Plant and Soil (2005) 276:235–249
DOI 10.1007/s11104-005-4894-4

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Tillage and nitrogen application effects on nitrous and nitric oxide emissions from irrigated corn fields

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Received 1 December 2004. Accepted in revised form 2 April 2005

Key words: continuous corn cropping, conventional-till, N_2O, NO, N fertilizer, no-till

Abstract

A 2-year study was conducted to investigate the potential of no-till cropping systems to reduce N_2O and NO emissions under different N application rates in an irrigated corn field in northeastern Colorado. Flux measurements were begun in the spring of 2003, using vented (N_2O) and dynamic (NO) chambers, one to three times per week, year round, within plots that were cropped continuously to corn (*Zea mays* L.) under conventional-till (CT) and no-till (NT). Plots were fertilized at planting in late April with rates of 0, 134 and 224 kg N ha^{-1} and corn was harvested in late October or early November each year. N_2O and NO fluxes increased linearly with N application rate in both years. Compared with CT, NT did not significantly affect the emission of N_2O but resulted in much lower emission of NO. In 2003 and 2004 corn growing seasons, the increase in N_2O-N emitted per kg ha^{-1} of fertilizer N added was 14.5 and 4.1 g ha^{-1} for CT, and 11.2 and 5.5 g ha^{-1} for NT, respectively. However, the increase in NO-N emitted per kg ha^{-1} of fertilizer N added was only 3.6 and 7.4 g ha^{-1} for CT and 1.6 and 2.0 g ha^{-1} for NT in 2003 and 2004, respectively. In the fallow season (November 2003 to April 2004), much greater N_2O (2.0–3.1 times) and NO (13.1–16.8 times) were emitted from CT than from NT although previous N application did not show obvious carry-over effect on both gas emissions. Results from this study reveal that NT has potential to reduce NO emission without an obvious change in N_2O emission under continuous irrigated corn cropping compared to CT.

Introduction

Nitrous oxide (N_2O) is a greenhouse gas that also participates in the destruction of stratospheric ozone (Bouwman, 1990; Crutzen, 1981). Agricultural soils are major source of N_2O (IPCC, 2001) and account for about 35% of global annual emissions (Kroeze et al., 1999). Nitric oxide (NO) is also produced in soils, as a byproduct or intermediate product of two biological processes: nitrification and denitrification. NO is an important trace gas in atmospheric chemistry, and soils are an important source of this gas. Skiba et al. (1997) estimated a 10 Tg NO-N soil source, 41% of which originated from agricultural soils. Once emitted to the atmosphere, NO is rapidly oxidized to nitrogen dioxide (NO_2). The NO_x gases (NO plus NO_2) together with organic radical species regulate the photochemical production of tropospheric ozone (Hutchinson and Davidson, 1993). Consequently, emissions of N_2O and NO from agricultural soils may lead to not only fertilizer N loss (Bouwman et al., 2002) but also cause serious environmental problems. As the emission ratio of N_2O and NO in soils changes in response to changes in environmental factors such as soil moisture, temperature,

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and organic manure (Akiyam and Tsuruta, 2002, 2003; Liu et al., 2004), N_2O and NO fluxes should be measured simultaneously.

Measurement of N_2O and NO emissions from agricultural soils have been reported across a range of edaphic, climatic, and agronomic conditions (Aulakh et al., 1984; Bouwman et al., 2002; Harrison et al., 1995). However, it is still difficult to accurately predict N_2O and NO loss under a specific agricultural field. One "so-called" consistent finding is the high variability of N_2O and NO emissions, both in time and space. Another consistent finding is that NO/N_2O ratio tends to decrease with increasing soil water content. This trend has generally been attributed to (i) various microbiological responses to decreased O_2 availability, which inhibit nitrification while promoting denitrification, and (ii) decreased NO gas diffusivity resulting from increased soil water content (Davidson, 1993; McTaggart et al., 2002).

Conservation tillage or no-till (NT) is a common practice in North and South America and some regions of Europe (Holland, 2004). Reducing the intensity of soil cultivation under NT lowers energy consumption and the emission of carbon dioxide, while carbon sequestration is raised through the increase in soil organic matter (Halvorson et al., 2003). However, the systematic evaluation of NT effect on N_2O and NO fluxes from fertilized agricultural soils are still scarce. The main objective of the current study is to examine the impact of NT and N fertilization on N_2O and NO emissions in irrigated corn field. In addition, we would like to analyze the possible influence of environmental factors such as soil water content and climate condition on the two N gas emissions.

Materials and methods

Site description

The tillage by N rate experiment was initiated in 1999 at the Agricultural Research, Development, and Education Center (ARDEC) northeastern Colorado near Fort Collins, USA (40°39′ N; 104°59′ W; 1530 m a.s.l.). The region has a semi-arid temperate climate with typical mean temperature of 10.6 °C and low rainfall of 382 mm year^{-1} (the average of 1900–2003). Corn (*Zea mays* L.), wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) are the main crops in local agriculture. The soil is a Fort Collins clay loam classified as fine-loamy, mixed, superactive, mesic Aridic Haplustalfs. The field was in CT continuous corn for 6 years before the experiment. The selected chemical and physical properties of the soil at 0–15 cm at the beginning of the experiment are shown in Table 1.

Experimental design and management

A randomized factorial experimental block with three replicates was established, with two tillage systems: CT = conventional till, and NT = no-till, and three N rates: 0, 134 and 224 kg N ha^{-1} as liquid UAN. 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, however, left the residues on the soil surface after corn harvest without mechanical tillage. Tillage treatments with different N rates are denoted as CT 0N, CT 134N, CT 224N, and NT 0N, NT 134N, NT 224N. Fertilizer N as UAN solution (containing 32% N) was injected to about 5 cm below the soil surface as band application just prior to planting corn in late April each year. Besides basal N application, a subsurface band application of phosphorus (0-46-0) was applied at a rate of 56 kg P ha^{-1} prior to planting in 1999 and 2004 for both CT and NT systems. Liquid starter fertilizer containing P and K was applied to the seed row at planting in 2000, 2002, 2003 and 2004. A lateral move sprinkler irrigation system is used to apply water to CT and NT plots when soil water content is low (e.g. 40–45%WFPS) or corn plants face potential water stress. Herbicides were used for weed control in all treatments. Biomass samples were collected in mid

Table 1. Some chemical and physical properties of the soil (0–15 cm) used in the study

Soil texture	pH (0.01 *M* $CaCl_2$)	OM (g kg^{-1})	Total N (g kg^{-1})	Olsen-P (mg kg^{-1})	Clay %	Silt %	Sand %
Clay loam	7.71	20.3	1.37	9.85	33.4	26.4	40.2

to late September each year for determination of residue production. Grain yields were measured at physiological maturity in late October to early November each year by collecting two rows 7.6-m long per plot. Other details of the study are provided by Halvorson et al. (2003).

N_2O and NO measurements

Fluxes of N_2O (begun in April 2002, Mosier et al., 2005) and NO (begun in May 2003) were measured one to three times per week, year-round, midmorning of each sampling day. Ten-centimeter-high vented rectangular aluminum chambers were installed on permanently fixed anchors (78.6 × 39.3 × 10 cm) in a water channel at each sampling. Anchors were set perpendicular to the corn row so that the corn row and inter-row were contained within each chamber. Anchors were removed for tillage and planting operations and reinstalled near the initial locations. Duplicate flux measurements were made within each replicate of each treatment plot for a total of six measurements per treatment for N_2O. N_2O gas samples from inside the chambers were collected by syringe at 0, 15, and 30 min after installation. Gas samples (25 mL to insure over pressure of sample in the tubes) were then injected into 12-mL evacuated tubes that were sealed with butyl rubber septa and transported to the laboratory in Fort Collins for analysis by gas chromatography. The gas chromatograph used was a fully automated instrument Varian 3800 equipped with thermoconductivity, flame ionization, and electron capture detectors to quantify CO_2, CH_4, and N_2O, respectively (Mosier et al., 2005). N_2O fluxes were calculated from the linear or non-linear increase in concentration (selected according to the emission pattern as 'best' flux) in the chamber headspace with time (Hutchinson and Livingston, 1993). If the accumulation rate of N_2O in the second gas sampling period (from 15 to 30 min) is lower than 40% of that in the first gas sampling period (from 0 to 15 min), linear equation will be selected, otherwise non-linear equation is selected to calculate the final flux of N_2O. Detailed information on this was discussed by Hutchinson and Mosier (1981) and Hutchinson and Livingston (1993).

NO emissions were measured using a dynamic chamber technique (a separate chamber with the same size as that for N_2O, Martin et al., 1998) in conjunction with a commercial NO-NO_2-NO_x analyzer (model 42C; Thermo Environmental Instruments). 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. After equilibrium, a portion of the outlet air stream from each chamber was sampled consecutively via a quarter-inch outer-diameter polytetrafluoroethylene (PTFE) tube for NO and NO_2 analysis. NO and NO_2 concentrations were recorded by a Campbell data logger. In 2003, as an initial study, NO emissions were measured with one replicate (two measurements each plot) and did not include treatment NT 134N. In 2004, the NO measurements were based on two replications (four measurements within each treatment). 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. All connections and tubing from the chambers to the instruments were covered with a PTFE film 'Tygaflor' on the inside walls to ensure the minimum uptake of the soil-emitted NO by the walls. Total N_2O and NO emissions during the growing season and the fallow season (November to April the next year) were calculated from the averaged daily-based fluxes times the hours in the specific period. The total emissions of both gases during growing season of each year were calculated from planting to late October (N_2O) or to the end of August (NO) because the NO fluxes were very low and negligible from early September to late October (harvest).

Other measurements

Soil water content and soil/air temperature were measured at the time of each gas flux sampling event using a dielectric constant measurement (Decagon Devices, Inc.) and hand held digital thermometers, respectively. Soil water content (v/v) was then expressed as WFPS values according to bulk density (WFPS (%) = Soil water content × $1/(1-B_d/2.65) \times 100\%$). Mean bulk densities were 1.38 and 1.44 g cm^{-3} for CT and NT soils, respectively. Soil samples (0–15 cm) were collected for several times during each corn growing season and were analyzed for mineral N (ammonium and nitrate) using a continuous flow analyzer (Lachat QickChem FIA + 8000 Series) after extraction with 1 *M* KCl (soil: solution ratio1:5). The date and amount of precipitation and irrigation were also recorded during the study period.

Statistical analysis

Determination of differences in N_2O (2003 and 2004) and NO (only in 2004) emissions by tillage, N rate, and year as well as soil moisture, temperature and mineral N affected by tillage and N rate were determined statistically (ANOVA and GLM regressions) using a MINITAB statistical software (release 13 for windows, Minitab Inc.). Significant differences are expressed at $P < 0.05$, unless otherwise stated.

Results

Weather and soil conditions

Dynamics of weather conditions and soil properties from April 2003 to October 2004 are shown in Figure 1. Mean air temperature in 2003 (19.5 °C) was higher than in 2004 corn growing season (17.9 °C), while air temperatures in the fallow season (2.3 °C) were greatly lower than those in the two corn seasons (Figure 1a). Soil temperature at 5 cm depth followed the similar pattern of air temperature for both CT and NT plots (Figure 1b). However, soil temperature under NT was consistently lower than under CT in early growing season (e.g. May and June) in both 2003 and 2004.

Total precipitation and irrigation were 162 and 451 mm for 2003 and 145 and 346 mm for 2004 (planting to the end of October, Figure 1c), respectively. However, more precipitation occurred in May 2003 than in May 2004, which caused the higher soil moisture content during that period of 2003 (Figure 1d). Water filled pore space (WFPS) in 0–15 cm soil ranged from 38 to 80% for CT and 47–94% for NT during corn growing seasons (Figure 1d). WFPS was generally greater in NT than in CT. The average values of WFPS were 65.9 and 58.7% in CT plots and 75.2 and 74.8% in NT plots in 2003 and 2004, respectively.

In addition, soil mineral N in 0–15 cm peaked just after N fertilization then dropped to the

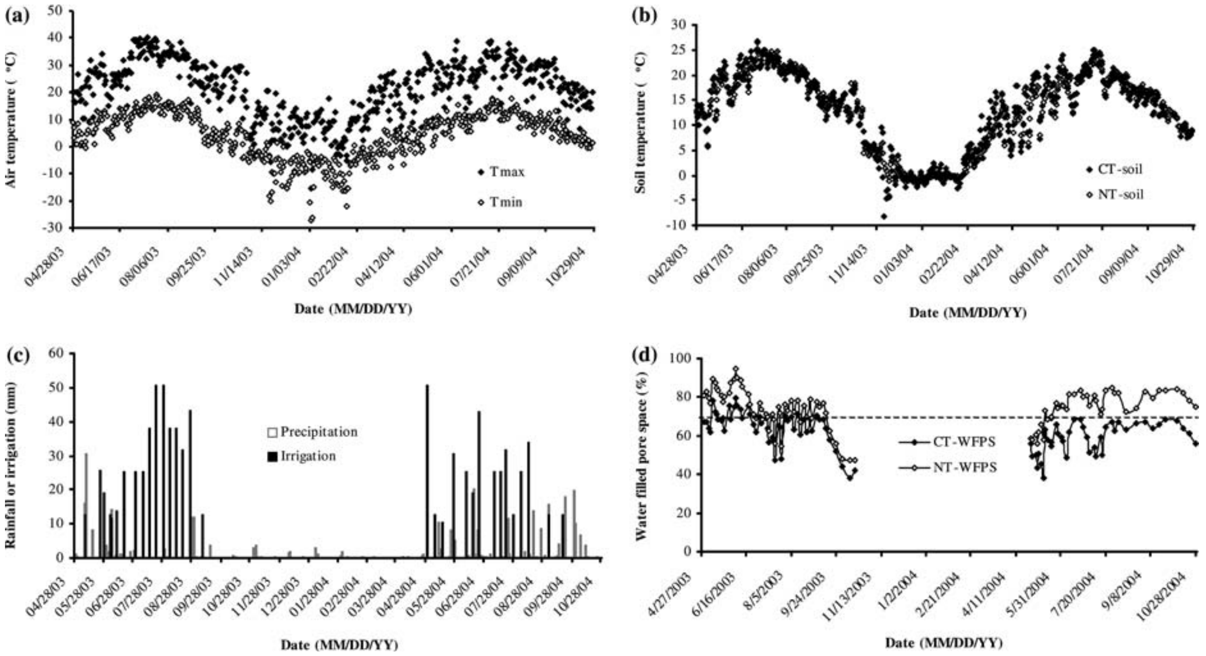

Figure 1. Dynamics of maximum and minimum air temperature (a), soil temperature at 5 cm depth (b), precipitation and irrigation (c), and water field pore space (WFPS) in 0–15 cm soil (d) in CT and NT plots during 2003 and 2004 corn growing seasons as well as the corresponding fallow season (April 2003 to October 2004).

background level within one month (data not shown). Most mineral N existed as NO_3-N (0.8–166 mg kg^{-1}), while NH_4-N content (0.2–3.4 mg kg^{-1}) was always small, with the exception of the short period after fertilization (up to 244 mg kg^{-1} in CT 224N), suggesting that hydrolysis and nitrification processes rapidly occurred after fertilization in both CT and NT soils. However, mineral N or NO_3-N was generally lower in NT soils than in CT soils at each N level in both years (data not shown).

Nitrous oxide emissions

N_2O fluxes as affected by tillage and N fertilization are shown in Figure 2. In 2003, N_2O emissions increased quickly with N fertilization and the first emission peak appeared about two weeks after fertilization, and the second emission peak followed within one month (late May). After three months (up to the end of July), the N_2O emission rates dropped to the background level (similar to zero N treatment) and remained at a relatively low level until early April the next year. The sharp increase in N_2O emissions in mid April (the end of 2003–04 fallow season) was probably induced by the spring thaw due to the warmer air and soil temperatures (Figure1). Similar phenomenon was observed by Lemke et al. (1998), who reported the spring snowmelt event accounted for up to 70% of the annual N_2O flux in Boreal and Parkland regions of Alberta, Canada. In the 2004 corn season, the N_2O fluxes followed the similar pattern as in 2003. However, the peak emissions were much lower in 2004 than in 2003 for both CT and NT systems. The 2004 N_2O flux rates were similar to those observed in 2002 (Mosier et al., 2005).

N_2O emissions increased with increasing N rate in both tillage systems. The fertilizer-induced N_2O emissions in CT lasted for a longer period than in NT in both years although N_2O emissions peaked earlier and stronger in NT than in CT especially at N rate of 224 kg N ha^{-1} (Figure 2 a, b). The average N_2O fluxes were 38.4 and 33.6 μg N m^{-2} h^{-1} for CT and NT, respectively, across N rates and 5.3, 39.9 and 62.7 μg N m^{-2} h^{-1} for N rates of 0, 134 and

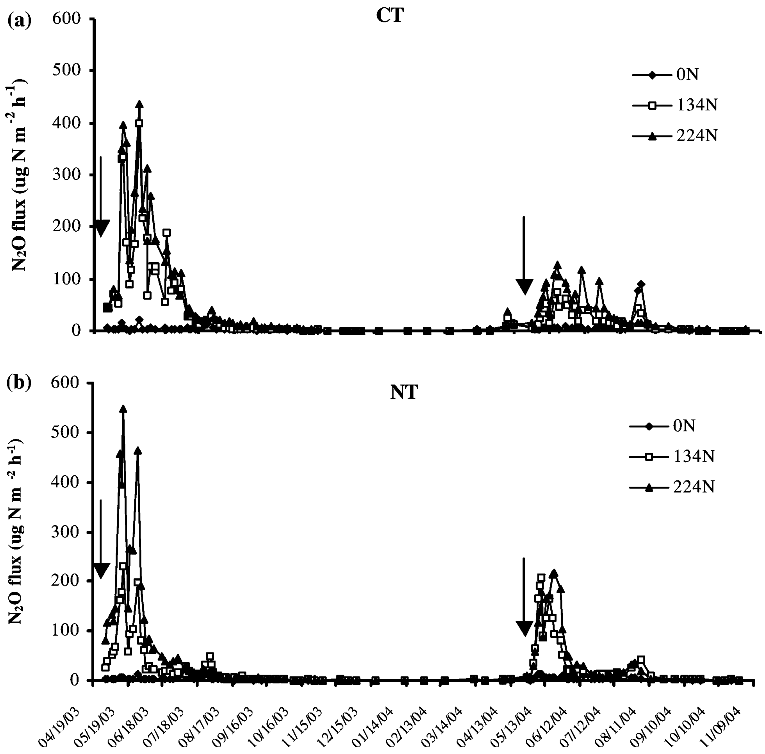

Figure 2. N_2O fluxes in 2003 and 2004 as affected by tillage and N rate over time. Arrows denote time of N fertilization.

224 kg N ha^{-1} across tillage systems over the 2-year study period, respectively.

The accumulated N_2O emission in 2003 and 2004 (planting to late October of each year) were shown in Figure 3. In 2003, N_2O emissions accumulated rapidly following N fertilization. The relative emissions reached 44 and 69% of total annual emissions for CT and NT across two N rates (134 and 224 N) within one month after fertilization, respectively. More than 92% of N_2O emissions occurred before the end of July (about three months after fertilization) for both CT and NT treatments. In 2004, the accumulated curves of N_2O in all treatments (especially in CT 134N and CT 224N) lasted much longer, while the total emissions were significantly lower in 2004 than in 2003.

Total N_2O emission in the two corn seasons and one fallow season are summarized in Table 2. Total N_2O emissions (0.04–0.33 kg N ha^{-1}) were relatively small in zero N treatments in both growing and fallow seasons. NT did not significantly increase or decrease N_2O emissions from either 2003 or 2004 corn growing season. NT only resulted in significantly lower N_2O emissions from the 2003 to 2004 fallow season compared to CT ($P < 0.01$, Table 2). Statistical analysis (ANOVA GLM) showed that tillage did not significantly affect overall N_2O emissions when two growing seasons plus the fallow season were considered (data not shown). Total N_2O emissions increased significantly ($P < 0.01$) and linearly with N-fertilizer rate in both years (Figure 4). No interaction between tillage and N rate was observed in the two growing seasons and the fallow season. In 2003 and 2004, the increase in N_2O-N emitted per kg ha^{-1} of fertilizer N added was 14.5 and 4.1 g ha^{-1} for CT and 11.2 and 5.5 g ha^{-1} for NT (Figure 4), respectively.

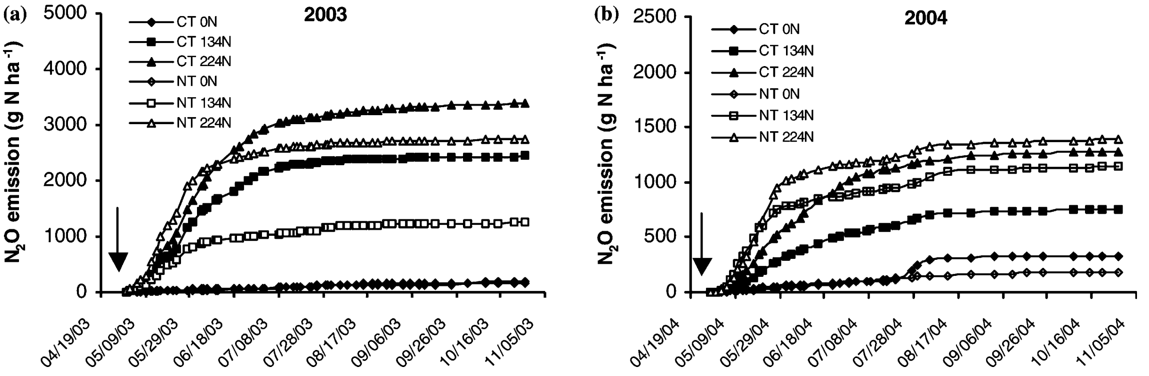

Figure 3. Accumulated N_2O emissions during 2003 (a) and 2004 (b) growing seasons as affected by tillage and N rate. Arrows denote time of N fertilization.

Table 2. Total N_2O production (g N ha^{-1}) as affected by tillage and N rate during 2003 and 2004 corn growing (planting to harvest) and fallow (harvest to planting) seasons

Treatment	CT 0N	CT 134N	CT 224N	NT 0N	NT 134N	NT 224N
2003 corn	185	2437	3380	155	1245	2733
03–04 fallow	114	103	145	37	51	58
2004 corn	332	751	1275	184	1138	1383
Statistical analysis						
	Tillage (T)		Nitrogen (N)		Interaction (T × N)	
2003 corn	NS		**		NS	
03–04 fallow	**		NS		NS	
2004 corn	NS		**		NS	

NS and ** represent not significant at 0.05 level and significant at 0.01 level, respectively.

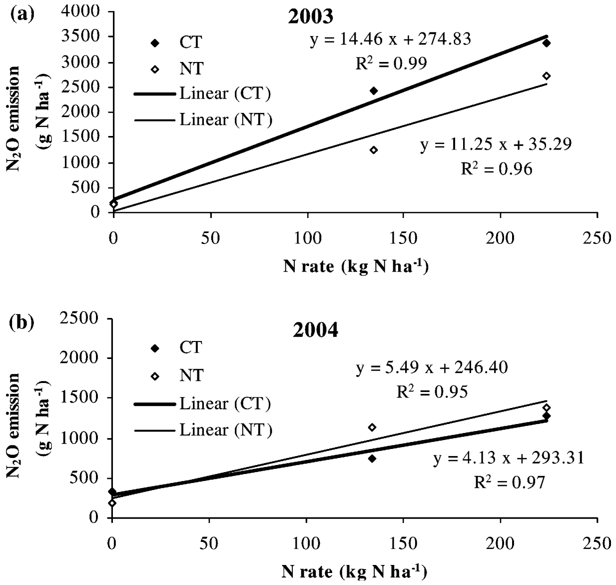

Figure 4. Relationship between N_2O emission and N application rate under CT and NT conditions in 2003 (a) and 2004 (b) corn growing seasons.

Nitric oxide emissions

NO fluxes as affected by tillage and N fertilization are shown in Figure 5. In 2003, NO emissions peaked about three weeks after fertilization (May 21) then declined sharply to the background level in early June for both CT and NT (134 and 224N). NO emissions in the control (0N) remained very low levels during the whole corn season and the ensuing fallow season (until early December). In 2004, NO fluxes increased rapidly after fertilization and remained high, with several peaks, during the following five weeks. The first peak occurred on 10 May (about two weeks after fertilization), the second was on 20 May for both CT and NT, and the third on 3 June (for CT 224N only). The fertilizer-induced NO emission lasted for nearly two months after fertilization in 2004 compared with less than one month in 2003 (Figure 5). Average NO fluxes were higher in 2004 than in 2003 across tillage and N rate. Compared with CT, NT greatly reduced the NO emissions in both years. NO emission increased with N rate in both tillage systems. In addition, similar to N_2O, we also observed moderate NO fluxes (35–69 μg N m^{-2} h^{-1}) in those CT plots in early April, suggesting that the increase in air and soil temperatures associated with spring thaw (Figure 1) promoted NO emission from tilled soils.

The accumulated curves of NO emissions in 2003 and 2004 are shown in Figure 6. The NO emissions followed a similar pattern to N_2O in both years. In 2003, about 97 and 93% of growing season emissions occurred for CT and NT at two N rates within one month after fertilization, respectively. In 2004, only 64 and 82% growing season emissions happened in the same period for CT and NT, respectively. Most NO emissions (94%) from CT and NT soils had occurred by the end of June.

Total NO emission varied greatly in 2003 and 2004 corn seasons. As opposed to N_2O, much higher NO emissions in all treatments were observed in 2004 than in 2003. But NT greatly reduced NO emission in both corn seasons and the fallow season (Table 3). The total NO emissions in NT 224 were even lower than those in CT 134N. The same as N_2O, NO emissions increased linearly with N-fertilizer rate in both years (Figure 7). In 2003 and 2004, the increase in NO-N emitted per kg ha^{-1} of fertilizer N added was 3.6 and 7.4 g ha^{-1} for CT and 1.6 and 2.0 g ha^{-1} for NT, respectively. It should be noted that we observed a significant interaction ($P < 0.01$) between tillage and N rate in 2004 corn season (Table 3).

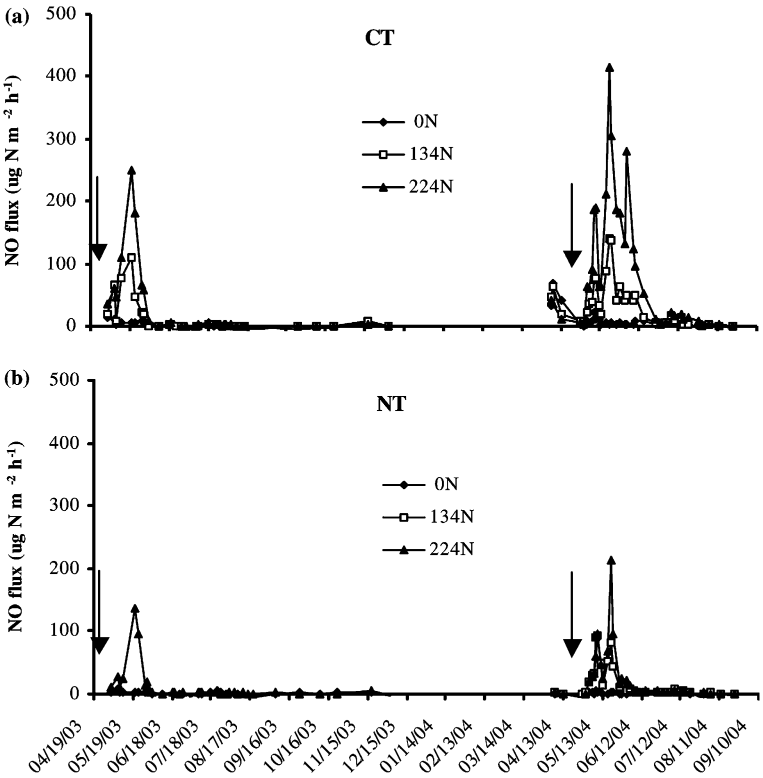

Figure 5. NO fluxes in 2003 and 2004 as affected by tillage and N rate over time. Arrows denote time of N fertilization.

Effect of soil temperature on NO fluxes

Soil temperature effects on NO fluxes from CT and NT soils receiving different N rates at two selected dates (5 and 7 May, 2004) are shown in Figure 8. The NO fluxes in the morning (from about 8:30 to 11:30 a.m.) were consistently lower than those in the afternoon (from 12:30 to 3:30 p.m.) across tillage and N application rate (Figure 8a). ANOVA on NO flux showed that the difference between the morning and the afternoon fluxes was significant ($P < 0.05$) at each measurement. This emission pattern coincided well with the changes of soil temperature at a depth of 5 cm, where soil temperatures in the afternoon were 5.1–7.6 °C higher in CT plots and 6.2–8.6 °C higher in NT

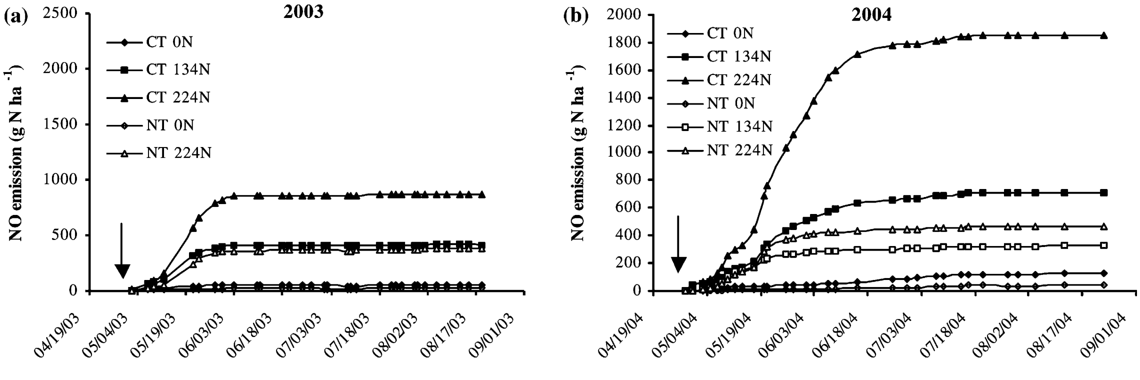

Figure 6. Accumulated NO emissions in 2003 and 2004 corn growing seasons (planting to the end of August, about 120 days) as affected by tillage and N rate. Arrows denote time of N fertilization.

Table 3. Total NO production (g N ha^{-1}) as affected by tillage and N rate during 2003 and 2004 corn (planting to the end of August) and fallow seasons (November to April)

Treatment	CT 0N	CT 134N	CT 224N	NT 0N	NT 134N	NT 224N
2003 corn	52	413	873	22	–	377
03–04 fallow	218	183	105	13	–	8
2004 corn	122	674	1833	34	325	469
Statistical analysis						
	Tillage (T)		Nitrogen (N)		Interaction (T × N)	
2003 corn	n.d.		n.d.		n.d.	
03–04 fallow	n.d.		n.d.		n.d.	
2004 corn	**		***		**	

The '–' indicates that no measurement was made. n.d., ** and *** represent not determined, significant at 0.01 and 0.001 levels, respectively.

plots than in the morning (Figure 8b). The daily average soil temperature (19.6 °C for CT and 16.6 °C for NT) occurred between 11 a.m and 12 p.m. In addition, we also found higher soil temperatures (about 3 °C) in CT plots compared to NT plots during the measurement period (Figure 8b), which corresponded to greater NO fluxes in CT than in NT. The pattern of NO flux suggested the importance of suitable time (e.g. mid-morning) for flux measurements in order to obtain the representative daily flux of trace N gases. Passianoto et al. (2004) also found the soil temperature-induced diurnal changes of NO fluxes from conventional tillage and pasture sites.

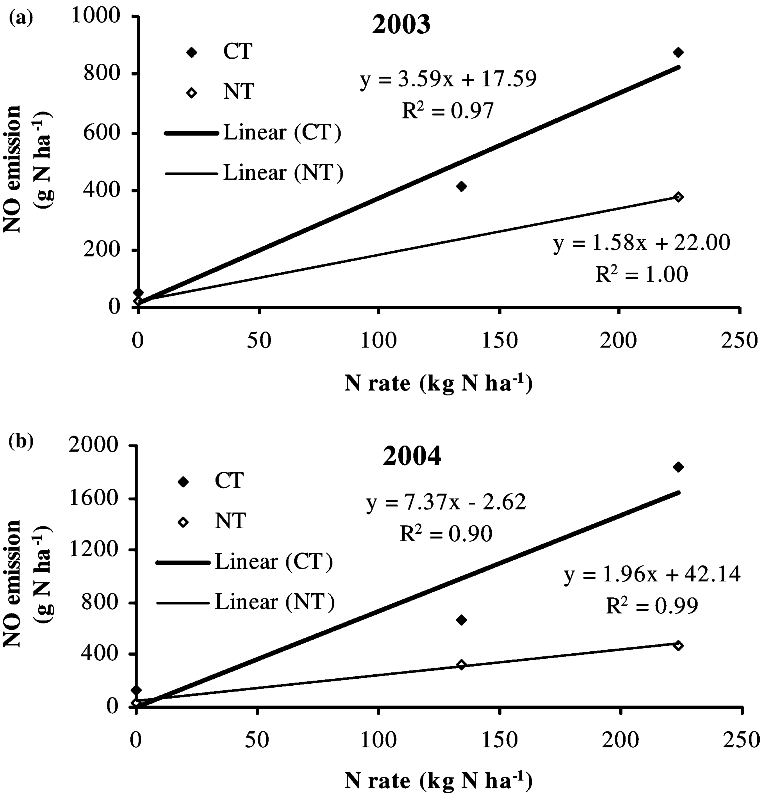

Figure 7. Relationship between NO emission and N application rate under CT and NT conditions in 2003 (a) and 2004 (b) corn growing seasons (planting to the end of August).

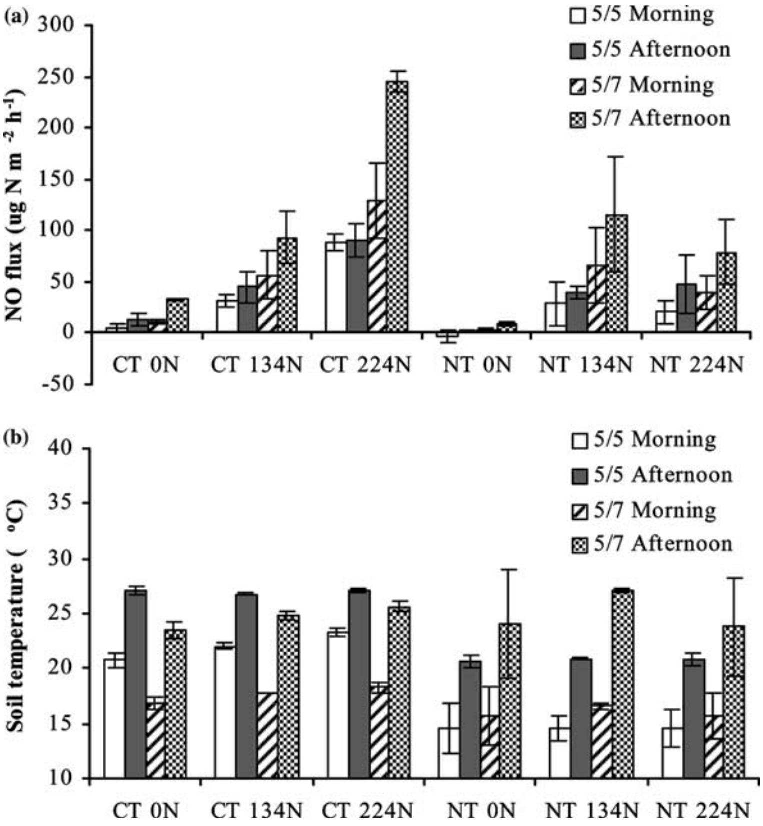

Figure 8. Effect of soil temperature on NO flux on May 5 (a) and May 7 (b) 2004 as affected by tillage and N rate. In the morning measurement, averaged soil temperatures were 21.8 and 17.6 °C for CT and 14.6 and 15.6 °C for NT on May 5 and May 7, respectively. In the afternoon measurement, averaged soil temperatures were 27.0 and 24.6 °C for CT and 20.7 and 24.2 °C for NT on May 5 and May 7, respectively.

NO/N_2O emission ratio

NO/N_2O emission ratios (based on N) are illustrated in Table 4. We found that NO/N_2O ratios in CT were consistently greater than in NT at each N rate, reflecting that NT favors N_2O emissions but CT favors NO emissions, respectively. NO/N_2O ratios were not affected by fertilizer N rate in 2003 corn growing season while they significantly increased with N rate in 2004 corn

Table 4. NO/N_2O emission ratios as affected by tillage and N rate during 2003 and 2004 corn and fallow seasons

Treatment	CT 0N	CT 134N	CT 224N	NT 0N	NT 134N	NT 224N
2003 corn	0.28	0.17	0.26	0.14	–[a]	0.14
03–04 fallow	1.91	1.78	0.72	0.35	–	0.14
2004 corn	0.37	0.90	1.44	0.18	0.29	0.34
Statistical analysis						
	Tillage (T)		Nitrogen (N)		Interaction (T × N)	
2003 corn	n.d.		n.d.		n.d.	
03–04 fallow	n.d.		n.d.		n.d.	
2004 corn	***		**		*	

[a] Indicates no NO and N_2O ratio available. N.d., *, ** and *** represent not determined, significant at 0.05, 0.01 and 0.001 levels, respectively.

growing season. However, NO/N_2O ratios in the fallow season decreased with previous N rate. In 2003–04 the fallow season NO/N_2O ratios in CT were more than double of those in NT, indicating that the risk of NO (not N_2O) emissions from CT-soil should be greater than from NT-soil.

Discussion

Tillage effect

The environmental consequences of NT (e.g. trace N gas emission) have become a concern given its widespread adoption since the 1980s (Holland, 2004). The present study showed that NT significantly reduced NO emission but did not affect N_2O emission in the corn growing season although emissions of both gases from NT were decreased in the fallow season. The question is why NT did not consistently show the potential to reduce N_2O emission in the corn season? It is not easy to give a simple answer because there are many factors involved in the process of N_2O formation in the soil (Bouwman, 1996; Linn and Doran, 1984; Mosier et al., 1998). As we know, the soil environment under NT is very different from soils under CT. Soils under NT are generally moister, and have organic carbon and soil microbial populations more concentrated near soil surface (Lemke et al., 2004). These conditions are thought to favor N_2O production. In Saskatchewan, Aulakh et al. (1984) reported higher emissions of N_2O from NT compared to CT during the crop growing season. Burford et al. (1981) also found more total N_2O loss from direct-drilled plots (1.8–7.0 kg N ha^{-1}) than from ploughed plots (0.5–5.6 kg N ha^{-1}) in a 2-year field study. On the other hand, soil mineral N and soil temperature are other key factors that affect N_2O production (Pinto et al., 2004; Müller and Sherlock, 2004). Under NT (generally covered with a 2–3 cm residue layer), soil mineral N and soil temperature are usually lower than under CT, especially during early growth stage of corn (e.g. Figure 1). Such conditions, however, are considered to inhibit N_2O emission from NT soils. Our study shows that NT did not increase the total emission of N_2O compared to CT, although NT led to higher peak fluxes of N_2O after fertilization than CT (Figure 2). This result is similar to some recent studies (Kaharabata et al., 2003; Lemke et al., 2004; Mosier et al., 2005). Pinto et al. (2004) found that the earlier tillage (12 days before measurement) resulted in higher NO and N_2O emissions than later tillage (1 days before measurement), the difference being related to differences in soil mineral N and WFPS. Meanwhile, Yamulki and Jarvis (2002) provided evidence that compaction plays a more important role in promoting the emission of N_2O compared with tillage. In their short-term study, compaction resulted in 3.5 times more N_2O emissions compared to uncompacted plots while tillage did not affect N_2O emission. They concluded that the least compacted system should be the best option to reduce N_2O, NO_x, CH_4 and CO_2 from fertilized soils regardless of tillage status. Therefore, N_2O emissions from NT could be controlled to a comparable or even lower level compared with CT if suitable N application rate and management practice (e.g. less compaction) are used.

Different from N_2O, NO emission was greatly reduced by NT in comparison to CT in this study. Yamulki and Jarvis (2002) also reported that NO emissions from non-tilled plots were only 42% of those from tilled plots. Although most NO and N_2O are the by-products either from nitrification and/or denitrification, NO is generally thought to be from nitrification and N_2O mainly from denitrification (Azam et al., 2002; Skiba et al., 1992; Wolf and Russow, 2000). Furthermore, the emission of NO from soils is more sensitive to soil moisture content than that of N_2O (Gut et al., 1999; McTaggart et al., 2002). Two possible mechanisms responsible for lower NO emission in NT than in CT are (i) that the microbial production of NO from nitrification decreases while the consumption of NO induced by denitrification increases due to higher water content in NT and (ii) that NO diffusion is limited at higher water content in NT. Some studies (Davidson, 1993; Galbally, 1989; Harrison et al., 1995) show that NO diffusion rates are typically more than one hundred times slower through H_2O than through the equivalent thickness of air. In this study, WFPS was on average 10–16% higher in NT than in CT across years and higher in 2003 (65–74%) than in 2004 (58–73%) across tillage systems. Such differences in soil water content mainly explained the different flux patterns of N_2O and NO under CT and NT in the two seasons. The changes of soil moisture content as well as other environmental conditions (e.g. air and soil temperature, soluble organic C) are the main reasons why the NO/N_2O ratio varied with tillage, N rate and year.

The distribution of rainfall and irrigation in 2003 and 2004 represent two typical soil water conditions: the one with early moisture plus late drought (2003), the one with early drought plus late moisture (2004, Figure 1d). As a result, N_2O fluxes were greater in 2003 than in 2004 in all fertilized plots across tillage. For the same reason, NO fluxes were significantly inhibited in 2003 (only one emission peak) compared with 2004 (several emission peaks). Davidson (1991) observed that the largest NO emissions could be expected at WFPS values of 30–60% and the highest N_2O emissions at WFPS values of 50–80%. In addition, the larger difference of WFPS between NT and CT in 2004 could explain a little higher fluxes of N_2O in NT than in CT across N rate. In those semi-arid regions like Colorado, the relatively dry weather condition (e.g. 2004) is more common compared with the wet climate condition. Therefore, the environmental impact of NO (not N_2O) will be the main concern when fertilizer N is applied. From this viewpoint, the practice of NT should be accepted more widely because of its great potential to decrease NO fluxes compared with CT.

The loss of NO and N_2O during the fallow season is another concern in this study. Both NO and N_2O emissions in the fallow season (winter and spring) from fertilized plots were comparable or even higher than those from control treatments (CT 0N and NT 0N) during the growing seasons. We observed moderate emissions of NO and N_2O from CT plots in early to mid April when the spring thaw occurred. Similar studies (Lemke et al., 1998; Wagner-Riddle and Thurtell, 1998) stressed the important role of winter and spring thaw on N_2O emissions from soils. Izaurralde et al (2004) observed relatively high fluxes of N_2O (up to 1.7 kg N ha^{-1}), especially in depressional areas, during spring thaw period in both cropland and grassland of Canada. Syvasalo et al. (2004) also reported that the N_2O fluxes during winter and during the thawing period in spring increased with increasing number of freeze–thaw events. However, as far as we know, no previous studies have investigated the effect of thaw on NO_x emissions. Our study further confirms that conditions during freeze–thaw can increase NO emissions from tilled-soil. The possible reasons are (i) the rapid cycles of wetting and drying on soil surface, which probably increase the biological and abiotic nitric production, and (ii) the accelerated N mineralization during thawing period, which provides N source for nitrification. Fertilizer-induced NO and N_2O emissions from the fallow season ranged from 2 to 34% of those emitted during the growing seasons (on average). In general, the loss of NO and N_2O during the fallow season should be included in estimating the annual emissions, especially under CT.

N application effect

Higher N rates lead not only to higher grain yields but also more N loss such as gaseous emissions and leaching (Liu et al., 2003). Based on the information from 846 N_2O emission measurements in agricultural fields and 99 measurements for NO emissions, Bouwman et al. (2002) estimated that global mean fertilizer-induced emissions of N_2O and NO amounted to 0.9 and 0.7%, with total amount of 2.8 Tg N_2O-N and 1.6 Tg NO-N emitted from fertilized soils, respectively. Mosier et al. (2004) summarized the relationship of crop type to measured N_2O emissions in temperate agricultural systems from 35 studies. They found N_2O emission from maize fields ranged from 0.5 to 7.3% of N applied compared with 0.1–1.0% of N applied from fallow fields. Duxbury and McConnaughey (1986) found total gaseous N loss during corn growth was less than 3% of the applied N, and loss of N as N_2O during nitrification of NH_4^+ was not a major route of N loss.

This study clearly indicated that NO and N_2O loss coincide linearly with increasing N rate. We found that the fertilizer-induced N gas losses were 0.31–1.68% (N_2O) and 0.16–0.76% (NO) of N applied across tillage, with more than 50% emitted from the first month after fertilization. Total N_2O and NO losses were less than 1–2% of fertilizer N input in all treatments. Thus, the results on fertilizer-induced N_2O and NO emissions in the present study fell into the lower range of the above studies. A similar study by Harrison et al. (1995) at Broadbalk field, Rothamsted Experimental Station in England also showed that the emissions of both NO and N_2O increased with increasing N rate but NO/N_2O ratio tended to decrease. Approximately 90% of the total fertilizer-derived emissions of the two gases occurred within a 25-day sampling period.

In general, adjusting fertilizer N rate to a suitable level is crucial for reducing both N_2O and NO emissions. On the other hand, we should keep in mind the importance of improving N use efficiency by crops by changing fertilizer application methods, placement and timing, etc. Since denitrification and nitrification depend on a source of labile soil N, the higher emissions of NO and N_2O will occur at higher concentrations of N in the soil (Williams et al., 1998). Of course, the efficient utilization of N by crops will help reduce the N gas emissions from soils. In our study, all the fertilizer N was applied as band application at planting. Nitrogen uptake by corn was small during the early growing stage when the largest emissions of NO and N_2O occurred. Consequently, there is a potential for reducing gaseous N loss through splitting fertilizer N by several topdressings or subsurface banding applications.

Conclusions

The influence of tillage and fertilizer application rate on N_2O and NO were studied. Generally, NT reduced NO emissions significantly but did not affect N_2O emissions compared with CT when averaged over two corn seasons. N_2O and NO emissions increased linearly with N application rate under both CT and NT. In the 2003 and 2004 corn growing seasons, the increase in N_2O-N emitted per kg ha^{-1} of fertilizer N added was 14.5 and 4.1 g ha^{-1} for CT, and 11.2 and 5.5 g ha^{-1} for NT, respectively. At the same time, the increase in NO-N emitted per kg ha^{-1} of fertilizer N added was 3.6 and 7.4 g ha^{-1} for CT and 1.6 and 2.0 g ha^{-1} for NT in 2003 and 2004, respectively. In the fallow season, N_2O and NO emissions from CT were 2.0–3.1 and 13.1–16.8 times of those from NT, but previous N application did not show obvious carry-over effect on both gas emissions. Fertilizer-induced NO and N_2O emissions from the fallow season ranged from 2 to 34% of those emitted during the growing seasons (on average). Change of climate and soil conditions (e.g. moist and temperature) explained the emission patterns of N_2O and NO as well as their emission ratios under different tillage systems and in different years. The present results reveal potential of NT to reduce NO emission without changing N_2O emission under continuous irrigated corn cropping compared to CT. Of course, long-term studies in various climate and soil conditions are needed to get a general conclusion of tillage and N fertilization effects on both N_2O and NO fluxes from main croplands.

Acknowledgements

We greatly thank A. Kear, W. Morgan, M. Smith, G. Smith, S. Crookall, P. Norris, C. Reule, and B. Floyd for their technical assistance. We also acknowledge the financial support of USDA-ARS and USDA-CSREES-NRI (Grant # 2001-35108-10719), and the support of Chinese National Natural Science Foundation (Grant # 30370287 and 30390080) as well as the support of Key Import Project of Chinese Ministry of Agriculture (Grant # 202003-Z53). 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.

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Section editor: S. Recous