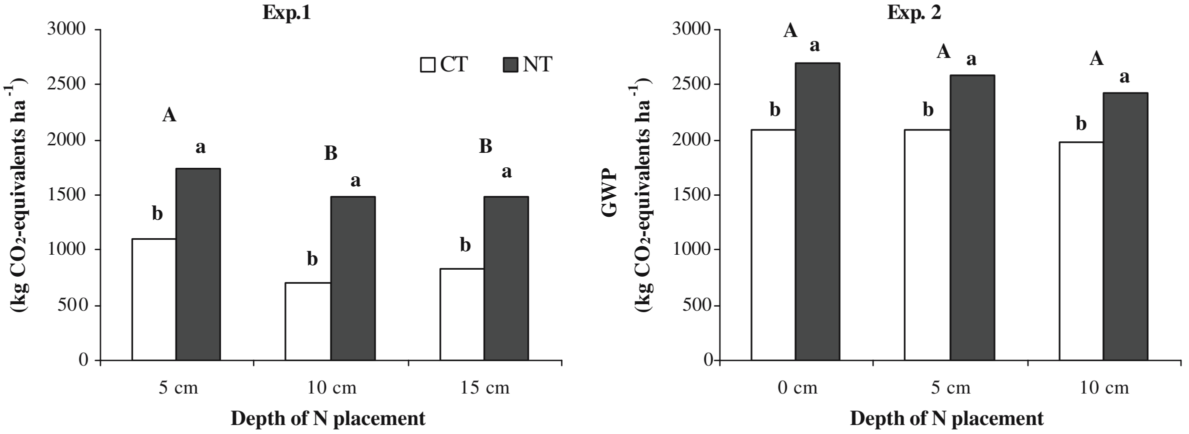

Figure 4. Estimated global warming potential (GWP, kg CO_2-equivalents ha^{-1}) of three greenhouse gases (N_2O, CH_4 and CO_2) emitted from soils as affected by N placement and tillage in both experiments. Column pairs labeled with different uppercase letter for N placement across tillage are significantly different. Columns labeled by different lowercase letters for tillage within each N placement depth are significantly different.

Mineral N in 0–30 cm soil layers

Soil mineral N as NH_4-N and NO_3-N in 0–30 cm layers at the end of both experiments is shown in Figure 5. In Exp. 1, most NH_4-N was transformed to NO_3-N in the soil with CT across N placement, while NH_4-N in the soil with NT still remained as high as 30–40 kg N ha^{-1} and NH_4-N mainly concentrated on the specific layer where fertilizer N was injected (e.g., NH_4-N in NT 10 cm treatment mainly distributed in 7.5–15 cm layer, Figure 5a), indicating slower rates of nitrification in NT soils

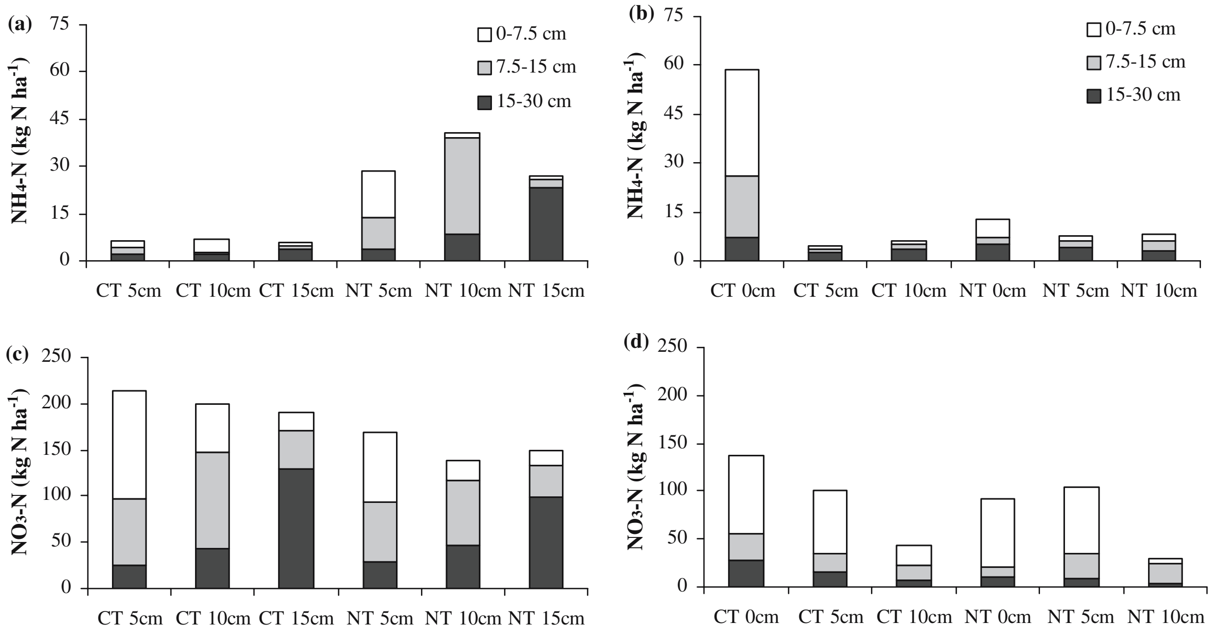

Figure 5. Effect of N placement depth on the distribution of NH_4-N (a,b) and NO_3-N (c,d) in CT and NT soil profiles (0–7.5, 7.5–15 and 15–30 cm) at the end of Exp. 1 (left) and Exp. 2 (right). Fertilizer nitrogen rate of 224 kg N ha^{-1} was injected to 5, 10, 15 cm depths in Exp.1 and 0, 5, 10 cm depths in Exp. 2, respectively.

than in CT soils. Opposite to NH_4-N, we observed more NO_3-N in soils with CT than in NT soils. The distribution of NH_4-N and NO_3-N in soil profile suggests that the fluxes of N oxides originate mainly from the depth at which N fertilizer was applied. Total mineral N in soils ranged from 177 to 198 kg N ha^{-1} for NT and from 196 to 220 kg N ha^{-1} for CT (Figure 5c) while the initial NH_4-N plus NO_3-N were only 39 and 31 kg N ha^{-1} for CT and NT plots. In Exp. 2, the distribution pattern of mineral N in soil profile was similar to that in Exp. 1. NH_4-N in each soil layer was very small (less than 6 kg N ha^{-1}) across tillage and N placement with the exception of the surface N application in CT, while NO_3-N in soils was the major part of mineral N in 0–30 cm layers (Figure 5b,d). Accordingly, the initial NH_4-N plus NO_3-N were only 20 and 18 kg N ha^{-1} for CT and NT plots at the beginning of Exp. 2. Compared with Exp. 1, however, total mineral N in soils with either CT or NT was much lower in Exp. 2 except for the CT 0 cm treatment. That suggests fertilizer N, particularly NO_3-N, leached out of 0–30 cm soil profile because of higher WFPS in the second experiment. Plant N uptake was likely greater in the second experiment as well.

Discussion

Nitrogen oxides

The present study shows that both N placement and tillage had a significant effect on fluxes of NO (Exp. 1) and N_2O (Exps. 1 and 2) from soils. The negative relationship between the depth of N placement and NO and/or N_2O emission showed that deep N placement could be an effective option to reduce the emissions of two trace N gases from arable soils. While the total cumulative flux of NO was decreased by NT, N_2O fluxes in contrast were increased by NT. In an earlier study, Hilton et al. (1994) found that deep placement of N (as a 28% N solution of UAN) in NT reduced N_2O emissions to levels similar to soil incorporation of N fertilizer in CT, and much less than N_2O emissions from NT with surface application and incorporation of N. These results indicate that factors controlling emissions of these gases are different.

A complicated relationship between N placement and NO and N_2O emissions was observed from the results in Exp. 1 and Exp. 2. For example, no further decline in NO emission occurred when the depth of N application was increased from 10 to 15 cm in Exp. 1 (Table 1). Surface N application decreased N_2O emission from both CT and NT soils compared with shallow N placement (5 cm depth) in Exp. 2 (Table 2). The movement of fertilizer a few days after application because of a 40 mm rain may have confounded the observations, however. In Alberta of Canada, Drury et al. (2004) also found shallow N placement (2 cm depth) decreased N_2O emissions from the soil by 25% compared to deep N placement (10 cm depth). Their results were similar to our findings from the Exp. 2. Surface soil is more likely to be aerobic compared to subsoil following rainfall. Dry soil conditions usually enhance NO emissions but decrease N_2O emissions when fertilizer N was applied at or near surface soil according to the hole-in-the-pipe model (Firestone and Davidson, 1989). In the conceptual model, the amount of N that 'leaks' out of the pipe as NO and N_2O is determined by several soil properties, but most commonly and most strongly by soil water content. In dry soils, NO is the dominant gas that leaks out of the pipe while in wetter soils N_2O is the most important end product (Davidson and Verchot, 2000). Davidson (1991) observed that the largest NO emissions could be expected at WFPS values of 30–60% and the highest N_2O emissions at 50–80% WFPS. In the present study, we also observed similar linear relationships of WFPS and N oxide emissions in the two experiments: higher WFPS due to rainfall and irrigation enhanced N_2O emissions (Exp. 1: $R^2 = 0.2719$ for CT and 0.0405 for NT; Exp. 2: $R^2 = 0.3927$ for CT and 0.4037 for NT) but reduced NO emissions (Exp. 1: $R^2 = 0.2329$ for CT and 0.2688 for NT; Exp. 2: $R^2 = 0.7901$ for CT and 0.5982 for NT) compared with lower WFPS (Figure 2). This relationship was also found in soils under CT and NT in this study. Generally, NO emissions from NT-soil (with higher WFPS) were lower than from CT-soil (with lower WFPS) but N_2O emissions were reversed (Figure 2, Tables 1 and 2). Moreover, the location of ammonia oxidizing and denitrifying bacteria with soil depth may affect NO and N_2O emissions. It was reasonable that ammonia oxidizing bacteria mainly concentrate on the upper soil layer (e.g., 0–7.5 cm depth) while deeper soil layer (e.g., 7.5–15 cm depth) may be the most likely location of denitrifying bacteria if considering both soil organic carbon distribution and change of soil aerobic condition with depth (Mosier, 2005, pers. commun.). So deep N placement usually led to slower nitrification rates and delayed denitrification. As a consequence, deep N placement resulted in lower N_2O and NO emissions compared with shallow N placement in this study. In addition, we suspect that greater NH_3 volatilization induced by surface N application (soil pH value of 7.7 will favor such volatilization loss) may explain less N_2O emission compared with deeper N placement in Exp. 2.

Mineral N content in soils is another important factor that controls the emissions of both NO and N_2O from nitrification and denitrification (Liu et al., 2004). The mineral N contents in 0–30 cm soil layers at the beginning (to see result section) and the end of each experiment (Figure 4) suggests that fertilizer N utilization and loss from Exp. 1 were much less than from Exp. 2. The sum of NO and N_2O emissions also reflected more N oxide losses in Exp. 2 compared with Exp. 1 (with the exception of treatment NT 5 cm, calculated from Tables 1 and 2). In fact, more N_2 loss as well as NO_3-N leaching might have occurred due to greater WFPS in Exp. 2 especially under NT. Additionally, many corn roots were found below the anchors (10 cm soil depth) in Exp. 2, indicating that N uptake by corn may have happened during the study period of the Exp. 2 (June to July, 2004). Liu et al. (2005b) observed that N uptake by corn was as high as 60 kg N ha^{-1} within a 4 week of rapid corn growth. Thus the greater N loss and N uptake by corn could explain why residual mineral N in Exp. 2 was much less than that in Exp. 1.

The effect of NT on trace N gas emissions has become a concern given its increased adoption since the 1980s (Campbell et al., 2001; Six et al., 2004). The present study showed that NT led to lower NO emissions but greater N_2O emissions in both experiments (from May to July). Similar results in the 2004 corn growing season were observed in a long-term tillage experiment with different N rates at the same site (Liu et al., 2005a). Greater N_2O emissions from NT soil in this short-period study were probably related to: (i) higher WFPS in NT compared to CT; (ii) corn residues on the surface of NT soil providing soluble organic C that enhances denitrification;

and (iii) less N uptake by corn due to delayed corn growth by NT. However, Lemke et al. (1999) found that combined estimates (spring plus summer) of N_2O loss under zero tillage were equal to or lower than those under intensive tillage although emissions of N_2O during summer were sometimes slightly higher in zero tillage than those under intensive tillage. They conclude that zero tillage management systems have potential for reducing agricultural greenhouse gas emissions in the Alberta Parkland region, Canada. Their results agreed well with Liu et al. (2005a) and Mosier et al. (2005) when several years' results of N_2O and NO emissions were summarized together. Therefore, we should keep in mind that the influence of NT on N oxide emissions largely depends on specific crop, soil and weather conditions.

CH_4 and CO_2

In the current study, CH_4 emissions were negligible (near zero) or negative but CO_2 emissions were much greater (up to 622 kg C ha^{-1}). N placement did not affect either CH_4 uptake (negative emission) or CO_2 emissions in the two experiments. NT tended to reduce CH_4 uptake compared with CT presumably due to higher WFPS and greater bulk density in NT soil, as also shown in other studies (Yamulki and Jarvis, 2002). In contrast, NT increased CO_2 fluxes by 40–110% (Exp. 1) or 16–23% (Exp. 2) compared to CT where CO_2 emissions prior to initiation of this study was greater than in NT system due to tillage and residue decomposition. This could be explained by the higher microbiological activity induced by crop residues on the soil surface and relatively higher WFPS under NT (Lupwayi et al., 1999). Similar results were reported by Linn and Doran (1984) with 3.4 times greater CO_2 production from non-tillage soils over 24 h than from plowed soils. They indicated 90% was accounted for by a difference in WFPS regardless of the application of N fertilizer. However, Kessavalou et al. (1998) indicated a significantly higher CO_2 flux from a plowed than a NT system. Sanhueza et al. (1994) showed insignificant differences in CO_2 emissions between control (unplowed soil) and plowed soil with or without fertilization. The above inconsistent results suggest that the tillage effects on CO_2 flux will depend on other factors (e.g., water content, temperature) involved in CO_2 production. What should be stressed is that CO_2 emission from NT is similar or slightly lower than that from CT if entire crop growing and fallow seasons are considered (Mosier et al., 2005).

Total GWP

The overall balance between the net exchange of CO_2, CH_4 and N_2O constitutes the net GWP of a cropping system. No-till management has been promoted as a practice that offsets the GWP from emissions of N_2O and CH_4 in crop production because of its ability to sequester carbon in the soil (Cole et al., 1997). In our study, total GWP for $N_2O + CH_4 + CO_2$ was increased by NT mainly due to the increase in both N_2O and CO_2 emissions when the change in soil organic carbon was neglected. Nitrogen placement, however, did not show consistent effects on the total GWP in Exp. 1 and Exp. 2. Deep N placement reduced total GWP substantially in Exp. 1 but such effect diminished in Exp. 2. It was mainly because the increase in CO_2 emissions induced by higher soil temperature more than offset the decrease in N_2O emissions (CH_4 emissions were negligible) in Exp. 2. Six et al. (2004) summarized all available data of soil-derived GHG emission comparisons between CT and NT systems for humid and dry temperate climates. They found that newly converted NT systems increase GWP relative to CT practices, in both humid and dry climate regimes, and longer-term adoption of NT (>10 years) only significantly reduces GWP in humid climates. Mean cumulative GWP over a 20-year period is reduced under continuous NT in dry areas, but with a high degree of uncertainty (Six et al., 2004). Our results provide evidence on the potential of NT in increasing GWP in a semi-dry climate regime. In the same site near Fort Collins of Colorado, Mosier et al. (2005) found that N_2O and CO_2 emissions in NT plots, with the adoption of no till, tended to be from lower to higher than in CT plots at N rate ranged from 0 to 224 kg N ha^{-1} over a 3-year period. Therefore, the overall effects of NT and deep N placement on total GWP and/or GHG emissions mainly depend on the cropping history and specific soil as well as climate conditions.

Conclusions

In the present study, we evaluated the effect of fertilizer N placement and tillage on trace gas emissions in a cornfield. Deep N placement (e.g., 10 cm) significantly reduced both NO (Exp. 1) and N_2O (Exps.1 and 2) emissions without obvious influence on CH_4 oxidation and CO_2 evolution compared to shallow N placement (e.g., ≤ 5 cm). NT generally decreased NO emission and CH_4 oxidation but increased N_2O emissions compared with CT irrespective of N placement depths. Total GWP for N_2O, CH_4 and CO_2 was reduced by deep N placement only in Exp. 1 but was increased by NT in both experiments, suggesting that NT management has potential for increasing agricultural GHG emissions or GWP especially under moist soil condition. The study reveals that fertilizer N placement and tillage practices should be considered carefully when attempting to mitigate NO, N_2O, CH_4 and CO_2 emissions from agricultural soils.

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