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Controls on annual emissions of nitric oxide from soils of the Colorado shortgrass steppe

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Abstract. Estimates of NO_x ($NO+NO_2$) emissions from temperate grasslands range from 0.003 to 101 ng NO-N $m^{-2} s^{-1}$ (average 4.17 ng NO-N $m^{-2} s^{-1}$). As a result of this uncertainty, the potential contribution of soil NO_x emissions to the global budget and to nitrogen loss for this ecosystem is unclear. The few existing measurements are short-term observations of growing-season fluxes. We measured soil NO_x emissions from six sites within the shortgrass steppe at the Central Plains Experimental Range in Colorado from June 1994 through October 1995. The soils at these sites provided a range of texture (from a sandy loam to a clay loam) and soil moisture. Mean NO_x emissions over the sampling period ranged from 2.6 to 5.7 ng NO-N $m^{-2} s^{-1}$ from the four unfertilized sites. Temperature was the dominant control on seasonal variations in NO_x fluxes. Seasonal fluxes were highest in the summers (5.4 to 10.5 ng NO-N $m^{-2} s^{-1}$) and lowest in the winter (0.2 to 1.5 ng NO-N $m^{-2} s^{-1}$). The winter NO_x emissions contribute up to 25% to the mean annual flux. Water-filled pore space (WFPS) alone was a poor predictor of NO_x emissions; however, peak NO_x emissions were found near the field capacities for these soils (32-35% WFPS for coarse soils and 66% WFPS for fine-textured soils). Water additions produced large (22-51 ng NO-N $m^{-2} s^{-1}$) but short-lived (24 hour) pulses of NO_x emissions that were independent of both the amount of water added and the number of antecedent dry days. Short-term increases in NO_x flux stimulated by wetting are significant, and increase the summer estimate of NO_x emissions 8 times estimates calculated from periodic sampling. Nitrogen applied in previous studies, 5 to 12 years earlier, increased the average annual NO_x emissions approximately 1.5 times. Extrapolating our estimate to similar systems around the world, we estimate that grassland ecosystems, globally, emit 1.0 Tg N yr^{-1} as NO_x. A current estimate of NO_x emissions from grassland soils is 0.6 Tg N yr^{-1} [*Davidson*, 1991].

1. Introduction

Nitric oxide emissions from soils represent an important pathway for nitrogen loss from the soil system as well as a pathway for gaseous exchange of nitrogen between the soil and the atmosphere. Nitric oxide (which we will refer to as NO within the soil atmosphere) is produced during the microbial processes of nitrification and denitrification that occur naturally in the soils of many ecosystems. Once emitted from soil NO is quickly (within seconds) converted to NO_2 and persists in chemical equilibrium with NO and ozone; thus when discussing the biosphere-atmosphere exchange of these gases it is more convenient to refer to NO + NO_2 as NO_x [*Prather et al.*, 1995].

NO_x controls the oxidative capacity of the troposphere [*Prather et al.*, 1995]. At high concentrations(>30 parts per trillion by volume (pptv)), NO_x contributes to the net production of ozone and the HO_2 radical through the oxidation of carbon monoxide (CO) and methane (CH_4). At low concentrations (10-20 pptv) NO_x will destroy ozone and OH radicals during the oxidation of CO and CH_4 [*Crutzen*, 1979; *Prather et al.*, 1995]. Owing to the relatively short atmospheric lifetime of NO_x, approximately 1 day [*Prather et al.*, 1995], the impact of soil NO_x emissions on tropospheric chemistry tends to be highly localized [*Williams et al.*, 1992a].

Emissions from soils are a major source of NO_x globally, contributing between 4 and 20 Tg of N yr^{-1} to the atmosphere, accounting for up to 40% of the global NO_x source (a range of 25-99 Tg N yr^{-1}) [*Davidson*, 1991; *Logan*, 1983; *Williams et al.*, 1992a]. *Williams et al.* [1992a] estimated that grassland emissions comprise about 28% of the total soil NO_x emissions estimated for natural land areas, but this value is based on a wide range of flux estimates (0.003 to 101 ng NO-N $m^{-2} s^{-1}$). Furthermore, measurements used to develop regional and global estimates of NO_x from grasslands have been taken only during the summer or growing season and neglect winter measurements. Although *Davidson et al.* [1991] estimates that grassland emissions only contribute 3% to the global N source, they may have a large impact on the regional air chemistry in unpolluted rural regions [*Williams et al.*, 1992a].

NO is produced during nitrification, denitrification, and through the chemical decomposition of HNO_2 [*Firestone and Davidson*, 1989]. Factors such as temperature, soil water content, soil texture, wetting of dry soil, and fertilization practices have all been shown

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to be key controls over NO_x emissions from soils [*Anderson and Levine*, 1987; *Galbally*, 1989; *Rosswall et al.*, 1989; *Williams et al.*, 1992b].

We examined the influence of biotic and abiotic factors on seasonal soil NO_x emissions from the shortgrass steppe at the Central Plains Experimental Range (CPER) in Colorado. We focused our study on the quantification of NO_x emissions throughout the year, including the winter, as well as following wetting of a dry soil, the interacting effects of texture, soil temperature, and soil water content, and the effect of N application history on NO_x emissions. This experiment is part of a larger, long-term study examining the biogeochemistry of and trace gas emissions (N_2O, CH_4, and CO_2) from soils at the CPER [*Mosier et al.*, 1981, 1991, 1996; *Mosier and Parton*, 1985; *Schimel and Parton*, 1986; *Parton et al.*, 1988, 1996].

2. Site Characteristics

This experiment was conducted at the Central Plains Experimental Range (CPER) (40°48'23"N,104°45'15"W, and elevation 1650 m) about 60 km northeast of Fort Collins, Colorado. The precipitation averages approximately 322 mm a year, with 70% of the precipitation falling between April and September. The vegetation is characteristic of a shortgrass steppe, dominated by blue gramma (*Boutelous gracilis* Lag.), with fringed sagebrush (*Artemisia frigida* Wild.) and plains prickly pear (*Opuntia polyacantha* Haw.) as secondary dominants [*Lauenroth and Milchunas*, 1992]. Soil textures ranged from sandy loam (three sites, SL1, SL2, one fertilized SL2F) to a sandy clay loam (two sites, SCL, one fertilized SCLF) to a clay loam (CL) (Table 1). Nitrogen was applied to soils at two sites during previous experiments 5 to 12 years earlier. The SL2F site was fertilized with 2.2 g N m^{-2} yr^{-1} of ammonium nitrate from 1976 to 1989 [*Mosier et al.*, 1996]. The SCLF is located on a 25 m^2 area that was fertilized once in 1982 with a solution containing 45 g m^{-2} of urea-N [*Mosier and Parton*, 1985].

3. Methods

3.1. Field NO Measurements

Soil NO_x measurements were made using a flow-through chamber method [*Slemr and Seiler*, 1984]. At each site, soil NO_x measurements were taken by fitting a 6.28 L chamber (lined with Teflon to inhibit chemical transformation of NO) onto a PVC pipe anchor. A portable Scintrex LMA-3 chemiluminescent instrument and LNC converter (Scintrex Unisearch, models LMA-3 and LNC-3) were used to measure soil NO_x in the field. The instrument was calibrated monthly in the laboratory. A calibration curve was determined using at least four data points with a dilution of an NO gas standard (10.8 ppm).

Steady increases of NO_x within the chamber were observed between 2 and 8 min after the chamber was placed on the anchor. Sampling times of 3 and 6 min within this steadily increasing range were chosen for calculation of the NO_x concentration within the chamber. Fluxes were calculated using the following equation:

$$r = F(C_{chamber}-C_{ambient})\, W_N\, 10^9 / (V_{mole}\, A\, (1-e^{-Ft/V}))$$

where r is the rate of NO production (ng NO-N m^{-2} s^{-1}), F is the flow rate through the chamber (m^3 s^{-1}), $C_{ambient}$ is the ambient concentration of NO in the atmosphere at the location of the inlet port (in parts per billion by volume), $C_{chamber}$ is the concentration of NO (in parts per billion by volume) measured from the chamber at a given time t, W_N is the molecular weight of nitrogen (g mol^{-1}), V_{mole} is the molar volume of NO (m^3 mol^{-1}) at a given chamber temperature, A is the area of soil (in square meters) which the chamber covers, V is the chamber volume, and t is a finite time after chamber closure (seconds) [*Martin*, 1996].

Following the procedures used in previous experiments at these sites summarized by *Mosier et al.* [1996], six anchors (20.3 cm inside diameter and 8 cm deep) were installed at random locations at each site (except sandy clay loam fertilized (SCLF) where four previously established anchors were sampled) in mid-May 1994, at least 3 weeks prior to sampling to minimize the effect of disturbance [*Mosier et al.*, 1991]. Fluxes were sampled weekly except in the winter when they were sampled biweekly. Fluxes were sampled at each sampling date from the six anchors and used as replicates in statistical analyses.

3.2. Ancillary Measurements

Air temperature (measured approximately 10 cm above the soil surface) and soil temperature (measured at a depth of 5 cm) were taken before and after every set of NO_x flux measurements. Soil samples to10 cm depth were collected for determination of gravimetric moisture content (GMC) on each sampling date. GMC was then used to calculate percent water-filled pore space (WFPS) when

$$\%WFPS = 100\ GMC\ D_B / P$$

where GMC is gravimetric moisture content (g H_2O g dry $soil^{-1}$), D_B is the bulk density (mg m^{-3}), and P is porosity of the soil = 1-(D_B/2.65), where 2.65 is the particle density for most soils in this region (mg m^{-3}) [*Linn and Doran*, 1984].

Table 1. Site Characteristics

Site	Site Abbreviation	Texture	Sand, %	Silt, %	Clay, %	Bulk Density, g cm^{-3}	Total N, %	Total C, %
Sandy loam-1	(SL1)	sandy loam	70	17	13	1.33	0.14	1.30
Sandy loam-2	(SL2)	sandy loam	74	13	13	1.41	0.12	1.07
Fertilized sandy loam-2	(SL2F)	sandy loam	74	11	15	1.34	0.14	1.18
Sandy clay loam	(SCL)	sandy clay loam	58	18	24	1.34	0.19	1.84
Fertilized Sandy Clay Loam	(SCLF)	sandy clay loam	58	18	24	1.34	0.22	2.22
Clay Loam	(CL)	clay loam	42	18	30	1.32	0.17	1.80

All soil characteristics were measured in the top 15 cm of the soil [modified from *Mosier et al.*, 1996].

Table 2. Details of Field Wetting Experiments

Date	Site	Amount of Water Added, mm	Number of Replicate Anchors	NO Emissions Sampling Times (Hours SinceWetting)
Experiment A (Wetting to Field Capacity)				
June 7, 1994	SL2F	6.4	6	0, 0.5, 2, 4, 6, 8, 24, 48, 72
June 8, 1994	SL2	16.0	6	
June 13, 1994	CL	22.3	6	
June 14, 1994	SL1	22.3	6	
June 15, 1994	SCL	27.9	6	
Experiment B ("Small" and "Large" Water Additions)				
July 26, 1994	SL2F	4.0	3	0, 0.5, 2, 4, 6, 21, 26, 29, 48
		25.5	3	
		0	3	
July 27, 1994	SL2	4.0	3	
		25.5	3	
		0	3	
August 16, 1995	SCL	4.0	3	0, 0.5, 2, 4, 7, 24, 48
		25.5	3	
		0	3	
August 17, 1995	SL2	4.0	3	
		25.5	3	
		0	3	

3.3. Field-Wetting Experiments

Soil-wetting experiments were conducted in the field in June, July, and September 1994 and August 1995 to examine the effects of precipitation on soil NO_x emission. In each experiment described below, different amounts of deionized water were sprinkled on the soil inside the PVC anchors at each of the sites using a watering can. NO_x fluxes were recorded several times from 0.5 to 72 hrs, post-wetting (Table 2). Soil samples for GMC were collected from additional anchors at each site. Two additional anchors for each water treatment were installed at each site. Soil samples for GMC were collected during every set of flux measurements, except during experiment A when they were only collected at 0, 0.5, 8, 24, 48, and 72 hours after wetting. Details of the amount of water added, number of anchors, and sampling times for each experiment are given in Table 2.

3.3.1. Experiment A: Wetting above field capacity, June 1994. In order to examine the effect of precipitation on NO_x emissions deionized water was added to each site. Field capacity was approximately 12% GMC for the sites with coarser soils (SL2F, SL2, and SL1) and 25% GMC for finer soils (CL and SCL) [*Mosier et al.*, 1991]. Calculated WFPS is 32% for SL2F and SL1, is 35% for SL2 and is 66% for CL and SCL.

3.3.2. Experiment B: "Small" and "large" water additions, July 1994 and August 1995. Two treatments of water were added to the SL2 site (both 1994 and 1995), the SL2F site (1994), and the SCL site (1995) to examine the effect of light (125 mL = 4.0 mm) and heavy (800 mL = 25.5 mm) rains. Water was added to three anchors per treatment (Table 2).

3.4. Data Analysis

We used regression analyses to examine the relationship between NO_x emissions, soil temperature, WFPS, and soil texture [Systat, version 5.0]. All data were log-transformed prior to analysis to satisfy the assumptions of normality. Average seasonal NO_x fluxes and associated standard errors were calculated by averaging NO_x fluxes measured from each anchor at each sampling time during the season and then averaging the six anchors at each site. The summer, and consequently, the annual calculations include data from both 1994 and 1995 because there were relatively fewer measurements collected in 1995. Mean annual NO_x fluxes and standard errors were calculated by averaging the seasonal NO_x fluxes from each anchor and then averaging the six anchors at each site. For consistency with previous experimental design at this site, we used the Wilcoxon rank sum test with Tukey's multiple comparison of ranks [SAS/STAT, 1991] to test for the effects of texture and previous nitrogen application on NO_x emissions. In the wetting experiments, NO_x emissions were integrated over 24 hours post-wetting for each anchor. Owing to the small sample size, the Wilcoxon rank sum test [Systat, version 5.0] was used on these integrated fluxes to examine the effect of water addition. Regression analysis was used to examine the relationship between initial NO_x flux and peak NO_x flux after wetting. Initial and peak NO_x fluxes were calculated as the mean of NO_x flux measurements from three to six anchors, depending on the experiment.

4. Results

4.1. Mean Seasonal Emissions

Mean seasonal NO_x emissions from the unfertilized sites (SL2, SL1, CL, and SCL) varied by an order of magnitude at the CPER, ranging from approximately 0.8 ng NO-N m^{-2} s^{-1} in the winter to 7.7 ng NO-N m^{-2} s^{-1} in the summer. The NO_x emissions from the fertilized sites range from 2.0 ng NO-N m^{-2} s^{-1} in the winter to 14.5 ng NO-N m^{-2} s^{-1} in the summer (Figure 1, Table 3).

Fluxes of NO_x were largest in the summer and were lowest in the winter at all sites, corresponding to seasonal changes in temperature (Table 3). Of the measurements made, soil temperature was found to be the most important control on seasonal NO_x emissions from all sites ($r^2 = 0.31$ and $p < 0.05$, Figure 2). The soil temperature at 5 cm measured at the time of the flux measurements varied between -7.5°C and 35.8°C. WFPS was a poor predictor of NO_x flux ($r^2 =$

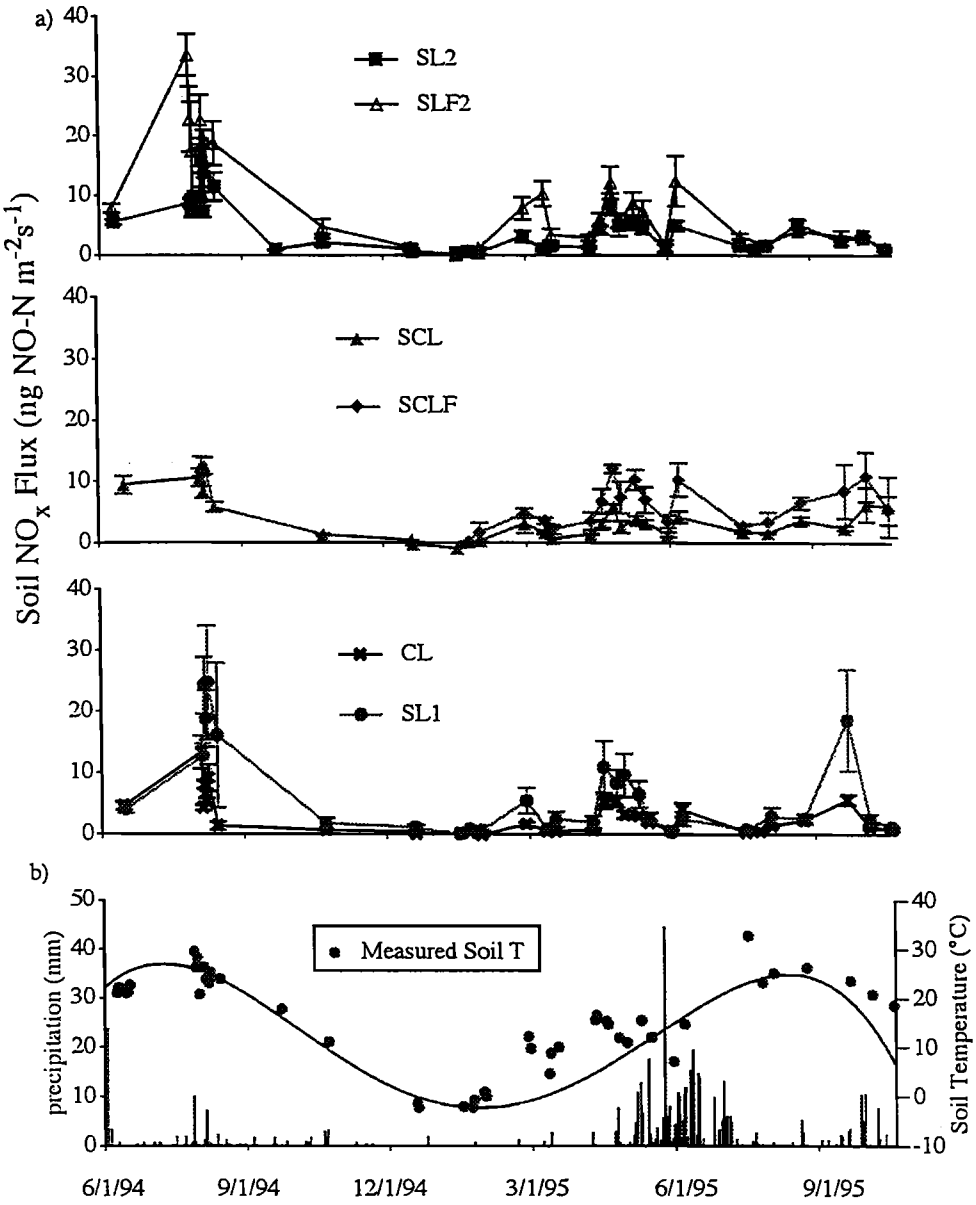


Figure 1. a) Average seasonal soil NO_x emissions (ng NO-N m^{-2} s^{-1}) from six sites at the Central Plains Experimental Range (CPER). Error bars are standard error $n = 6$ for SL2F, SL2, SL1, and CL, and $n = 4$ for SCL and SCLF. b) Precipitation (in millimeters, bars) and soil temperature (in degrees Celsius, line) measured at the CPER weather station and measured soil temperature (in degrees Celcius, dots) from the time of the flux measurements.

0.001) using a linear relationship; however, the inclusion of WFPS strengthened the relationship between NO_x emissions and temperature. The relationship between NO_x emissions and soil temperature was strongest in a range bracketing the field capacity of the soils in our study (35±10% WFPS for coarser soils and 70±10% WFPS for finer textured soils). The correlation between NO_x flux and soil temperature improved to $r^2 = 0.81$ ($p < 0.05$) for the combined coarse- and fine-textured sites (Figure 3). When we aggregated the data by soil texture, the correlation between NO_x flux and soil temperature was $r^2 = 0.88$ ($p < 0.05$) for coarser soils (Figure 4a), and $r^2 = 0.76$ ($p < 0.05$) for finer textured soils (Figure 4b).

4.2. Effect of Water Addition

Large transient pulses of NO_x were observed at all sites when water was added to anchors. The peak NO_x flux occurred between 30 min and 4 hours after wetting (Figure 5). The magnitude of peak NO_x emissions was independent of the amount of water added (Tables 4 and 5). Furthermore, the peak NO_x emission values were not correlated to the initial NO_x fluxes.

NO_x emissions, averaged over 24 hours postwetting, from five sites wet above field capacity did not differ significantly from each other (Table 4). NO_x emissions, averaged over 24 hours postwetting, increased significantly ($p < 0.05$) from the integrated

Table 3. Mean and Median Soil NO Flux for Five Sites at the CPER Measured From June 1994 Through October 1995

Site (Abbreviation)	Season	Soil NO Flux Mean, ng NO-N m^{-2} s^{-1}	Median, ng NO-N m^{-2} s^{-1}
Sandy loam-1 (SL1)	Spring	4.6±1.5*	2.7‡
	Summer	10.5±2.5*	9.2‡
	Fall	6.0±2.5*	3.6‡
	Winter	1.5±0.6*	10.9‡
	Annual	5.7±1.9†	4.1§
Sandy loam-2 (SL2)	Spring	3.2±0.7	3.0
	Summer	6.8±0.6	6.3
	Fall	1.9±0.2	1.9
	Winter	0.9±0.2	0.9
	Annual	3.2±0.3	3.6
Fertilized sandy loam-2 (SL2F)	Spring	7.0±1.2	7.1
	Summer	14.5±1.8	13.6
	Fall	3.1±0.5	2.9
	Winter	2.0±0.5	1.9
	Annual	6.6±0.9	6.5
Sandy Clay Loam (SCL)	Spring	2.7±0.4	2.4
	Summer	8.0±0.6	8.7
	Fall	3.0±1.4	2.0
	Winter	0.2±0.2	0.1
	Annual	3.5±0.6	3.4
Clay Loam (CL)	Spring	2.5±0.3	2.4
	Summer	5.4±0.5	5.7
	Fall	2.1±0.3	2.2
	Winter	0.4±0.1	0.4
	Annual	2.6±0.2	2.7

*Average seasonal soil NO fluxes and associated standard error were calculated by averaging the measurements from each anchor over the season and then averaging the six anchors at each site (n=6 for all sites, except SCL where n=4).

†The average annual soil NO fluxes (ng NO-N m^{-2} s^{-1}) were calculated by using the seasonal NO flux for each anchor to calculate and average annual flux for each anchor and then averaging the six anchors at each site (n=6 for all sites, except SCL where n=4).

‡Seasonal median soil NO fluxes were calculated from all the anchors for all sampling times during the season at each site.

§The annual median soil NO fluxes were calculated from all the anchors for all the sampling times throughout the experiment at each site (n = 114 for SL1; n = 104 for SL2; n = 114 for SL2F; n = 76 for SCL; n = 76 for SCLF; and n = 111 for CL).

control for 4 mm and 25.5 mm of water added to both the SL2 and SL2F sites in July 1994 (Table 5). In August 1995, the NO_x emissions, averaged over 24 hours post wetting, were significantly higher ($p < 0.05$) for 4 mm of water added to the SL2 site and 25.5 mm of water added to the SCL site (Table 5).

Soil NO_x fluxes in the summer were 8 times greater following simulated summer rainfall. The increase was estimated by comparing the NO_x flux measured 24 hours following the application of water with anchors that had not received any additional water. The largest increase was in the July 1994 experiment (NO_x flux was 15 times larger when water was added), while the smallest increase (3.5 times) occurred in August 1995 (Table 5).

Inclusion of the influence of precipitation in the calculation of our summer resulted in enhancement of NO_x flux of 12.6 ng NO-N m^{-2} s^{-1}. The increase in summer NO_x flux stimulated by water addition was calculated by multiplying the average summer NO_x flux from the unfertilized sites (3.8 ng NO-N m^{-2} s^{-1}) by 8. This enhanced NO_x flux was then multiplied by number of precipitation events (21 events) during the summer of 1994, and the average summer emissions were recalculated. The summer of 1994 had a typical number of precipitation events as well as an typical amount of rainfall (21 days and 134 mm, Table 6).

4.3. Textural Influences

Data from all replicates on the four unfertilized sites (SL2, SL1, CL and SCL), measured from June 1994 to October 1995, were used to examine the effect of texture on NO_x fluxes. Average soil NO_x fluxes were greatest from SL1 and were lowest from CL ($p < 0.05$, Figure 6). Although NO_x emissions appear to increase with increasing sand content, the sites did not differ significantly from one another.

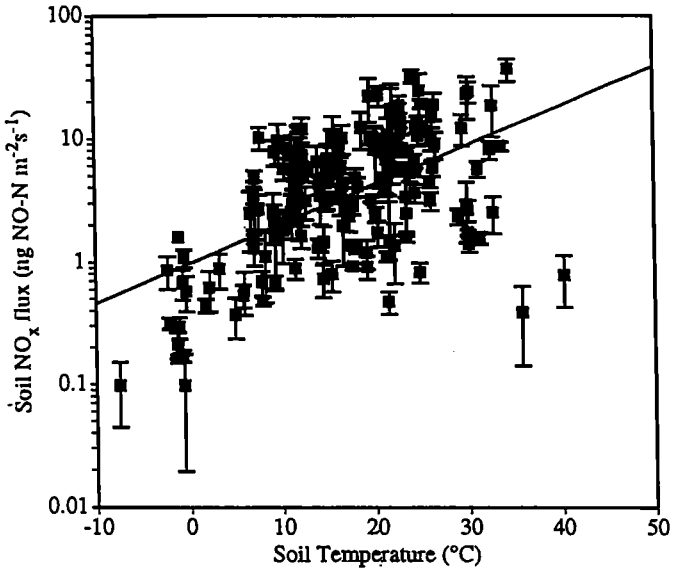


Figure 2. Mean soil NO_x flux (ng NO-N $m^{-2}s^{-1}$) versus soil temperature (in degrees Celsius) for all measurements ($r^2 = 0.31$, and $p < 0.05$).

4.4. Effects of Nitrogen Application From Previous Studies

Annual NO_x fluxes were 1.5 times greater from sites where nitrogen was applied in studies 5 to 12 years earlier (SL2F and SCLF) than from sites of like texture (SL2 and SCL) ($p < 0.05$, Figure 7). The increase was independent of soil texture; SL2 had a sand content of 74%, whereas SCL had a sand content of 58%. The effects of previous nitrogen application may have been complicated by differences in bulk density between the SL2 and SL2F sites. Aside from the nitrogen applications, all other management practices were identical on the paired sites.

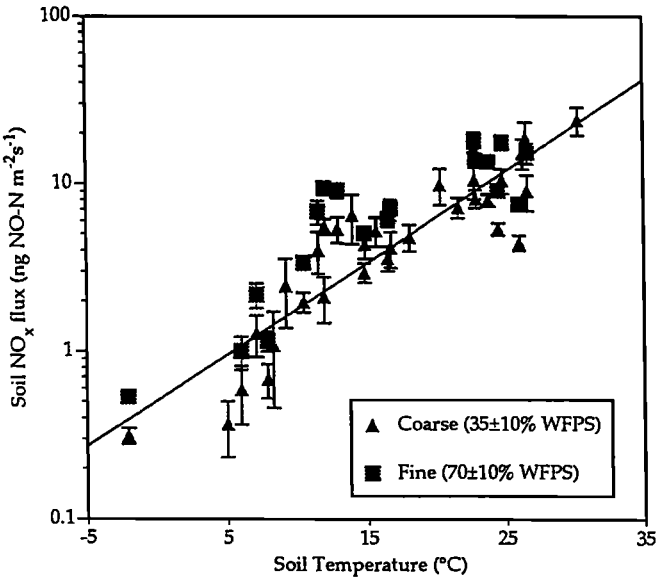
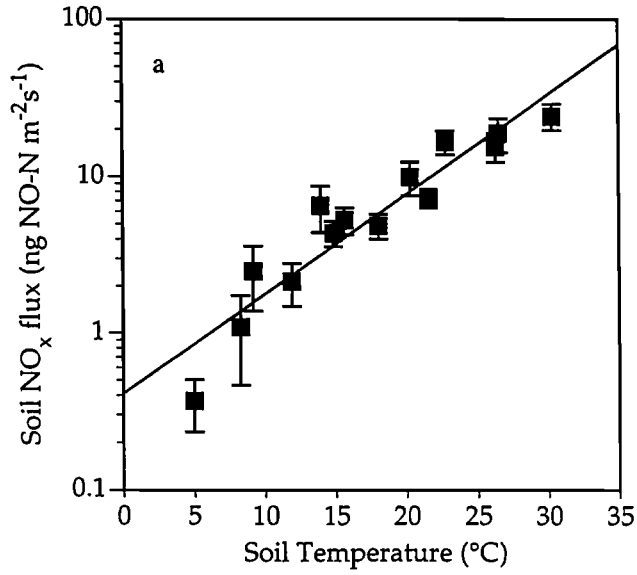


Figure 3. Soil NO_x flux (ng NO-N m^{-2} s^{-1}) versus soil temperature (in degrees Celsius) for the coarse-textured sites (≥ 70% sand and ≤ 15% clay) sites, SL2 and SL1, and the finer-textured (≤ 58% sand and ≥ 24% clay) sites, CL and SCL. The error bars represent standard error $n = 6$ for SL2, SL1, and CL, and $n = 4$ for SCL. Value $r^2 = 0.81$, $p < 0.05$, and $y = \exp(-0.68+0.13(\text{soil } T))$.

5. Discussion

5.1. Seasonal and Annual NO Emissions

Soil NO_x emissions averaged over the year from the unfertilized sites at the CPER were 3.8 ng NO-N m^{-2} s^{-1} (2.7 to 4.1 ng NO-N m^{-2} s^{-1}) (Table 3). Our average included winter measurements, which although it was low, 0.8 ng NO-N m^{-2} s^{-1} (0.2 to 1.5 ng NO-N m^{-2}



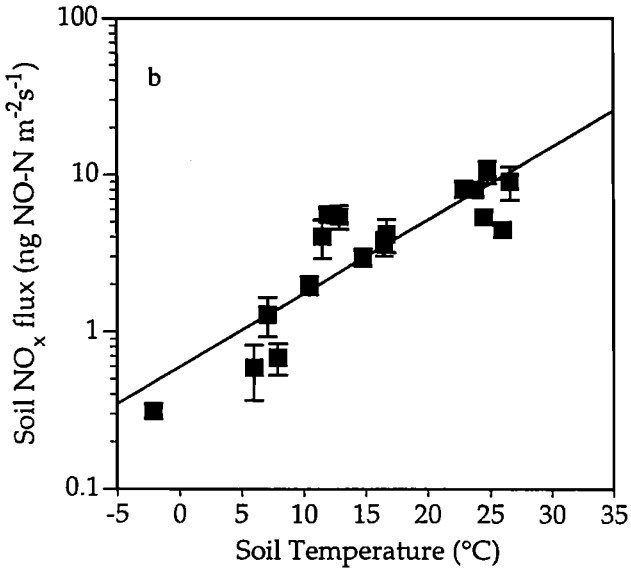


Figure 4. Soil NO_x flux (ng NO-N $m^{-2}s^{-1}$) versus soil temperature (in degrees Celsius) for the coarser-textured (≥ 70% sand and ≤ 15% clay) sites, SL2 and SL1 (a). Value $r^2 = 0.88$, $p < 0.05$, and $y = \exp(-0.90+0.15(\text{soil } T)$. Soil NO flux (ng NO-N $m^{-2}s^{-1}$) versus soil temperature (in degrees Celsius) for the finer-textured (≤ 58% sand, ≥ 24% clay) sites, CL and SCL (b). Fluxes were optimized over water-filled pore space levels of 70±10%. Value $r^2 = 0.76$ and $y = \exp(-0.52+0.11(\text{soil } T))$. Error bars represent the standard error.

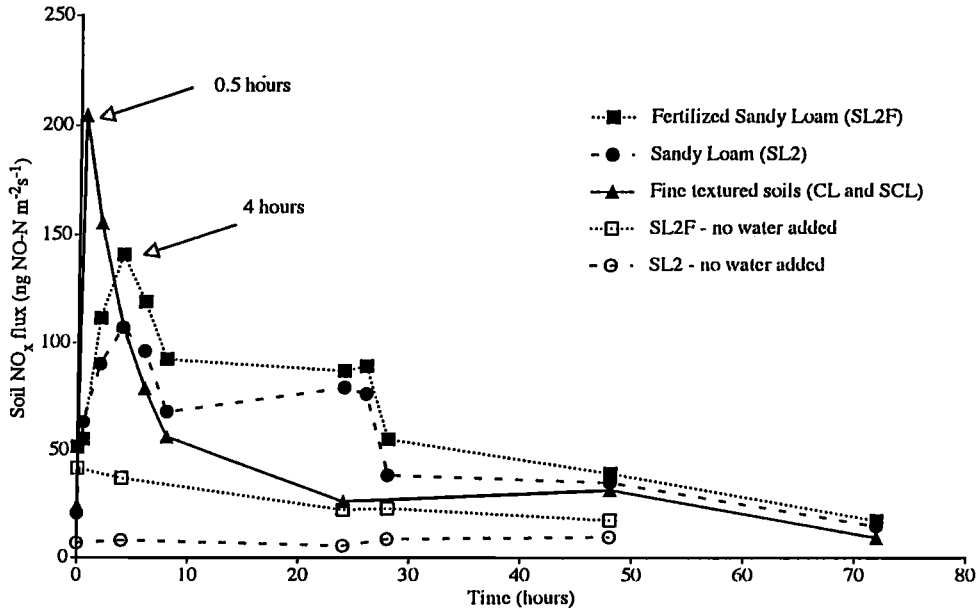


Figure 5. Examples of the short-term effect of water addition on soil NO_x emissions from sites differing in nitrogen content and texture.

s^{-1}), accounted for up to 25% of the NO_x emissions from soils at the CPER.

Williams and Fehsenfeld [1991] measured NO_x emissions from a similar site at the CPER during the growing season. Their average NO_x flux (10 ng NO-N m^{-2} s^{-1}), although it was higher than we measured at the CPER (3.8 ng NO-N m^{-2} s^{-1}), falls within the range of our summertime fluxes (5.4 to 10.5 ng NO-N m^{-2} s^{-1}) (Table 3). The average soil NO_x emissions from the CPER, 3.8 ng NO-N m^{-2} s^{-1}, are consistent with measurements made from other grasslands compiled by *Davidson* [1991], ranging from 1.7 to 10 ng NO-N m^{-2} s^{-1} with an average of 4.2 ng NO-N m^{-2} s^{-1} based on four experiments.

5.2. Influences of Temperature

We found a positive exponential relationship between NO_x and soil temperature at our sites at the CPER ($r^2 = 0.31$ and $p < 0.05$). Similar exponential relationships between soil temperature and NO_x flux have been observed in other studies on grasslands, agricultural sites, and savannas in temperate regions [*Johansson and Granat*, 1984; *Slemr and Seiler*, 1984; *Anderson and Levine*, 1987; *Hutchinson and Brams*, 1992; *Skiba et al.*, 1992; *Yamulki et al.*, 1995]. The relationship between temperature and NO_x emissions was strongest for water contents close to field capacity (35±10% WFPS for coarser-textured soils, $r^2 = 0.88$ and 70±10% for finer-textured soils, $r^2 = 0.76$, Figures 4a and 4b, respectively). Q_{10} values calculated for our NO_x emissions at the CPER were 3.0 for finer-textured soils and were 4.6 for coarser-textured soils. These are higher than those found by *Johansson and Granat* [1984] in savanna systems, where Q_{10} values ranged from 2.7 to 3.6. However, our Q_{10} estimates are consistent with those found for N_2O production from the same soils during nitrification (1.5 to 5) [*Mosier and Parton*, 1985]. Our higher Q_{10} estimates could be due to two factors: (1) We used seasonal data, which may include changes in nutrient availability, thereby adding the effects of seasonal changes in temperature, (2) We included NO_x emissions measured at soil water contents near field capacity thus limiting the interaction of soil water content and temperature.

5.3. Influences of Soil Water

At our sites, the WFPS measured at the time of the flux measurements ranged from 7 to 48% on sand-textured soils and 13 to 79% on finer-textured soils [*Martin*, 1996]. NO_x emissions

Table 4. Initial, Peak, and Integrated NO Fluxes, Field-Wetting Experiment A June 1994

Site	Amount of Water Added, mm	Initial NO Flux,* ng NO-N m^{-2} s^{-1}	Peak NO Flux,* ng NO-N m^{-2} s^{-1}	Integrated NO Flux,† mg N m^{-2} d^{-1}
SL2F	6.4	7.8	37.6	2.4 a
SL2	15.9	5.5	31.6	2.0 a
SL1	22.3	4.1	46.4	2.6 a
CL	22.3	4.6	44.7	1.1 a
CLL	27.9	9.4	51.4	1.9 a

*Initial and peak NO fluxes (ng NO-N m^{-2} s^{-1}) are means of measurements from six replicate anchors at each site.

†NO fluxes (mg NO-N m^{-2} d^{-1}) averaged over 24 hours postwetting are means of measurements from six replicate anchors at each site.

Table 5. Initial, Peak, and Integrated NO Fluxes, Field-Wetting Experiment B

	No Water Added		4.0 mm H_2O		25.5 mm H_2O	
Site	Initial NO Flux*	Integrated NO Flux†	Peak NO Flux*	Integrated NO Flux†	Peak NO Flux*	Integrated NO Flux†
			July 1994			
SL2	8.8	0.2 a	46.9	2.5 b	44.0	2.9 b
SL2F	32.2	0.9 a	54.8	3.2 b	52.6	3.3 b
			August 1995			
SL2	4.0	0.2 a	31.1	1.2 a	31.7	1.3 b
SCL	4.4	0.2 a	38.4	0.7 ab	31.7	0.9 a

*Initial and peak NO fluxes (ng NO-N m^{-2} s^{-1}) are means of six replicate measurements at each site.
†NO fluxes (mg NO-N m^{-2} d^{-1}) averaged over 24 hours postwetting are means of measurements from six replicate anchors at each site. Compared across rows values followed by a different letter differ significantly at the $p < 0.05$ level (analysis of variance with Tukey mean comparison tests).

increased with increasing WFPS until field capacity (32-35% WFPS for the coarser-textured sites, SL2 and SL1, and 66% for the finer-textured sites, CL and SCL) and decreased thereafter. This relationship between NO_x emissions and WFPS has been observed in other studies [*Cardenas et al.*, 1993; *Davidson et al.*, 1991, and 1993; *Davidson*, 1992; *Yamulki et al.*, 1995]. Two possible explanations for the decrease in soil NO_x emissions at higher soil water contents are (1) that the microbial production of NO from nitrification decreases and (2) that diffusion is limited. Microbial production of NO from nitrification is decreasing at higher water contents. Nitrification dominates in soils with low soil water contents (< 60% WFPS and well aerated [*Linn and Doran*, 1984]). Nitrification inhibitors were not used in our study; therefore we cannot accurately assess this mechanism. The diffusion of NO through the soil is slowed at higher soil water contents, decreasing the rate of escape of NO to the surface, as well as increasing the probability of consumption of NO [*Davidson*, 1991]. NO diffuses 10^5 times slower through water than through the equivalent thickness of air [*Galbally*, 1989; *Galbally and Johansson*, 1989].

The relationship between NO_x emissions and soil water content is complicated by the effect of small precipitation events. On average, small events (< 5 mm) dominate the precipitation regime at the CPER, accounting for 87% of the total number of precipitation events annually [*Sala et al.*, 1992]. In this study, water was added to the anchors to simulate rain, caused large but transient pulses of NO_x. NO_x emissions increased to between 22 and 55 ng NO-N m^{-2} s^{-1} from initial values ranging from almost 0.5 to 32 ng NO-N m^{-2} s^{-1}. Peak fluxes were not related to the number of days without rain prior to wetting. The average number of antecedent dry days before a wetting experiment was 4, with the shortest dry period lasting 1 day and the longest lasting 6 days. In contrast, *Davidson* [1992] found a relationship between antecedent dry days and peak flux when there was a prolonged dry season before the wetting [*Davidson*, 1992]. The summer at the CPER is drier than the winter, but even in the summer there are frequent small rain events (twice a week on average). Our data suggest that large short-term (24 hour) pulses caused by wetting events significantly increase summer NO_x fluxes. These precipitation

Table 6. Total Number of Precipitation Events and the Total Amount of Precipitation calculated for Each Month

	1994		1995	
	Total Precipitation Events	Total Precipitation, mm	Total Precipitation Event	Total Precipitation, mm
January	2	2.8	1	0.5
February	5	4.6	1	1
March	10	6.9	2	3.3
April	11	23.8	10	21.6
May	8	22.4	24	181.8
June	5	28.2	16	117.7
July	7	15.8	8	6.6
August	9	12.7	6	10.4
September	4	4.1	7	47.8
October	7	10.7	8	ND*
November	3	1	ND*	ND*
December	1	1.8	ND*	ND*

Calculated from unpublished Long Term Ecological Research data.
*ND indicates no data available.

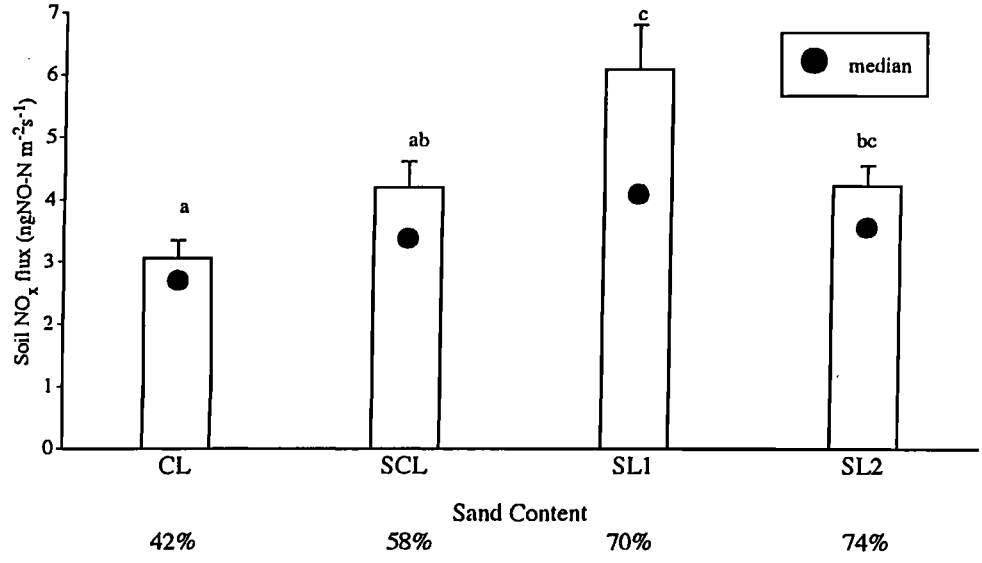


Figure 6. Mean and median soil NO_x fluxes (ng NO-N m^{-2} s^{-1}) for all data collected from the unfertilized sites (SL2, SL1, CL, and SCL). Error bars are standard error (n = 188, 171, 186, and 136, respectively). Means with a different letter differ significantly at the $p < 0.05$ level.

event-driven pulses are often missed by periodic sampling and require quantification in order to obtain an accurate annual estimate of NO_x emissions.

5.4. Influences of Texture

In this study, NO_x emissions were measured from four soil types ranging in texture from sandy loam soil (74% sand and 13% clay) to clay loam soil (42% sand and 30% clay). Although NO_x emissions increase slightly with increasing sand content, only the NO_x emissions from the site with the lowest sand content, CL, were significantly different than those found on the sandy loam sites (SL2 and SL1), 2.7 ng NO-N m^{-2} s^{-1} compared to 3.6 and 4.1 ng NO-N m^{-2} s^{-1} (Table 3). Few studies report soil texture associated with NO_x emissions. However, the trend of higher NO_x emissions from coarser soils was also found by *Bakwin et al.* [1990] in their study in a tropical rainforest. NO_x fluxes from sandy-textured soils were higher than those measured from a fine-textured soil by nearly a factor of 4. A similar trend was also observed on agricultural soils in Scotland [*Skiba et al.*, 1992]. In finer-textured soils, molecular

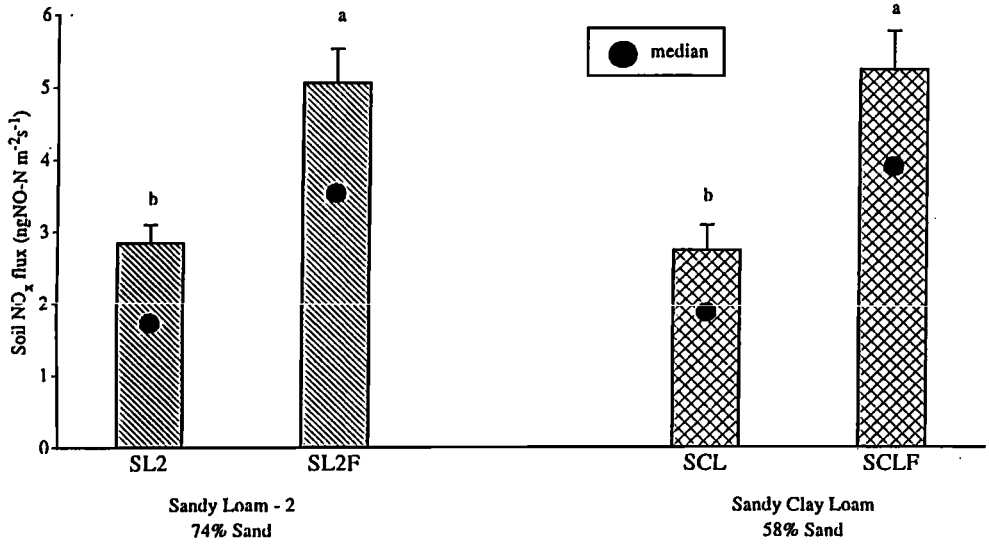


Figure 7. Average and median soil NO_x fluxes (ng NO-N m^{-2} s^{-1}) for data collected on the SL2, SL2F, SCL and SCLF sites. Error bars represent standard errors (n = 104 for SL2; n = 114 for SL2F; n = 76 for SCLF; n = 76 for SCL). . The error bars represent standard error. The data were taken from only the time both fertilized sites were measured (January 19, 1995 to October 11, 1995). Means with different letters differ significantly at the $p < 0.05$ level.

diffusion dominates gas transport, whereas in coarser, sandier soils the importance of advective transport increases [*Livingston and Hutchinson*, 1995]. This has the potential to increase the soil-atmosphere exchange rate several fold over that due to molecular diffusion alone [*Livingston and Hutchinson*, 1995]. The mechanism maintaining high diffusivity through the soil is continuous air-filled porosity [*Livingston and Hutchinson*, 1995; *Bakwin et al.*, 1990]. Therefore, coarser soils tend to be better ventilated, allowing NO_x to escape more freely [*Bakwin et al.*, 1990; *Skiba et al.*, 1992]. The escape efficiency of NO_x is more important than that of other trace gases, such as N_2O and CO_2, because of its high reactivity. A larger range of soil texture would provide more information about the relationship between soil texture and NO_x emissions at the CPER.

5.5. Influences of Nitrogen Application From Previous Studies

Increases in NO_x fluxes have been associated with the application of nitrate, nitrite, and urea ammonium. In contrast with these other studies which observed short-lived increases in NO_x fluxes (a few days, weeks, or months) after nitrogen application, we observed increases in NO_x fluxes 5 and 12 years following nitrogen application. Soil NO_x fluxes from the SCLF site were 1.9 times higher than from the SCL site (5.2 ng NO-N m^{-2} s^{-1} compared to 2.7 ng NO-N m^{-2} s^{-1}). Soil NO_x fluxes from the SL2F site were 1.5 times higher than from the SL2 site (4.3 ng NO-N m^{-2} s^{-1} compared to 2.8 ng NO-N m^{-2} s^{-1}).

The increases in NO_x fluxes mirror increases in N_2O fluxes measured by *Mosier et al.* [1996]. Measurements made from 1991 to 1995 show an increase in soil N_2O emissions, 1.9 to 2.8 μg N m^{-2} h^{-1} from SCL compared to SCLF and 1.7 to 3.0 μg N m^{-2} h^{-1} from SL2 compared to SL2F [*Mosier et al.*, 1996]. These elevated N_2O fluxes from the SL2F site remain despite a large drop in ammonium concentration from 10 μg N g^{-1} in 1991 to back to the level found on the SL2 site (1 μg N g^{-1}) in 1994 [*Mosier et al.*, 1996]. The persistence of elevated fluxes of both NO_x and N_2O indicate that bulk soil nitrogen measurements may not reflect the relative amounts of N turnover needed to sustain these fluxes.

5.6. Annual N Flux

The annual release of NO_x was 1.3 kg N ha^{-1} (0.8 to 1.8 kg N ha^{-1}) for the CPER calculated as a weighted mean of the coarse- and fine-textured soils. Following the calculations of *Mosier et al.* [1996], the annual release of NO_x from the spatial extent of the CPER was calculated using a mean weighted by soil texture (70% coarse-textured soils and 30% fine-textured soils) based on a spatial textural analysis by *Yonker et al.* [1988].

The gaseous NO_x flux is approximately 10 times that of N_2O, 0.14 kg N ha^{-1} yr^{-1} [*Mosier et al.*, 1996], and equivalent to 3 to 4% of the annual net nitrogen mineralization rate [*Schimel et al.*, 1985; D. Valentine, personal communication, 1995]. The NO: N_2O of 10 indicates that nitrification is the dominant pathway of N gas production at the CPER. This is consistent with other controls on the microbial production of N gases. The soil moisture content at the CPER is generally at or below field capacity, the range most suitable for nitrification [*Mosier et al.*, 1996]. The use of the acetelyne inhibition technique in a previous study on N_2O indicated that 60 to 80% of the N_2O production at the CPER was through nitrification [*Parton et al.*, 1988].

Measurements of NO_2 made using the eddy-correlation method from towers at 2 and 6 m heights at the CPER found approximately the same concentrations of NO_x as measured from soil chambers [*Williams et al.*, 1987; *Williams and Fehsenfeld*, 1991; and *Stocker et al.*, 1993]. This suggests two things: (1) chambers which enclose the canopy include the effect of NO_x scrubbing by the canopy, and (2) the NO_x escaping the soil persists in the atmosphere to at least 6 m, well above the plant canopy of the CPER. The annual release of NO_x is a significant nitrogen loss from the ecosystem, representing 20% of the total annual nitrogen inputs, which are low, 6.0 kg N ha^{-1} yr^{-1} wet deposition [recorded by the National Atmospheric Deposition Program (NADP) site at the CPER in 1994 and 1995, NADP/National Trends Network (NTN), (NADP/NTN Coordination Office, Natural Resource Ecology Laboratory, Colorado State University, Fort Collins.)

6. Conclusions

Seasonal NO_x emissions at the CPER ranged from barely detectable fluxes and 1.5 ng NO-N m^{-2} s^{-1} in the winter to highs between 5.4 and 10.5 ng NO-N m^{-2} s^{-1} in the summer. The NO flux is 10 times great than the N_2O flux at the CPER, indicating that nitrification is the dominant pathway for the microbial production of N gases. Winter NO_x emissions added up to 25% to the annual NO_x flux from the CPER. Winter fluxes are often assumed to be zero so they are rarely collected or considered when calculating annual NO_x flux estimates from temperate regions. Water additions performed in concert with the long-term periodic sampling show that wetting of dry soil at the CPER can produce pulses of NO_x that are 8 times greater on average than the fluxes from unamended soils. The inclusion of the elevated NO_x fluxes translates into a 230% increase in the estimate of summer NO_x emissions at the CPER. Water addition experiments or an event-driven sampling scheme in conjunction with year-round periodic sampling is needed to obtain an accurate annual estimate of NO_x fluxes. Temperature was the strongest predictor of NO_x flux from the CPER. Although WFPS alone was a poor predictor of NO_x flux, the NO_x fluxes produced from soils with soil water contents near field capacity exhibit a stronger relationship with temperature. NO_x fluxes increase slightly with increasing sand content but are significantly lower only from the site with the lowest sand content (CL, 42% sand) compared to the sites with the greatest sand content (SL1, 70% sand and SL2, 74% sand). The relation between sand content and NO_x flux may be improved by the addition of sites that extend the range of soil textures. NO_x fluxes from sites on which N was applied in previous studies 5 and 12 years earlier were at least 1.5 times greater than the unamended sites despite the fact that the bulk soil nitrogen contents had returned to the levels of that on the control sites. Nitrogen application has a long lasting effect on gaseous N emissions from the CPER.

The annual soil NO_x emissions calculated as the annual flux estimate from the grassland ecosystems globally contribute 1.0 Tg N per year to the global NO flux, slightly higher than the average global flux estimate (0.6 Tg N y^{-1}) calculated by Davidson [1991]. His estimate was based on only fluxes from four experiments. The value 1.0 Tg N per year represents 5% of the total global NO_x flux (20 Tg N yr^{-1}) [*Davidson*, 1991].

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