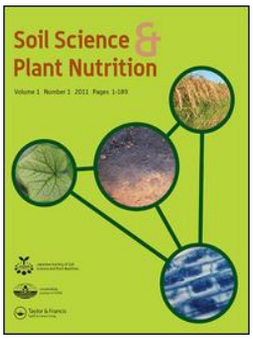

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ORIGINAL ARTICLE

Influence of increasing temperature and nitrogen input on greenhouse gas emissions from a desert steppe soil in Inner Mongolia

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Abstract

We investigated the effect of increasing soil temperature and nitrogen on greenhouse gas (GHG) emissions [carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)] from a desert steppe soil in Inner Mongolia, China. Two temperature levels (heating versus no heating) and two nitrogen (N) fertilizer application levels (0 and 100 kg N ha^{-1} $year^{-1}$) were examined in a complete randomized design with six replications. The GHG surface fluxes and their concentrations in soil (0 to 50 cm) were collected bi-weekly from June 2006 to November 2007. Carbon dioxide and N_2O emissions were not affected by heating or N treatment, but compared with other seasons, CO_2 was higher in summer [average of 29.6 versus 8.6 mg carbon (C) m^{-2} h^{-1} over all other seasons] and N_2O was lower in winter (average of 2.6 versus 4.0 mg N m^{-2} h^{-1} over all other seasons). Desert steppe soil is a CH_4 sink with the highest rate of consumption occurring in summer. Heating decreased CH_4 consumption only in the summer. Increasing surface soil temperature by 1.3°C or applying 100 kg ha^{-1} $year^{-1}$ N fertilizer had no effect on the overall GHG emissions. Seasonal variability in GHG emission reflected changes in temperature and soil moisture content. At an average CH_4 consumption rate of 31.65 μg C m^{-2} h^{-1}, the 30.73 million ha of desert steppe soil in Inner Mongolia can consume (sequestrate) about 85×10^6 kg CH_4-C, an offset equivalent to 711×10^6 kg CO_2-C emissions annually. Thus, desert steppe soil should be considered an important CH_4 sink and its potential in reducing GHG emission and mitigating climate change warrants further investigation.

Key words: Desert steppe, increasing temperature, methane, nitrogen fertilizer application, nitrous oxide.

INTRODUCTION

World-wide increases in greenhouse gas (GHG) emissions are influenced by agriculture and other anthropogenic activities (Moore and Dalva 1993; Mosier *et al.* 1996; Loro *et al.* 1997). Within the agricultural sector, nitrogen (N) fertilizer application has contributed the most to increases in GHG emission as N influences plant growth, carbon (C) and N mineralization/immobilization, biological activity, and conversion of plant residue into soil organic matter (Hyde *et al.* 2006; Maljanen *et al.* 2006; Al-Kaisi *et al.* 2008). However, there are conflicting reports on nitrous oxide (N_2O) and carbon dioxide (CO_2) emission from, and methane (CH_4) consumption by, soil following N fertilizer application (Kowalenko *et al.* 1978; Sitaula *et al.* 2000; Lampe *et al.* 2006), which may be explained by soil moisture content (Liu *et al.* 2008) and temperature (Moore and Dalva 1993).

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Nitrous oxide emissions generally increase as a result of denitrification following an increase in soil moisture content (Maag and Vinther 1996; Schaufler *et al.* 2010) as soil becomes more anaerobic. The soil moisture content has a better relationship with CO_2 and CH_4 emission (Schaufler *et al.* 2010), it has been found that the CO_2 emission was higher between 20 and 60% water-filled pore space, while CH_4 uptake was highest at driest soil moisture condition, and was negatively correlated with soil moisture content.

Increasing temperature resulted in an exponential increase in N_2O emission and linear increase in CH_4 consumption on a shortgrass steppe (Mosier *et al.* 1996) while CO_2 emissions increased 25–40% when soil temperature increased by 5°C (Rustad and Fernandez 1998). Similar emission increases were reported by Zhou *et al.* (2006) in upland tallgrass prairie soil and Lang *et al.* (2011) in grassland soils. Greenhous gas emission could also be impacted indirectly by temperature increases (Gregorich *et al.* 2006) by influencing soil nutrient interactions (Mosier 1998) and availability (Hyde *et al.* 2006). Increases in soil temperature are generally associated with a decrease in moisture content (Harte *et al.* 1995) but, in some cases, warming may increase soil moisture content through accelerated canopy senescence and reduced transpiration losses (Zavaleta *et al.* 2003).

World-wide grassland occupies about 24% of the land area and contributes to 17% of total agricultural GHG emissions (Schils *et al.* 2005). In China, grasslands occupy about 400 million ha. Of this, 78.8 million ha is located in Inner Mongolia with 30.7 million ha (39%) as desert steppe (Han *et al.* 2008).

The desert steppe in Inner Mongolia is the most arid and least productive grassland in China. It has experienced an increase in air temperature of 0.2°C per decade from 1959 to 1994 (Han 2002). Even if GHG concentrations in the atmosphere were to remain at the year 2000 level, increases of about 0.1°C per decade could still be expected (IPCC 2007). Thus, we need to develop management practices that reduce GHG emission and mitigate global climate change.

Most research has focused on the effects of global warming on forestry and rice fields with few studies examining the effects on semi-arid natural grasslands. Others have examined GHG emissions from semi-arid grassland focusing on the effect of different management systems (Mosier *et al.* 1991; Mosier *et al.* 1998; Holst *et al.* 2007). The effects of increased temperature and N fertilizer application have rarely been studied in the arid desert steppe environment where soil processes are severely constrained by limited soil moisture content. Thus, the objectives of this research were to investigate the effect of increasing temperature and N input on GHG emission from a desert steppe. We hypothesized that increasing temperature and N input affects fluxes of CO_2, CH_4 and N_2O, but the effects would be different on the GHG emission. Increasing temperature and N input would increase CO_2 and N_2O emissions, while they would have no effects on the CH_4 emissions.

MATERIALS AND METHODS

Site description

The experiment was conducted from June 2006 to November 2007 in Siziwang Banner, Inner Mongolia, China (41°46′43.6″ N, 111°53′41.7″ E; elevation 1456 m) in the desert steppe. The dominant species are *Stipa breviflora* Griseb., *Artemisia frigida* Willd and *Cleistogenes songorica* (Roshev.) Ohwi. The mean vegetation canopy cover ranged from 17 to 20%. Sheep had grazed the experimental site year-round with the stocking rate at less than 1 sheep ha^{-1} $year^{-1}$ prior to 1988. The grassland had no previous fertilizer application and hydrological manipulations prior to our experiment. In the 1990s, the stocking rate in this region was increased to about 1.5 sheep ha^{-1} year, leading to some degradation reflected in a reduction of average vegetation height from about 10 cm to 5 cm (unpublished data).

The climate is continental with a mean annual precipitation of 183 mm. Over 50% of the precipitation occurs from June to August. Mean annual air temperature is 3.4°C with a 175 day frost-free period. Annual precipitation in 2006 (161 mm) and 2007 (162 mm) was about 88% of the annual mean with most (115 mm in 2006 and 90 mm in 2007) occurring during the growing season (June to August; Fig. 1). The mean annual air temperatures in 2006 (4.0°C) and 2007 (4.1°C) were above the long-term average.

The soil is a Kastanozem [Food and Agricultural Organization (FAO) soil classification] with a sandy loam texture (FAO-UNESCO 1988), pH 8.6 in the surface soil (0–10 cm), increasing to 8.9 at 20–30 cm. Soil organic C and total N was 13.7 and 1.45 g kg^{-1}, respectively, at the soil surface and decreased to 9.70 and 1.01 g kg^{-1}, respectively, at 20–30 cm soil depth. Soil bulk density averaged 1.42 g cm^{-3} in the 0 to 10 cm depth.

Experimental design

The effect of increased soil temperature (by heating) and N enrichment was examined in a 2 (heating versus no heat) × 2 (0 versus 100 kg N ha^{-1} fertilizer application) randomized complete split-plot factorial design with six replications. The main plots (3 m × 4 m) were either heated continuously (H_1) using infrared radiators (Kalglo Electronics, Bethlehem, PA, USA,

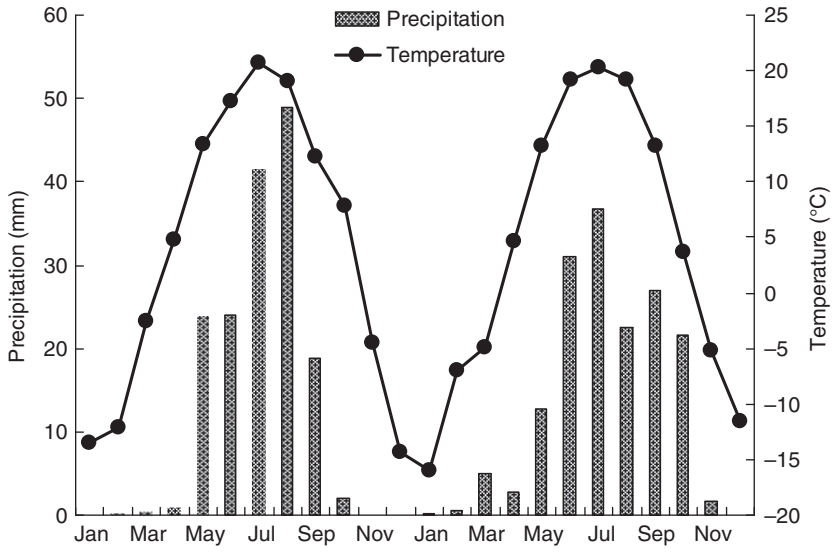

Figure 1 Monthly precipitation (bars) and mean monthly air temperature (line) from January 2006 to December 2007 in a desert steppe. Data was measured at a micro-meteorological station located adjacent to the experimental site.

power: 2000 watts) or left unheated as a control (H_0). The main plots were split into two sub-plots (3 m × 2 m in size) with one sub-plot receiving 100 kg N ha^{-1} $year^{-1}$ fertilizer application [F_1 ammonium nitrate (NH_4NO_3)] and the other receiving no N fertilizer (F_0). In order to simulate enhanced N deposition, the fertilizer application rate was approximately twice as much as the current N deposition rate (Lü and Tian 2007). The fertilizer was broadcast once each year during the rainy season (July) and coordinated with a high probability of rain. A total of 11.2 mm precipitation in six rain events occurred within 12 days following fertilizer application in 2006, and 9 mm precipitation in nine rain events occurred within 12 days in 2007. The heating equipment was mounted 2.25 m aboveground to cover the main plot area. A "dummy" heater with the same shape and size but no heating source was also mounted above the H_0 treatment. The heater increased surface soil temperature on average by 1.3°C, an increase that could be expected as a result of global warming within the current century.

Soil sampling and analyzes

Soil samples were collected from each sub-plot at the beginning of the study (May 2006) and again when the GHG experiment ended (November 2007). Samples were taken at 0–10, 10–20 and 20–30 cm in 2006, and 0–5, 5–15, 15–30 and 30–60 cm depths in 2007. Soil samples were air-dried and coarsely ground to pass a 2-mm sieve mesh; sub-samples were ground to pass a 0.150-mm size sieve. These fine ground soil samples were analyzed for total C (TC) and total N (TN) concentrations using a gas chromatography mass spectrometer (GC-MS CNS) analyzer (Carla Erba® Italy). Inorganic C was measured using a Varian GC-3400 analyzer (Varian Instruments, Walnut Creek, CA). The method was reference to the modified method by Amundson *et al.* (1998). Soil organic carbon (SOC) is the difference between TC and inorganic C. Coarsely ground samples were analyzed for available N [ammonium nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N)], measured by the alkali diffusion method (Khan *et al.* 1997) in 2006 and the potassium chloride (KCl)-extractable method in 2007. In the alkaline method, the available N is liberated by diffusion through 1 M sodium hydroxide (NaOH) from a 2-g soil sample and determined by titration with 0.005 M sulphuric acid (H_2SO_4), the available N can be calculated by the amount of titration solution. For the KCl-extraction methods, 2 M KCl at 1:5 solid to liquid ratio was shaken for 1 h, filtered and the concentration in the extract measured using a Bran+Luebbe AutoAnalyzer III (Bran + Luebbe, Germany). The values of available N obtained in 2006 were converted to equivalent values of NH_4^+-N and NO_3^--N using a regression equation developed between the two based on data (12 data points) from a nearby field.

The coarsely ground soil samples were also used to determine pH and electrical conductivity (EC) from a 1:5 solid to liquid ratio in water. The soil–water slurry was measured with a PHS-3D pH meter (Shanghai Precision and Scientific Instrument Co. Ltd, Shanghai, China) and a DDSJ.308A EC meter (Shanghai Precision and Scientific Instrument Co. Ltd, Shanghai, China). Soil bulk density was measured in May 2006 before

the experiment started. Undisturbed soil cores from each plot were collected in the surface 0–5 cm using steel rings (5 cm diameter) (Drewry *et al.* 1999).

Soil moisture content, temperature and gas measurements

Soil moisture content, temperature and gases were determined in three out of six randomly selected replicates for each treatment at approximately bi-weekly intervals over the duration of the experiment. Soil moisture content sensors (HOBO® model S-SMA-M003, ONSET Computer Corporation, Pullman, WA) were installed at three depths (10, 20 and 30 cm) horizontally in six of 12 main plots (three heated and three no heat) in May 2006 and in the other six plots in May 2007. Soil moisture content readings were logged hourly with a data logger (HOBO® Weather Station Data Logger, model H21-001, ONSET Computer Corporation, Pullman, WA), and downloaded to a computer at two-week intervals.

Temperature and gases were sampled at the soil surface (0 cm) and at 7.5, 15, 30 and 50 cm below the surface. Temperature readings and gas samples below the soil surface were obtained using a depth sampler as described by Hao *et al.* (2001). Briefly, a carrying tube with gas lines and temperature sensor inside and positioned at required depths was installed into the soil profile. Temperature readings were obtained every two weeks using the thermocouples (Digital Omega HH – 25TC, Omega Technology, Stamford, CT). Gas samples were taken without further disturbing soil at the same time temperature readings were taken. A digital thermocouple thermometer was used to measure surface soil temperatures.

Surface gas flux was measured using vented static chambers at opposite corners of the sub-plot. Chamber bases (circular polypropylene collar, 8 cm high and 10.5 cm diameter) were installed 6 cm into the soil, leaving 2 cm above the surface. During sampling, chambers with a volume of 1798 cm^3 (22 cm high by 10.2 cm diameter), were attached to the chamber base. At 0, 10, 20, 30 and 60 min after the chamber placement, 11 mL gas samples were drawn through a septum from the chamber headspace and immediately injected into pre-evacuated vials (Exetainer, Labco Ltd, Buckinghamshire, UK). During the winter months, snow was brushed off the soil surface before surface flux gas collection.

Gas samples from different soil depths (0, 7.5, 15, 30 and 50 cm) were taken at the same time when surface flux samples were taken. Vials containing gas samples were shipped to the Agricultural and Agri-Food Canada, Lethbridge Research Center via express air mail for analysis. Possible leakage from the vials during shipping was checked using vials filled with standard gas and shipped between the experimental site in China and the laboratory in Canada. Gas samples were analyzed for CO_2, CH_4 and N_2O using a gas chromatograph (Varian 3800, Varian Instruments, Walnut Creek, CA) equipped with an electron capture detector (ECD), thermal conductivity detector (TCD) and flame ionization detector (FID).

Data handling and statistical analyzes

Average daily soil moisture content, temperature, and TN, organic C, NO_3^--N and NH_4^+-N concentrations were analyzed using mixed linear models (PROC MIXED, SAS Institute Inc. 2008). Heating, N application, soil depth and their interactions were the fixed effects while replication and its interaction with heating and soil N treatment were the random effects. Soil depth was treated as a repeated variable and analyzed using the covariance structure type that produced the lowest AIC value.

The GHG data were calculated by fitting a second-order polynomial equation to the GHG concentration versus time, and flux levels were calculated by taking derivatives of the second-order polynomial equation (Hao *et al.* 2001). The GHG flux data were converted into mg or $\mu g\,m^{-2}h^{-1}$ and pooled for each season [defined as spring (March to May), summer (June to August), autumn (September to November), and winter (December to February)]. The cumulative annual GHG emissions over the study period were calculated based on bi-weekly flux measurements and assuming that the hourly rates, measured at the time, were representative of the two-week interval. These estimates were summed over the study period and expressed as $kg\,ha^{-1}\,year^{-1}$.

The effects of heating, soil N application, season and their interactions on average gas concentrations and gas flux rates were analyzed as previously described for soil properties. Heating, soil N application, season and their interactions were the fixed effects while replication and its interactions with heating and season were the random effects. When treatment effects were significant ($P < 0.05$), means were separated using least significant difference. Linear regression analyzes were used to investigate the relationship between surface GHG flux and soil temperature and soil moisture content.

RESULTS

Soil responses

The soil temperatures at the surface (0 cm) and in the soil profile (7.5, 15, 30 and 50 cm) ranged from −10 to 40°C. The average temperature in the H_1 treatment was

Table 1 Average desert steppe soil temperature (in °C) in heating (H_1) and no heating (H_0) treatment over the study period in different soil depth

Treatment	Season	Surface (0 cm)	7.5 cm	15 cm	30 cm	50 cm
H_1	Spring	16.7 ± 0.1†	3.7 ± 0.5	4.5 ± 0.4	4.6 ± 0.5	2.7 ± 0.4
	Summer	27.2 ± 0.1	22.7 ± 0.3	21.7 ± 0.1	21.3 ± 0.1	19.8 ± 0.1
	Autumn	19.8 ± 0.1	16.8 ± 0.8	16.2 ± 0.5	16.6 ± 0.3	16.7 ± 0.3
	Winter	−6.3 ± 0.1	−4.4 ± 0.3	−3.9 ± 0.3	−5.4 ± 0.4	−7.7 ± 0.3
H_0	Spring	15.1 ± 0.1	2.8 ± 0.2	3.3 ± 0.8	3.4 ± 0.9	1.6 ± 0.6
	Summer	26.2 ± 0.1	21.9 ± 0.2	20.9 ± 0.1	20.6 ± 0.1	19.2 ± 0.1
	Autumn	18.2 ± 0.1	15.6 ± 0.3	15.1 ± 0.4	15.6 ± 0.2	16.0 ± 0.3
	Winter	−8.0 ± 0.1	−4.6 ± 1.0	−3.8 ± 0.7	−5.7 ± 0.8	−8.3 ± 0.9

†Average and standard error, obtained using bi-weekly measurements over each season.

1.3 and 0.9°C warmer ($P < 0.05$) at the surface and subsurface (7.5–50 cm) than the H_0 treatment (Table 1).

Neither heating nor N fertilizer application had any effect on soil TN, organic C, nitrate ion (NO_3^-) and ammonium ion (NH_4^+) concentrations after two years of treatment ($P > 0.05$). However, the average NO_3^--N and NH_4^+-N concentrations in the H_1 were 10.5 and 7.8% lower than in H_0 treatment. The SOC and TN concentrations were highest in the surface soil, decreased significantly with soil depth and reached their lowest values at 30 to 60 cm depth. Soil NO_3^- and NH_4^+ concentrations from 0 to 30 cm were also higher than from 30 to 60 cm ($P < 0.05$).

The average soil moisture varied from 0.001 to 0.090 $m^3 m^{-3}$, with the surface soil moisture not affected by heating treatment. A significantly higher subsoil moisture content was observed with H_1 (0.08 $m^3 m^{-3}$) than the H_0 control (0.06 $m^3 m^{-3}$) (Fig. 2). Soil moisture was also higher in spring and summer than in autumn, with the value in winter being the lowest at all soil depths.

Greenhouse gas distribution in soil profile

The CO_2 concentration in the soil profile was not affected by heating and N applications, but was affected by season (S), depth (D) and their interactions (S × D). The CO_2 concentration in the soil profile was low (360–410 μL L^{-1}) and varied little in the soil profile during the winter months. The CO_2 concentration peaked during the summer for all treatments, increasing from 448 μL L^{-1} at the soil surface to 1174 μL L^{-1} at 50 cm. In addition, the lowest CO_2 concentration occurred at the surface and increased with soil depth (Table 2).

Methane concentration in the soil profile was not affected by N application, but was affected by heating (H), season (S), depth (D) and the S × D interaction. Methane concentration in the soil profile decreased sharply with soil depth in all treatments, and was higher in winter than the other three seasons at soil depths below 7.5 cm (Table 2).

The N_2O concentration in the soil profile was not affected by heating, N application, season or any interactions among them, but was affected by the sampling depth. The N_2O concentration was < 0.340 μL L^{-1} throughout the whole experimental period (Table 2). The N_2O concentration in summer was lower at the surface (0.319 μL L^{-1}) than at all other depths (0.322–0.324 μL L^{-1}) but not significantly different among soil depths for the other three seasons.

Greenhouse gas surface flux

The CO_2 emissions over the entire study period varied from 0 to 67 mg C $m^{-2} h^{-1}$ (Fig. 3a), and were affected by season (S) and the interaction of season and N (S × F). The average CO_2 emission of 29.6 mg C $m^{-2} h^{-1}$ was higher ($P < 0.05$) in summer (25.6–33.6 mg C $m^{-2} h^{-1}$) than all other seasons (average 8.6 mg C $m^{-2} h^{-1}$, range 4.2–14.2 mg C $m^{-2} h^{-1}$). Heating had no effect ($P > 0.05$) on CO_2 emission, while the CO_2 emission was higher from F_0 control than F_1, but only in summer (Table 3). Cumulative annual CO_2 emissions were not affected ($P > 0.05$) by heating or N application (Table 4).

Soil CH_4 surface flux exhibited seasonal variations that ranged from −120.8 μg C $m^{-2} h^{-1}$ to 0.9 μg C $m^{-2} h^{-1}$ (average −34.8 μg C $m^{-2} h^{-1}$) over the study period (Fig. 3b). The negative values indicate CH_4 consumption while positive values indicate CH_4 emissions. Of the 104 CH_4 surface flux data points collected, 103 were negative (consumption) and only one was positive (emission). The one positive CH_4 flux value was consistent with the high CH_4 concentration in soil profile at that time. The concentration at 50 cm depth was higher than at 30 cm which was responsible for the observed one time emission of CH_4. On average, maximum CH_4 consumption occurred during the summer. Methane consumption in summer was reduced ($P = 0.057$) by the heating treatment. In contrast, in

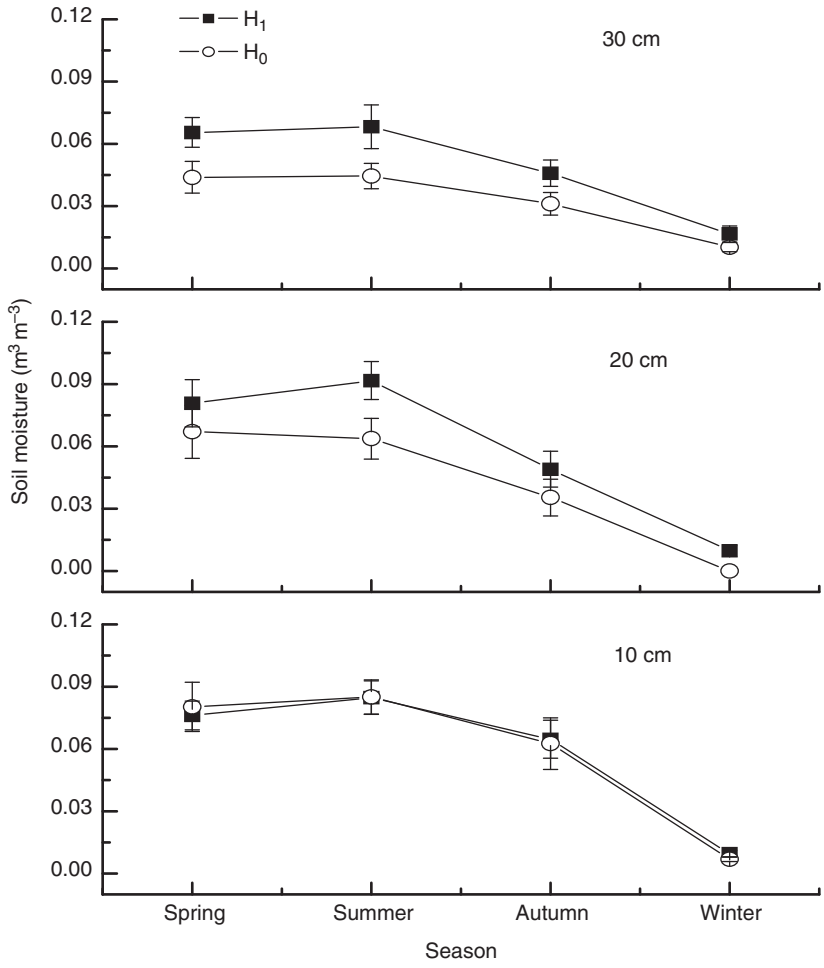

Figure 2 Soil volumetric moisture content in heated (H_1) and unheated (H_0) treatments recorded by sensors that were installed at three depths (10, 20 and 30 cm) during the entire study period.

Table 2 Average carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) concentration (in $\mu L\,L^{-1}$) in soil profile (0, 7.5, 15, 30 and 50 cm) in different seasons over the study period in a desert steppe†

	CO_2				CH_4				N_2O			
	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
H^1	586B	861A	527B	392B	1.03C	1.32BC	1.41B	1.98A	0.337A	0.323A	0.332A	0.331A
H^0	566B	911A	524B	377B	0.95C	1.19BC	1.39B	1.93A	0.330B	0.321A	0.332A	0.331A
Surface												
(0 cm)	404dA	448eA	409cA	410aA	2.04aA	2.00aA	2.00aA	2.00abA	0.325bA	0.319bA	0.330aA	0.327aA
7.5 cm	531cB	791dA	510abB	403aB	1.14bB	1.28bB	1.43bB	2.06aA	0.335aA	0.322abA	0.332aA	0.332aA
15 cm	572cB	898cA	498bB	386aB	0.66cC	1.11cB	1.27cB	2.04abA	0.335aA	0.323aA	0.332aA	0.332aA
30 cm	660abB	1117bA	567bB	360aB	0.54dC	0.95dB	1.15dB	1.92bA	0.338aA	0.324aA	0.336aA	0.332aA
50 cm	713aB	1174aA	641aB	364aC	0.57cdC	0.91dB	1.14dB	1.77cA	0.334aA	0.323aA	0.331aA	0.332aA

†Data in a column followed by different lowercase letters shown significantly different among different depth at $P < 0.1$. Different uppercase letters in row significantly different among different season at $P < 0.05$. H_1, heating treatment; H_0, no heating treatment.

spring CH_4 consumption in the heated treatment was double that of the unheated treatment (Table 3). Methane consumption was not affected ($P > 0.05$) by N application. Nevertheless, the cumulative annual CH_4 consumption/emission was not affected by either heating or N application (Table 4).

The N_2O emissions varied from −0.7 to 10.3 $\mu g\,N\,m^{-2}\,h^{-1}$ (Fig. 3c) but there was no consistent

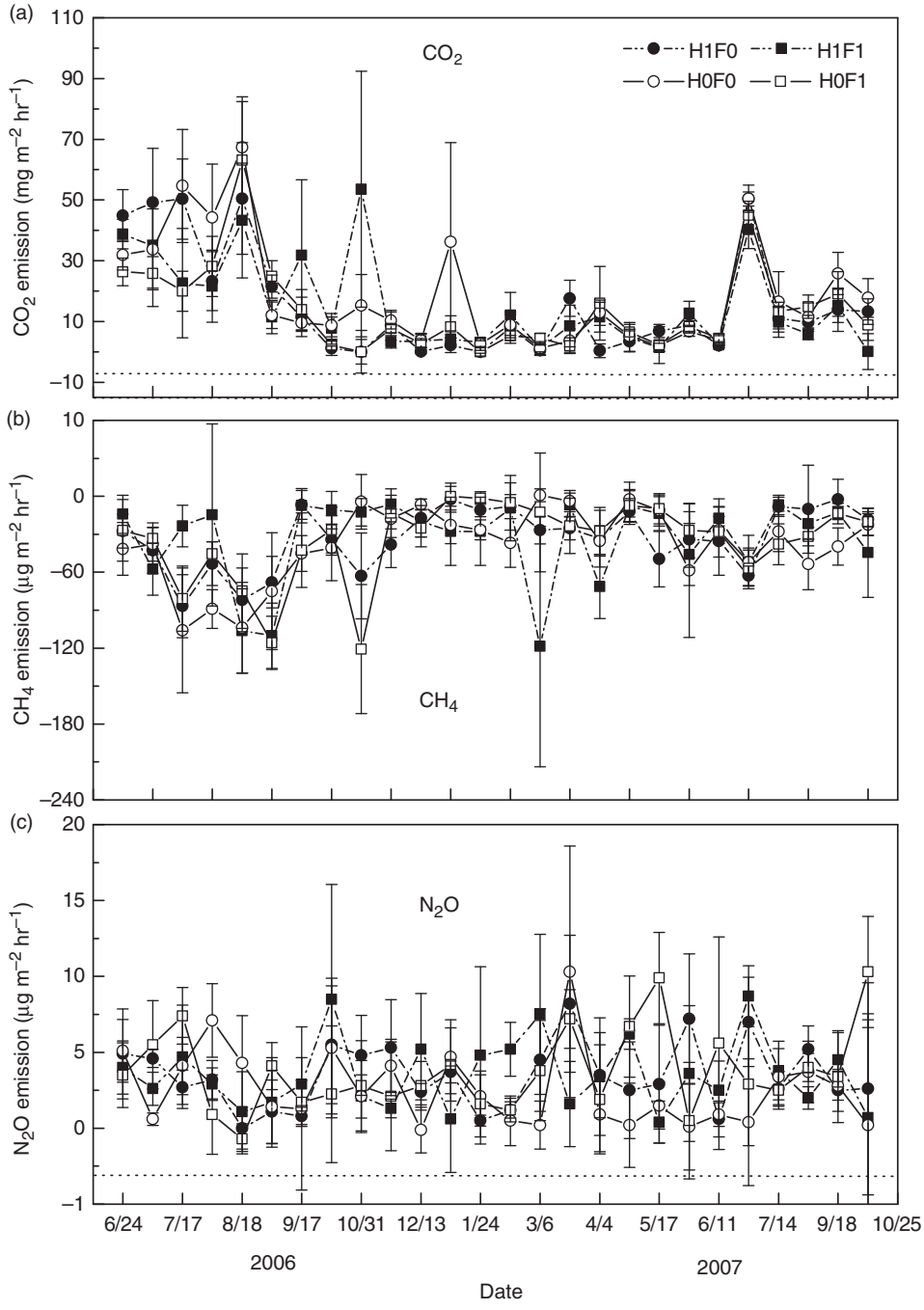

Figure 3 The surface flux of greenhouse gases (a) carbon dioxide (CO_2), (b) methane (CH_4) and (c) nitrous oxide (N_2O) from a desert steppe soil in relation to heating and nitrogen fertilizer treatments (H_1F_0, heating no fertilizer application; H_1F_1, heating fertilizer application; H_0F_0, no heating no fertilizer application; H_0F_1, no heating fertilizer application).

pattern for the four treatments. Heating, N application and their interactions had no significant effect ($P > 0.05$) on the cumulative annual N_2O emissions (Table 4). The overall cumulative N_2O emission was about 0.3 kg N ha^{-1} year^{-1}.

Effects of soil temperature and soil moisture content on greenhouse gas flux rates

Soil temperature and moisture had a positive effect ($P < 0.05$) on CO_2 emission and CH_4 consumption. However, the N_2O emission was unaffected ($P > 0.05$)

Table 3 The effects of heating, soil nitrogen level, season and their interactions on seasonal greenhouse gas flux rates over the whole study period from a desert steppe soil†

	CO_2 ($mg\,cm^{-2}\,h^{-1}$)				CH_4 ($\mu g\ C\ m^{-2}\,h^{-1}$)				N_2O ($\mu g\,N\,m^{-2}\,h^{-1}$)			
Season	H_1	H_0	F_0	F_1	H_1	H_0	F_0	F_1	H_1	H_0	F_0	F_1
Spring	6.4bA	5.9bA	5.7bA	6.6bA	−37.2abB	−18.2aA	−24.3aA	−31.0abA	4.3aA	3.6aA	3.5aA	4.4aA
Summer	28.4aA	30.8aA	33.6aA	25.6aB	−40.2bA	−53.0bB	−52.6bA	−40.6bA	3.5abA	3.4aA	3.4aA	3.6abA
Autumn	13.8bA	12.6bA	12.1bA	14.2bA	−31.1abA	−42.7bA	−34.0abA	−39.8bA	3.2abA	3.1abA	2.8abA	3.5abA
Winter	4.2bA	8.6bA	7.7bA	4.9bA	−15.3aA	−15.5aA	−16.4aA	−14.5aA	3.0bA	2.1bA	1.9bA	3.2bA

†Data in a column followed by different lowercase letters significantly different between different seasons at $P < 0.05$. Uppercase letters significantly different between heating and no heating, fertilizer application and no fertilizer application at $P < 0.05$. H_1, heating treatment; H_0, no heating treatment; F_0, no fertilizer application; F_1, fertilizer $100\,kg\,N\,ha^{-1}$ application.

Table 4 Annual rate of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions over the experimental period from the desert steppe soil†

	CO_2 ($kg\,C\,ha^{-1}\,year^{-1}$)		CH_4 ($kg\,C\,ha^{-1}\,year^{-1}$)		N_2O ($kg\ N\ ha^{-1}\ year^{-1}$)	
Parameter	F_0	F_1	F_0	F_1	F_0	F_1
H_0	1580 ± 217	1163 ± 48	−3.22 ± 0.54	−2.93 ± 0.39	0.220 ± 0.059	0.315 ± 0.055
H_1	1147 ± 125	1245 ± 186	−2.57 ± 0.43	−2.70 ± 0.34	0.296 ± 0.057	0.321 ± 0.081

†H_1, heating; H_0, no heating; F_0, no fertilizer application; F_1, $100\,kg\,N\,ha^{-1}\,year^{-1}$ fertilizer application.

Table 5 Relationships between mean daily greenhouse gas (GHG) flux rates and mean daily soil temperature (7.5 cm), moisture (10 cm) over the two year study period in the desert steppe

GHG flux†	Parameters	Intercept	Slope	r^2	$P > F$
CO_2-C ($mg\,C\,m^{-2}\,h^{-1}$)					
	Soil temperature (°C)	9.33	0.40	0.16	<0.001
	Soil moisture ($m^3\,m^{-3}$)	9.64	132.30	0.20	<0.001
CH_4-C ($\mu g\,C\,m^{-2}\,h^{-1}$)					
	Soil temperature (°C)	−26.71	−0.69	0.06	0.042
	Soil moisture ($m^3\,m^{-3}$)	−27.79	−152.28	0.09	0.006
N_2O-N ($\mu g\,N\,m^{-2}\,h^{-1}$)					
	Soil temperature (°C)	3.04	0.03	0.01	0.311
	Soil moisture ($m^3\,m^{-3}$)	2.89	5.03	0.02	0.266

†There are 104 daily GHG flux data points used in the linear regression model.

by either factor (Table 5). Soil moisture content explained greater variation in CO_2 (20%) and CH_4 flux (9%), while soil temperature explained less (16% for CO_2 and 6% for CH_4, respectively) (Table 5).

DISCUSSION

Effects of nitrogen fertilizer on greenhouse gas emissions

Nitrogen fertilizer application stimulates microbial activity, which produces N_2O and CO_2 production in the soil (Abbasi and Adams 2000; Mosier *et al.* 1996; Maljanen *et al.* 2006). The lack of a response of N_2O and CO_2 emissions from soils in our study indicates that the primary constraint to biological activity in desert steppe soil is not N fertilizer, it maybe correlated with soil moisture content (Yao *et al.* 2010). We did not observe reduced CO_2 emissions that might be associated with depressed microbial activity, which could have resulted from lower soil moisture (Yao *et al.* 2010).

The lack of CH_4 emission response to N fertilizer application in our study was inconsistent with the results of Mosier *et al.* (1996) who reported decreased CH_4 consumption with N application in a shortgrass steppe. The observations of Mosier *et al.* (1996) were the result of methanotroph activities in soil being inhibited by NH_4^+ and NO_3^- (Reay and Nedwell 2004). The relatively

low N application rates and more xeric soil environmental conditions of our study apparently did not produce the conditions that would inhibit methanotroph activities. Also, the weak response of N_2O emission on the N application reflected the lower use efficiency of N fertilizer in relative xeric soil condition. Most N fertilizer maybe lost via volatilization.

Effects of soil moisture content on greenhouse gas emissions

Our observation that soil moisture content below 10 cm depth increased with heating was consistent with that reported by Zavaleta *et al.* (2003). A possible explanation may be that heating increases plant senescence, which reduces water demand by the plants thus reducing water losses from transpiration. This argument is supported by a lower canopy cover (unpublished data) under heating observed in our study.

The largest CO_2 concentrations in the soil profile occurred in summer, corresponding to the highest precipitation and soil moisture content. High soil moisture content promotes the production of CO_2 in soil (Schaufler *et al.* 2010), which is particularly important in the desert steppe where soil moisture content levels are low most of the time. The increases in CO_2 emission, following each precipitation event in summer months, suggests that there is a positive relation between soil moisture content and CO_2 production, similar to upland tallgrass prairie soil reported by Zhou *et al.* (2006).

Carbon dioxide emissions are strongly related to soil moisture content and temperature (Gregorich *et al.* 2006; Liu *et al.* 2008). Soil moisture content affects gas diffusion and microbial activity in the soil (Mosier *et al.* 1996). In the desert steppe, soil moisture content was a more important factor affecting GHG emission than soil temperature as indicated by a higher regression coefficient and greater slope coefficient (Table 5).

Methane consumption is linked with soil moisture content (Liu *et al.* 2008). In our study, heating accelerated snowmelt in spring, which promoted microbial activity and increased CH_4 consumption (Liu *et al.* 2008). The result was consistent with Schaufler *et al.* (2010) in the laboratory incubation study, which concluded that soil moisture content has a positive effect on CH_4 consumption. The inhibition of CH_4 consumption in the summer appears to be caused by an increase of soil moisture content (Le Mer and Roger 2001) that was caused by precipitation.

The relatively low N_2O concentration in the soil profile and surface emission in our study reflects the weak denitrification and nitrification activity in soil, constrained by very low soil moisture content (Mosier *et al.* 1998; Abdalla *et al.* 2009). This was further confirmed by the simultaneous occurrence of low N_2O concentration and low moisture content in the soil profile of our study. Our results are consistent with those reported by Liu *et al.* (2010) from an *Leymus chinensis* typical steppe in Inner Mongolia, China.

Effects of soil temperature on greenhouse gas emissions

Similar to N fertilizer application, heating had no consistent effect on GHG surface emissions or the distribution of their concentrations in the soil profile of the desert steppe. As discussed earlier, GHG emissions are primarily the result of microbial activity, which is limited by soil moisture content conditions in the desert steppe. In our study, the lack of response ($P > 0.05$) to heating might be due to the relatively small temperature increases, which resulted in minimal impact on mineralizable N and C, or on the relatively xeric environment that impedes mineralization. The high CO_2 emission in summer observed in our study corresponded to high microbial (Rustad and Fernandez 1998) and root activities (Rastogi *et al.* 2002) when seasonally higher precipitation and temperature occurs. Zhou *et al.* (2006) reported a 13% increase in CO_2 emissions after elevating the soil temperature by 2°C in a more mesic upland tallgrass prairie (annual precipitation is ~915 mm).

Our study showed that increasing soil temperature by heating had no effect on CH_4 consumption, which is consistent with the study results of Lang *et al.* (2010) in grassland soil. We confirmed again that CH_4 production is less temperature-dependent in grassland soil. This may be the result of the narrow temperature changes between different heat treatments (Lang *et al.* 2010). On average, the CH_4 consumption rate was 31.65 $\mu g\,C\,m^{-2}\,h^{-1}$ from the desert steppe soil in Inner Mongolia. Mosier *et al.* (1996) observed that soil temperature had relatively little effect ($r^2 < 0.30$) on CH_4 consumption in the shortgrass steppe where average annual precipitation was about 350 mm. At a rate of 31.65 $\mu g\,C\,m^{-2}\,h^{-1}$ CH_4 consumption, the 30.73 million ha desert steppe soil in Inner Mongolia could consume (sequestrate) about 85×10^6 kg CH_4-C annually. This is equivalent to offset 711×10^6 kg CO_2-C emission annually since CH_4 global warming potential is 23 times that of CO_2. Thus, the desert steppe soil should be considered as an important CH_4 sink and its potential in mitigating climate change warrant future investigation.

The small variations (ranging from 0.319 to 0.338 $\mu L\,L^{-1}$) in N_2O concentration in the soil profile reflects low microbial activity at low soil moisture content (0.001 to 0.090 $m^3\,m^{-3}$). The N_2O emissions from the

desert steppe, which averaged 3.28 $\mu g\,N\,m^{-2}\,h^{-1}$, are lower than for meadow grassland (~5.7 $\mu g\,N\,m^{-2}\,h^{-1}$) and forest (290 $\mu g\,N\,m^{-2}\,h^{-1}$) soil (Ullah *et al.* 2005; Kanerva *et al.* 2007), but greater than that reported for shortgrass steppe soil (1.9 $\mu g\,N\,m^{-2}\,h^{-1}$; Mosier *et al.* 1997). The highest N_2O emission occurred during the spring, most likely when freeze–thawing occurred (Table 5). Freeze–thaw action can increase the availability of SOC, which promotes microbial activity and increases N_2O emission (Edwards and Killham 1986). Freeze–thaw also enhances nitrification and hence produces more nitrates for denitrification (Mosier *et al.* 1996). The relatively low annual N_2O emission from the desert steppe suggests that it is not a major contributor to global emissions and that global warming is not likely to significantly alter its contribution.

CONCLUSION

We could not detect any effect from warming or applying N fertilizer on GHG emissions from desert steppe soil. The variations in GHG emission associated with occurrence of precipitation events suggests that soil moisture is one of the most limiting factors affecting microbial activities that produce the GHG while temperature may influence indirectly through its impact on soil moisture. Thus, increasing soil temperature by 1.3°C or applying 100 $kg\,ha^{-1}\,year^{-1}$ N fertilizer had no significant effect on the overall GHG emissions. Our result rejected the hypothesis that heating and N application will increase GHG emission.

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