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Original Research

Spatial Variability of CO_2, CH_4, and N_2O Fluxes during Midsummer in the Steppe of Northern China

Jianzhong Cheng[1], Xinqing Lee[1]*, Benny K.G. Theng[2], Bin Fang[1, 3], Fang Yang[1, 3], Bing Wang[1], Like Zhang[1, 3]

[1]State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550002, PR China
[2]Landcare Research Private Bag 11052, Palmerston North 4442, New Zealand
[3]Graduate University of Chinese Academy of Sciences, 100049, Beijing, PR China

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Abstract

Spatial variability is a major source of uncertainty in estimating the fluxes of greenhouse gases between steppe and atmosphere. The fluxes of CO_2, CH_4, and N_2O were carried out between 08:00 and 10:00 h. of the following day during the midsummer period from a transect (area: 5.25×10^6 ha) in the semiarid steppe of northern China, using the dark static chamber technique and gas chromatography. Two land uses were chosen for this study: soils with plant covers and bare soils. Daily average GHG fluxes from the steppe transect were: 1.3×10^5 t C for CO_2, -66.3 t C for CH_4, and 1.1 t N for N_2O. The emission of CO_2 from soils with plant cover was significantly higher ($P < 0.05$) than that from the corresponding bare soils. The canopy effect, however, was observed for neither CH_4 ($P = 0.058$) nor N_2O ($P = 0.772$). Air temperature and relative humidity were the major factors affecting the diurnal variation in site-based CO_2 flux ($P < 0.05$), while soil pH controlled its spatial variation ($P < 0.05$). The spatial uptake of CH_4 correlated negatively with soil total N (TN) content ($P < 0.05$), while the flux of N_2O significantly increased with soil organic carbon ($P = 0.031$) and TN ($P = 0.022$), indicating that soil organic matter is an important factor determining the N_2O flux in the steppe of northern China.

Keywords: carbon cycle, greenhouse gas, climate change, grassland, semiarid region

Introduction

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are major greenhouse gases (GHG) in the atmosphere and significant contributors to global warming. Soils are important sources and sinks of CO_2, CH_4, and N_2O. Since the emission of these gases from soil is a microbially induced process, the variation in flux is influenced by soil temperature, moisture, O_2 concentration, fertilizers, and organic substrate decomposition as well as C and N availability [1, 2]. GHG fluxes show large spatial variability even in terrestrial ecosystems that appear to be homogeneous [3-6]. As a result, there is much uncertainty in estimating the flux of GHG between terrestrial ecosystem and atmosphere.

Grasslands make up about 25% of the Earth's terrestrial ecosystem [7] and hold 10-30% of the global soil carbon stocks [8, 9]. The exchange of CO_2, CH_4, and N_2O between grassland and atmosphere would, therefore, have a significant impact on atmospheric GHG concentrations and the

*e-mail: lee@mail.gyig.ac.cn

Table 1. Location and characteristics of sampling sites.

Symbol	Site name	Plant types	Soil type	Alt. (m)	Long. (E)	Lat. (N)	Date (mm/dd/yyyy)
A	Etuoke Banner	*Stipa bungeana* (St)	Castanozems	1286	107.36	38.86	08/20/2010
B	Otog Front Banner – A	*Peganum harmala* (Ph); *Stipa bungeana* (Sb)	Castanozems	1425	107.23	38.49	08/22/2010
C	Otog Front Banner – B	*Sophora alopecuroides* (Sa)	Aeolian soil	1328	107.56	38.36	08/25/2010
D	Yanchi	*Artemisia scoparia* (As)	Cinnamon soil	1370	106.76	37.53	08/28/2010
E	Tongxin-A	*Peganum harmala; Stipa bungeana*	Cinnamon soil	1362	106.49	37.34	08/30/2010
F	Tongxin-B	*Artemisia scoparia*	Cinnamon soil	1636	106.01	37.10	08/31/2010
G	Haiyuan	*Artemisia scoparia; Pennisetum centrasiaticum* (Pc)	Loess	1728	105.87	36.46	09/04/2010
H	Guyuan	*Pennisetum centrasiaticum*	Loess	1719	106.23	36.02	09/07/2010

Letters in brackets indicate the abbreviation of plant types.

biogeochemical cycling of C and N. Natural grasslands constitute ca 3.9×10^8 ha of China's territory, accounting for about 41% of the total national land area and nearly 12.5% of the world's area. The semiarid steppe in northern China accounts for about 78% of the total grassland area in the country [10]. Recently, climate change has led to rapid loss of soil organic carbon (SOC) in the northern Chinese steppe [11], which, in turn, may exert a significant effect on the GHG budget in the semiarid region.

Previous studies have indicated that spatial patterns in GHG fluxes at a relatively large scale are found to be complicated [3, 4, 6, 12, 13]. CO_2 fluxes from soils have high spatial heterogeneities [4, 12], which is a problem in precisely estimating CO_2 fluxes over large areas. CH_4 and N_2O fluxes also show large spatial variability [3, 4, 13]. Besides such large inconsistent spatial heterogeneities, GHG fluxes have been found to vary relationships with environmental factors. Working in the Xilin river catchment, Yao et al. [5] found that the spatial variability in N_2O and CO_2 emissions was primarily influenced by soil moisture, while in the Qinghai-Tibetan Plateau the flux of CH_4 and N_2O was negatively correlated with soil pH [6]. Similarly, soil moisture primarily controls the spatial variability of N_2O emissions in the semiarid grasslands, but soil temperature is the primary influencing factor for CH_4 uptake [14, 15]. On the other hand, Du et al. [16] did not find a linear relationship between soil moisture and N_2O flux, or between N_2O flux and soil temperature for semiarid grassland soils. This apparent inconsistency may be ascribed to the paucity of data as well as to the introduction of considerable errors when the results were extrapolated to large areas. Thus, the high spatial variability of GHG fluxes, related to influencing factors, requires further research using field measurements over a large scale and across a variety of plant communities [6]. Here we measure the flux of GHG from soils with different plant covers in the semiarid steppe of northern China in order to:

(1) understand its spatial variability
(2) explain the effect of vegetative cover and type on GHG fluxes
(3) determine the major factors affecting GHG emission fluxes

Materials and Methods

Site Description

During the midsummer period from August 20 to September 7, of 2010, we measured the flux of greenhouse gases (CO_2, CH_4, and N_2O) in soils along a transect from southern Inner Mongolia to the whole of Ningxia province (SIMWN); that is, from latitude 36º07′-38º52′ N to longitude 106º14-107º21′ E. The SIMWN transect is located in the semiarid steppe, comprising the pastoral area of Etuoke Banner and Otog Front Banner in Inner Mongolia, and the agro-pastoral ecotone in the Ningxia Hui Autonomous Region. We selected sampling sites in the vicinity of Etuoke Banner, Otog Front Banner, Yanchi, Tongxin, Haiyuan, and Guyuan, denoted by the symbols A to H (Fig. 1, Table 1). The total length of the sampling transect is about 400 km, and each of the plots selected was some distance away from roads, towns, and villages so as to minimize anthropogenic disturbance and influence.

The dominant regional climate is a temperate semiarid continental monsoon, with a short, variable frost-free growing season. The long-term annual air temperature ranges from 6.2 to 9.0ºC with a mean of 7.4ºC, a mean maximum of 21.5ºC in July, and a mean minimum of -8.7ºC in January. The average annual precipitation in the region varies from 220.4 to 439.0 mm, with a multi-year mean of 296.9 mm. Thus, less than 400 mm of annual precipitation is recorded in all of the sampling sites except for the site near Guyuan city. Data provided by meteorological stations along the transect indicate that the annual precipitation is unevenly distributed, with more than 60% of the rainfall falling in the July-September period. The dominant plant

communities at the measurement sites are *Stipa bungeana*, *Peganum harmala*, *Artemisia scoparia*, *Pennisetum centrasiaticum*, and *Sophora alopecuroides*. Each community has fewer than 10 common species, and the plants are generally shorter than 50 cm. The soil types along the SIMWN transect comprise Cinnamon soils, Castanozems, Aeolian soils, and Loess (Fig. 1). The location, altitude, latitude, longitude, and sampling date for each site along the transect are given in Table 1.

Experimental Design

At each sampling site, fluxes of CO_2, CH_4, and N_2O were determined for the bare soil and the corresponding soil covered with 15-30 cm high plants. Measurements were normally carried out from 08:00 h to 10:00 h. of the following day. One set of measurements were done every two hours, using the static black chamber method.

Individual chambers consisted of a fixed stainless steel base (30 cm×30 cm×10 cm) with a U-shaped groove at the top edge, lined with a moveable opaque polyvinyl chloride (PVC) sheet (volume: 0.045 m^3; 30 cm×30 cm×50 cm). Once the cover was placed over the base, the groove was filled with water, acting as an air seal. At 0, 5, 10, 15, and 20 minutes after the groove was sealed, a 30 mL air sample was taken from the chamber and then injected into a 12 mL glass bottle that was vacuum-sealed with a butyl rubber stopper and a plastic cap.

The concentrations of GHG were determined using an Agilent 7890 gas chromatograph (GC) equipped with an automatic injector (Gilson 223), an electron capture detector (ECD) for N_2O, and a flame-ionization detector (FID) for both CH_4 and CO_2 after reduction of the latter gas over a nickel catalyst. More details of the analytical procedure and methods for calculating GHG fluxes have been given by Wang and Wang [17]. Negative flux values indicate uptake by soil of GHC (from the atmosphere), and positive values represent GHG emissions from soil to atmosphere.

Calculation of Global Warming Potential (GWP)

The GWP of each gas is defined in relation to a given weight of CO_2 for a specified time period. According to the

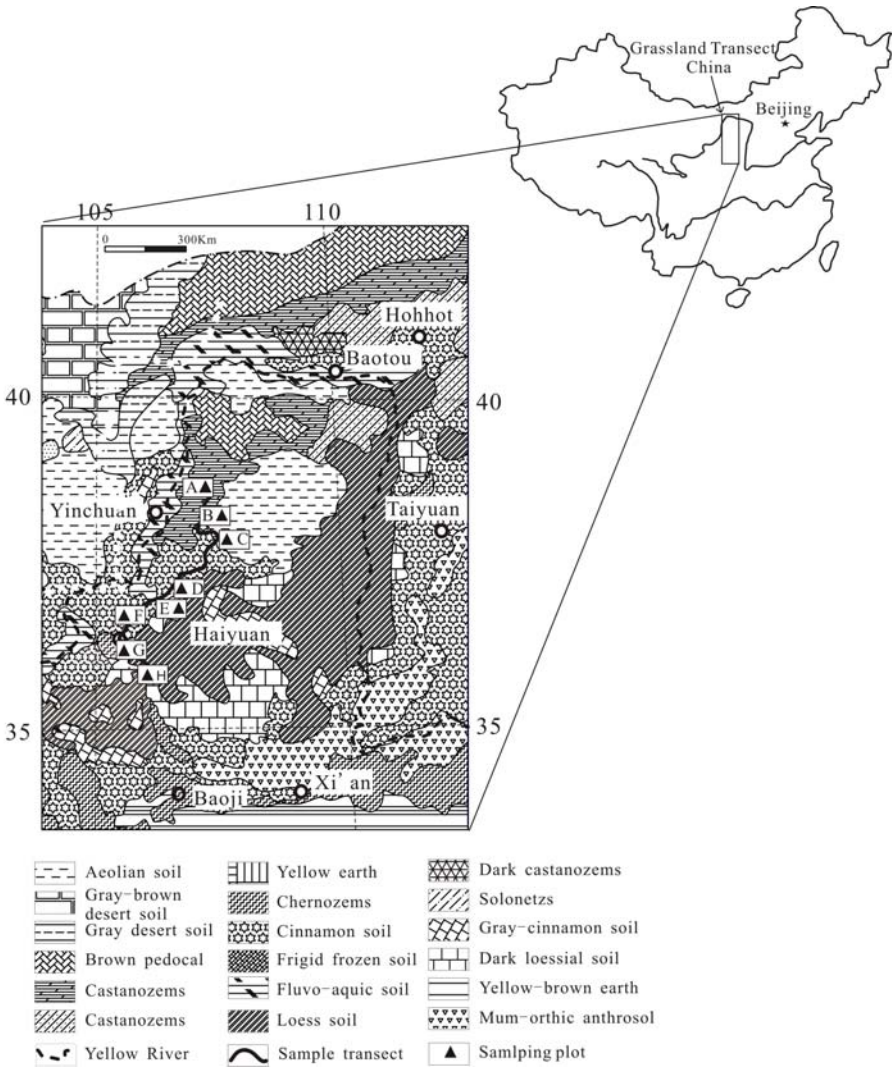

Fig. 1. Location of study sites along a transect from southern Inner Mongolia to the whole of Ningxia province (SIMWN) in northern China.

Table 2. Daily average, minimum, and maximum fluxes of CO_2, CH_4, and N_2O from bare soils and from soils with plant cover along the SIMWN transect.

Fluxes	Bare soil			Plant cover		
	Mean	Min.	Max.	Mean	Min.	Max.
CO_2 flux (mg C $m^{-2}·h^{-1}$)	40.3±16.8	13.0±6.8	68.3±28.3	132.7±56.6	43.7±24.2	344.7±183.7
CH_4 flux (μg C $m^{-2}·h^{-1}$)	-37.0 ±16.2	-67.4 ±19.1	-6.9±9.2	-59.3 ±17.7	-150.5±11.6	-26.5±15.4
N_2O flux (μg N $m^{-2}·h^{-1}$)	2.2±9.7	-2.9±11.6	6.1±5.4	0.3±8.8	-3.1±6.3	5.9±9.4

Numbers represent measured value±standard deviation

fourth Intergovernmental Panel on Climate Change (IPCC) report, the average GWP for CO_2, CH_4, and N_2O are 1, 25, and 298 at a 100 year time horizon, respectively. Using the IPCC definition, the diurnal GWP may be derived from the following equation:

$$GWP = FCO_2+FCH_4\times RFCH_4+FN_2O\times RFN_2O \quad (1)$$

...where FCO_2, FCH_4, and FN_2O are the diurnal fluxes of CO_2, CH_4, and N_2O between grassland ecosystems and the atmosphere, respectively; $RFCH_4$ and RFN_2O are constants indicating radiative forcing of CH_4 and N_2O in terms of a CO_2 equivalent unit, being 25 and 298, respectively, at a 100-year time horizon [18].

Soil Property Measurements

Soil samples (0-10 cm) were collected from each sampling site at the time of gas flux measurement. The soils were crushed, passed through a 100-mesh sieve, and air-dried. The C and N contents of the soils (and plant tissues) were determined using an elemental analyzer (Model: PE 2400II, Perkin Elmer, USA). Soil NH_4^+-N contents were determined by extracting the soils with a 2 M KCl solution (1:5 soil to KCl solution), shaking the suspension for 1 hour, filtering through a Whatman #42 filter paper, and analyzing the filtrate with a UV-VIS spectrophotometer. Soil pH was measured in 1:2.5 soil/water solution using a pH meter with a glass electrode. Gravimetric water contents were measured by drying the samples at 105ºC for 24 h (to constant weight).

Statistical Analyses

Differences and standard deviation in CO_2, CH_4, and N_2O fluxes between soil/plant system and atmosphere were analyzed using a one-way ANOVA method followed by the least significant differences (LSD) test. Linear regression models were used to examine the relationships between CO_2, CH_4, and N_2O fluxes, soil/plant properties, and environmental variables, including air temperature, relative humidity (RH), soil pH, NH_4^+-N, soil organic carbon (SOC), soil total nitrogen (TN), and total plant C and N contents. Multiple regression analysis was also used to assess the relationship between spatial N_2O fluxes and SOC as well as TN. All statistical analyses, based on a significance level of $P < 0.05$, were conducted using the SPSS 13.0 software package (SPSS Inc., Chicago, USA).

Results

Carbon Dioxide

Fig. 2 shows the variations in soil CO_2 emission and air temperature during a representative day for eight sites (A to H) along the SIMWN transect (Fig. 1, Table 1). With the exception of plot A, the diurnal variations in CO_2 emissions closely follow those of air temperature, accounting for 44.4-95.6% of the temporal variance in emissions ($P < 0.05$). Plot A received rain during the night, influencing CO_2 emissions from this site. A significant negative relationship was also observed between diurnal variations in CO_2 fluxes and relative humidity (RH), except for plot A as RH correlated negatively with air temperature across all sites ($R^2 = 0.56$-0.88, $P < 0.05$). Soil CO_2 emissions from all plots showed a similar daily variation, with a minimum flux being measured between 05:00 and 06:00 h, and a maximum flux between 11:00 and 14:00 h. The minimum and maximum values of air temperature and RH were recorded for the same time intervals. The flux of CO_2 emissions, measured between 08:00 and 10:00 h, was close to the daily average value (Fig. 2).

The CO_2 flux from bare soils at all sites along the transect ranged from 13.0 to 68.3 mg C $m^{-2}·h^{-1}$, while the flux from soils with plant cover ranged from 43.7 to 344.7 mg C $m^{-2}·h^{-1}$ (Table 2). Table 3 shows that CO_2 emissions from plots A to H increased in the order A < F < B < E < G < H < C < D, although the measured values for plots A, F, B, E, and G did not significantly differ from each other. Spatial variability of CO_2 emissions within individual plots was low, with coefficients of variation (CV) being 50%, 42%, 40%, 53%, 42%, 41%, 39%, and 15% for CO_2 fluxes for the A, B, C, D, E, F, G, and H plots, respectively. The average CO_2 emission flux of 579.7 mg CO_2 $m^{-2}·h^{-1}$ from the *Artemisia scoparia* and *Pennisetum centrasiaticum* plant

community (As+Pc type) (plots D, F, G, H) was lower than the value of 653.1 mg CO_2 $m^{-2}{\cdot}h^{-1}$, measured for the *Sophora alopecuroides* plant community (Sa type) (plot C), but the difference was not significant (P = 0.555) (Fig. 3). The average CO_2 flux (307.2 mg CO_2 $m^{-2}{\cdot}h^{-1}$) from the *Peganum harmala* and *Stipa bungeana* plant community (Ph+Sb type) (plots A, B, E), however, was significantly lower than that from either the (As+Pc) or (Sa) type.

For all sampling plots, CO_2 emissions were positively and significantly correlated with soil pH (P < 0.05) (Table 4, Fig. 4). The variation in soil pH at 0-10 cm depths could account for 53% of the spatial variation in CO_2 emissions across all investigated sites. The other soil properties, listed in Table 4, were not significantly correlated with spatial CO_2 emissions.

Methane

Soils in the semiarid steppe of northern China act as a net sink for atmospheric CH_4. Methane uptake by bare soils during the study period ranged from -67.4 to -6.9 μg C $m^{-2}{\cdot}h^{-1}$, while that by soils with plant cover ranged from -105.5 to -26.5 μg C $m^{-2}{\cdot}h^{-1}$ (Table 2). The uptake of CH_4 by the eight plots increased in the order: A < D < E < H < G < C < F < B. (Table 3). In each plot, CH_4 uptake was highly variable, with a coefficient of variation (CV) ranging from -93.5% to -8%. The uptake of CH_4 by the (Ph+Sb) plant community type (-92.4±20.3 μg $m^{-2}{\cdot}h^{-1}$) tended to be higher than that by the (S) type (-84.3±16.5 μg $m^{-2}{\cdot}h^{-1}$) but the difference was not significant (P = 0.110). However, the average CH_4 uptake (-67.5±27.8 μg $m^{-2}{\cdot}h^{-1}$)

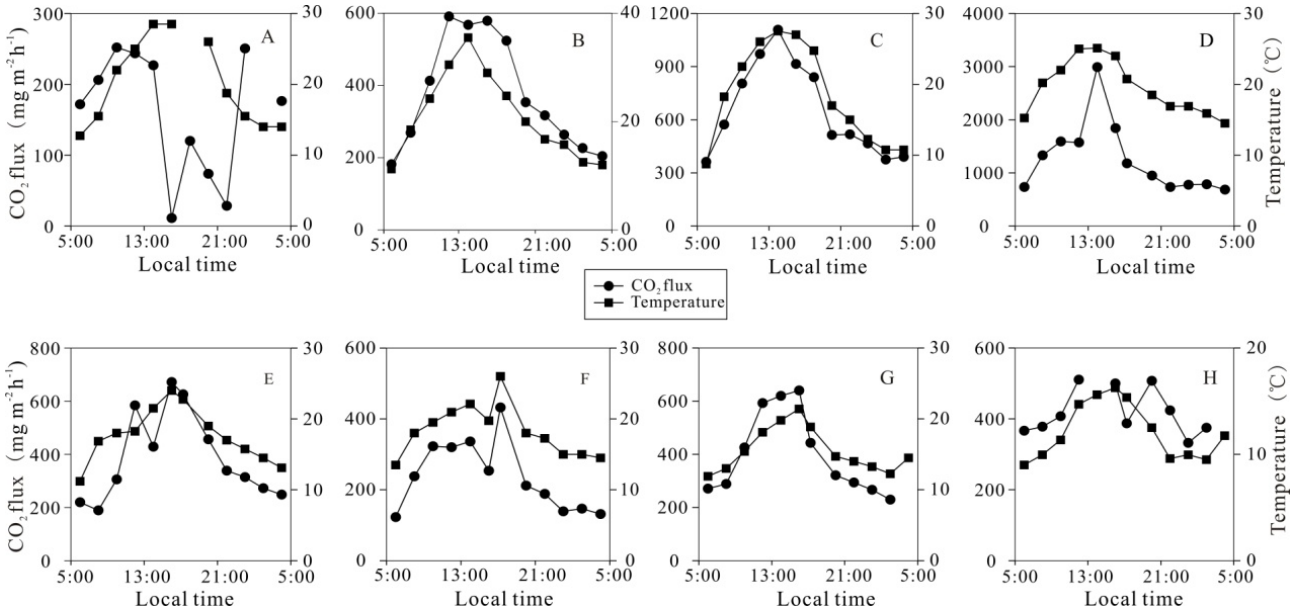

Fig. 2. Diurnal variations of CO_2 flux and air temperature in eight representative sites along the SIMWN transect. The symbols A to H refer to the sampling sites described in Table 1 and in the text.

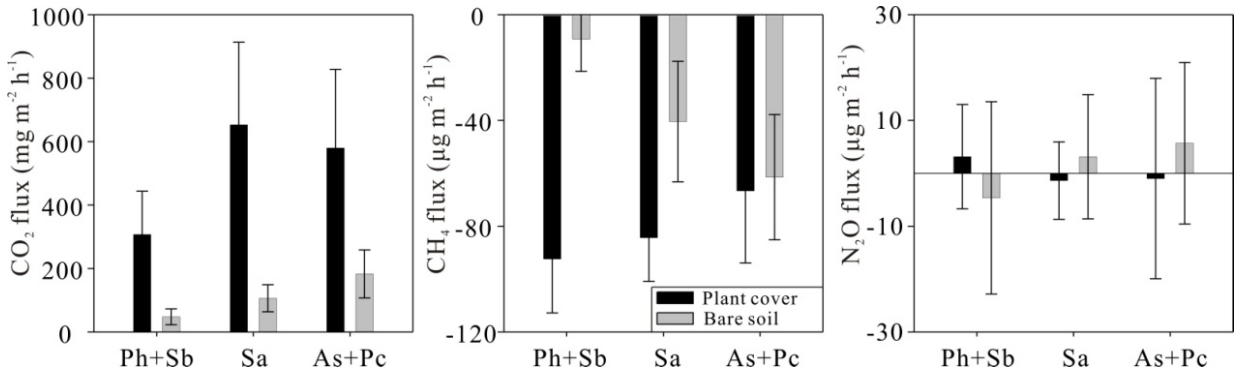

Fig. 3. Daily average CO_2, CH_4, and N_2O fluxes from bare soils and from soils with plant cover along the SIMWN transect. The notations (Ph+Sb), (Sa), and (As+Pc) indicate plant communities dominated by *Peganum harmala* and *Stipa bungeana*, *Sophora alopecuroides*, *Artemisia scoparia*, and *Pennisetum centrasiaticum*, respectively. Plant communities (Ph+Sb), (Sa), and (As+Pc) are associated with sampling plots (A, B, E), (C), and (D, F, G, H), respectively. Error bars indicate standard deviation of fluxes among chambers.

Table 3. Mean fluxes of CO_2 (mg $m^{-2}·h^{-1}$), CH_4 (μg $m^{-2}·h^{-1}$), and N_2O (μg $m^{-2}·h^{-1}$) and soil properties for eight sampling sites (A to H) along the SIMWN transect.

Site	CO_2 flux	CH_4 flux	N_2O flux	AT (ºC)	SW (%)	pH	NH4+-N (mg·kg^{-1})	SOC (g·kg^{-1})	TN (g·kg^{-1})
A	160.1d	-35.3a	0.98ab	20.7	1.9	7.91	12.4	9.8	0.54
B	373.8cd	-200.6e	-0.77ab	20.9	1.2	7.91	15.5	8.4	0.33
C	653.1b	-84.3d	-1.38ab	18.9	4.3	8.36	1.6	11.0	0.52
D	1264.0a	-40.1ab	-4.80b	19.6	2.0	8.24	12.4	9.2	0.43
E	387.9cd	-41.4ab	9.21a	17.7	10.6	7.95	7.0	27.9	0.67
F	236.9cd	-94.6d	-1.16ab	18.3	5.9	7.88	8.1	16.9	0.59
G	399.1cd	-76.7cd	1.04ab	15.6	13.1	7.98	8.7	19.5	0.51
H	418.7bc	-58.5bc	1.09ab	12.1	18.3	7.94	19.8	24.6	0.57

The symbols A to H refer to the sampling sites (plots) as described in Table 1 and in the text.
AT – air temperature; SW – soil water content (0-10 cm depth).
Letters in superscript indicate a significant difference among sites at the 5% level ($P < 0.05$).

Table 4. Correlation coefficients of GHG fluxes against air temperature and some soil/plant factors.

	CO_2 flux	CH_4 flux	N_2O flux
CO_2 flux	1	0.084	-0.545
CH_4 flux	0.084	1	0.374
N_2O flux	-0.545	0.374	1
Air temperature	0.114	-0.336	-0.231
Soil water content	-0.237	0.347	0.423
Soil pH	0.728*	0.226	-0.410
Soil NH_4^+-N	0.141	-0.282	-0.374
Soil organic C	-0.352	0.415	0.752*
Soil total N	-0.464	0.717*	0.781*
Soil C/N	-0.259	0.175	0.586
Plant total C	0.337	-0.095	-0.592
Plant total N	0.105	-0.387	-0.305
Plant C/N	-0.071	0.493	0.381

*indicates the significance level $P < 0.05$.

by the (As+Pc) plant community type was significantly lower than that by the (Ph+Sb) type ($P = 0.000$) or the (Sa) type ($P = 0.010$) (Fig. 3).

Stepwise linear regression analysis indicated that only soil total nitrogen (TN) had a significant influence on the spatial variability of CH_4 flux in the grasslands across the transect. TN could explain 51% of the spatial variance in CH_4 uptake ($P < 0.05$) (Table 4; Fig. 5). In other words, soil temperature, soil pH, soil organic carbon (SOC), C/N ratio, and C and N contents of plant tissues (Table 4) do not appear to be significantly related to spatial CH_4 flux.

Nitrous Oxide

The flux of N_2O (uptake and emission) for the bare soils at all eight sites ranged from -2.9 to 6.1 μg N $m^{-2}·h^{-1}$, which was comparable to the range measured for the soils with plant cover (-3.1 to 5.9 μg N $m^{-2}·h^{-1}$) (Table 2). However, the mean N_2O emissions from the bare soils (2.2±9.7 μg N $m^{-2}·h^{-1}$) was much higher than that from the plant-covered counterparts (0.3±8.8 μg N $m^{-2}·h^{-1}$). Statistical analysis indicated a significant difference in N_2O flux between plot D and plot E ($P = 0.031$), but the values measured for the other six plots were not significantly different (Table 3). Like that for methane, the coefficient of variance (CV) for the N_2O flux, ranging from -13.9 to 23.5%, showed a high heterogeneity among sampling plots. The mean N_2O uptake by the (Sa) plant community type of

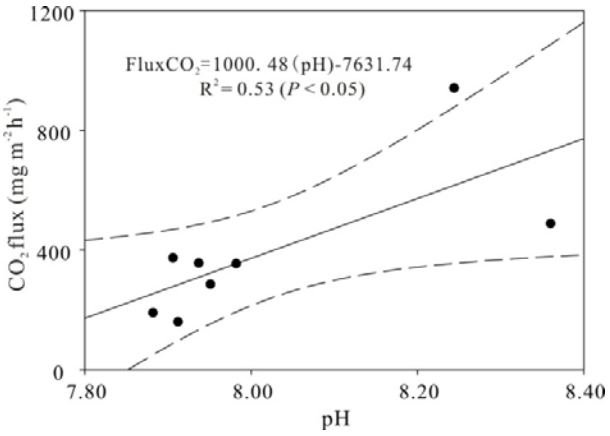

Fig. 4. Correlation of CO_2 emission rates corrected by vegetation coverage with surface soil pH for the eight sites (A to H) along the SIMWN transect. The solid lines were fitted by linear regression, the dotted lines represent the 95% confidence intervals.

Table 5. Comparison of the cumulative CO_2, CH_4, and N_2O fluxes and their global warming potentials (GWPs) (expressed in CO_2-equivalent) between the pastoral area and the agro-pastoral ecotone.

Land use	Vegetation	Area (ha)	CO_2 flux		CH_4 flux		N_2O flux	
			A	B	A	B	A	B
Pastoral area	Bare soil	831,000	8028.4	29437.3	-7.4	-245.8	0.44	208.0
	Plant cover	1,939,000	61770.2	226390.7	-27.6	-919.1	0.15	69.3
Agro-pastoral ecotone	Bare soil	744,000	7187.9	26355.5	-6.6	-220.1	0.40	186.2
	Plant cover	1,736,000	55303.3	202778.7	-24.7	-822.9	0.13	62.1

A – cumulative GHG fluxes (t CO_2-C d^{-1}, t CH_4-C d^{-1}, and t N_2O-N d^{-1}, respectively), B – cumulative GWP (t C-eq·d^{-1})

1.4±7.3 μg $m^{-2}·h^{-1}$ was higher than that by (As+Pc) type (1.0±18.5 μg $m^{-2}·h^{-1}$), but the difference was not significant ($P > 0.05$) (Fig. 3).

The average N_2O flux for all sites was positively and significantly correlated with both SOC and TN (Table 4, Fig. 6), with SOC accounting for 57% of the spatial variation in N_2O emissions ($P < 0.05$). Thus, a multiple linear regression model incorporating both SOC and TN led to a significant improvement in explaining the variability in N_2O emissions ($R^2 = 0.67$). The other soil factors in Table 4 did not appear to have a significant effect on N_2O fluxes.

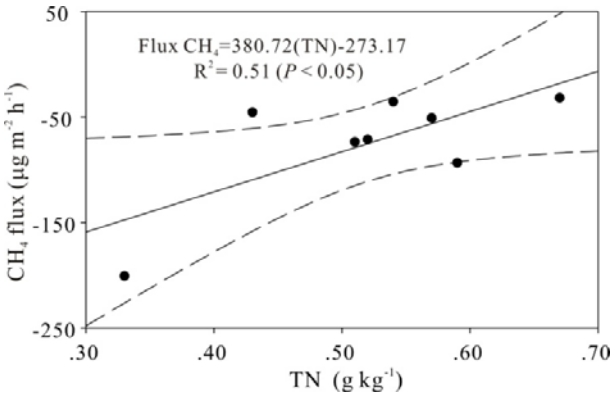

Fig. 5. Correlation of CH_4 flux rates corrected by vegetation coverage with soil total nitrogen (TN) for the eight sites (A to H) along the SIMWN transect. The solid lines were fitted by linear regression, the dotted lines represent the 95% confidence intervals.

Discussion

Regional Greenhouse gas Fluxes and Global Warming Potential

The daily average fluxes of GHG for the bare soils along the SIMWN transect were 40.3±16.8 mg CO_2-C $m^{-2}·h^{-1}$, -37.0±16.2 μg CH_4-C $m^{-2}·h^{-1}$, and 2.2±9.7 μg N_2O-N $m^{-2}·h^{-1}$. while the values for the soils with plant cover were 132.7±56.6 mg CO_2-C $m^{-2}·h^{-1}$, -59.3±17.7 μg CH_4-C $m^{-2}·h^{-1}$, and 0.3±8.8 μg N_2O-N $m^{-2}·h^{-1}$ (Table 2). In the semiarid steppe of northern China, the pastoral area covers $2.77×10^6$ ha and the agro-pastoral ecotone amounts to $2.48×10^6$ ha [19]. Assuming that our measurements are representative of regional GHG fluxes, and that 70% of the sites had a plant cover while 30% were bare during summer [20, 21], the cumulative GHG fluxes amounted to $7.0×10^4$ t CO_2-C, -35.0 t CH_4-C, and 0.6 t N_2O-N per day for the pastoral

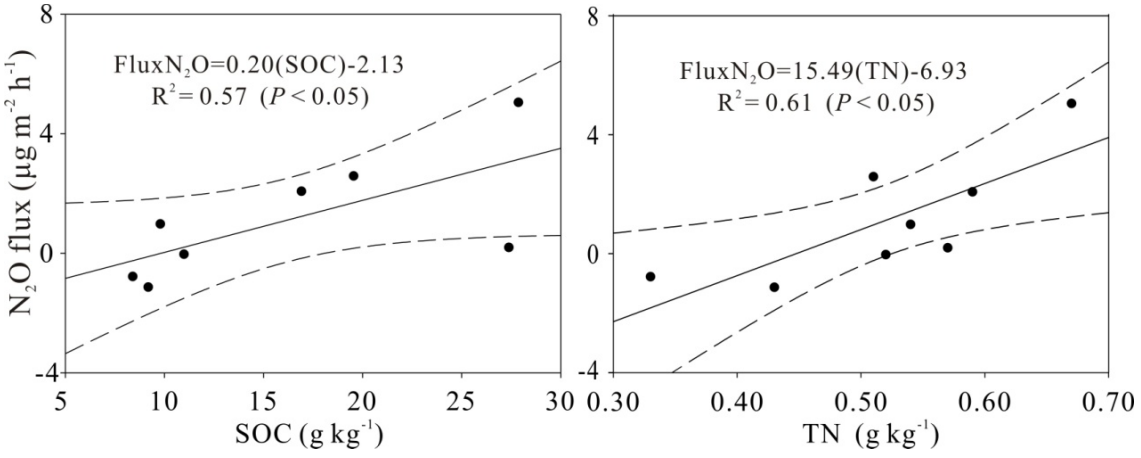

Fig. 6. Correlation of N_2O flux rates corrected by vegetation coverage with soil organic carbon (SOC) and soil total nitrogen (TN) for the eight sites (A to H) along the SIMWN transect. The solid lines were fitted by linear regression, the dotted lines represent the 95% confidence intervals.

area, while the corresponding values for the agro-pastoral ecotone were 6.2×10^4 t CO_2-C, -31.3 t CH_4-C, and 0.5 t N_2O-N per day (Table 5).

The daily average flux in CO_2 equivalents is estimated for each GHG based on global warming potentials (GWP). According to equation (1), the GWP from the pastoral area during the measurement period (8.9×10^2 t C-eq) is larger than that from the agro-pastoral ecotone (7.9×10^2 t C-eq). Thus, in terms of GWP the pastoral area exerts a greater mitigation effect than the agro-pastoral ecotone if only CH_4 and N_2O are considered (Table 5). When the emission of CO_2 is taken into account, however, the contribution of the pastoral area to the regional GWP (2.6×10^5 t C-eq·d^{-1}) during the measurement period is larger than that of the agro-pastoral ecotone (2.3×10^5 t C-eq·d^{-1}) (Table 5). As we did not consider the landscape (topography, soil texture) and seasonal amplitudes of GHG fluxes, the above estimate does not necessarily represent annual GWP, although it provides insight into the relative contribution of CO_2, CH_4, and N_2O to the GHG budget in the region investigated. Given its huge extent, however, the semiarid steppe in northern China would be expected to act as a net carbon source, at least in midsummer.

Effect of Vegetative Cover and Type on GHG Fluxes

Vegetation could affect ecosystem respiration by influencing plant community microclimate and structure, the quantity and quality of detritus supplied to the soil, and the overall rate of plant and soil respiration. Regardless of location along the transect, CO_2 emissions were significantly higher from soils with plant cover than that from bare soils ($P = 0.023$) (Table 2, Fig. 3). This finding is consistent with the suggestion that the rhizosphere of plant-covered soils is the site of high microbial activity [22, 23], and that most of the root respiration stems from recently fixed carbon associated with above-ground plant growth and below-ground root growth [24]. Assuming that plant respiration (R_{plant}) equals ecosystem (plant community) respiration (R_{eco}) minus bare soil respiration (R_{soil}), we estimate that the contribution of R_{plant} to R_{eco} for the plant community types (Ph+Sb), (Sa), and (As+Pc) during the measurement period was 84.5, 83.7, and 68.5%, respectively (Fig. 3). These percentages are consistent with the range of values reported by other investigators [25, 26].

In agreement with Schimel [27], more CH_4 was taken up by soils with vegetative cover (canopy) along the transect than by the corresponding bare soils (Table 2, Fig. 3). This finding indicates that the plant canopy acts as a physical barrier to CH_4 diffusion (from soil to atmosphere). The presence of plant cover also enhances the probability that CH_4 would be oxidized before being emitted to the atmosphere, as rhizospheric oxidation may contribute more than 80% to total oxidation in soil-plant systems [4]. Since such constraints do not apply to bare soils, relatively less methane was taken up in the absence of plant cover. Further, the oxygen released into the rhizosphere (by plant roots) would be consumed by methane-oxidizing bacteria, as a result of which methanogenesis is inhibited [28].

Several studies [29-31] have indicated that plants can contribute appreciably to the emission of N_2O from soil-plant systems. The N_2O emitted from above-ground plant biomass may comprise a mixture of phytogenic N_2O and N_2O produced by soil microorganisms but transported by plants [32]. Our results, however, suggest that different plant community types have different effects on N_2O emission (Fig. 3). But in general, the plant exerts a constraining influence on cumulative N_2O fluxes from the whole of semiarid steppe, which is in agreement with other studies [33, 34]. The flux of N_2O increased in the presence of plants, particularly when soil moisture was relatively high, and when soil temperature exceeded 19ºC [35]. Under such conditions, the parechymal system can actively transport oxygen from shoots to roots as well as gases from soil to atmosphere [34], whereas N_2O is largely emitted from soil to atmosphere when soil moisture is low [33].

As all of our sampling plots are located in the semiarid region, soil gravimetric water content was low (1.2-18.3% w/w, while nearly ⅔ of the grassland sites contain less than 6% w/w moisture) (Table 3). Under these conditions, N_2O is consumed by the plant community, as Donoso et al. [36] and Li et al. [37] have previously reported. Secondly, plants alter the community structure of soil microorganisms, and denitrification in the rhizosphere is enhanced by the increase in carbon stock from root decomposition. As a result, consumption of N_2O increases, as does N_2 formation through denitrification [32].

Environmental Factors Influencing GHG Fluxes

In the steppe of northern China, air temperature and relative humidity were the main factors regulating the diurnal variation of CO_2 fluxes (Fig. 2) except for plot A, where some rain fell during the night of measurement. Precipitation strongly stimulates soil CO_2 fluxes in surface layers where biological activity is concentrated by a "drying and rewetting effect" [38]. Similarly, CO_2 emissions increase with a rise in temperature. This effect is associated with an increase in root respiration and microbially induced mineralization of soil organic matter [39]. Diurnal variations in temperature, and their effect on CO_2 emissions, should therefore be considered in modeling CO_2 sources and sinks [40]. We might also add that global warming would increase CO_2 emissions from soils and accelerate the depletion of SOC.

The pH of surface soils and its variation between single measurement points at each site showed a significant positive correlation with CO_2 emissions (Table 4, Fig. 4) in accord with previous results for other soil types [41, 42]. CO_2 emissions increased with soil pH, presumably because of its positive effect of pH on the growth and proliferation of soil microbes.

No significant correlation ($P < 0.05$) was found between SOC and CH_4 fluxes with Pearson's coefficient being 0.415 in general (Table 4). A significant negative relationship, however, was observed between TN and spatial CH_4 fluxes for the semiarid steppe in northern China (Fig. 5), suggesting that the higher the TN the lower the uptake of atmospheric CH_4 by soil. A similar relationship has been reported for forest soils [43], agricultural soils [44], and grassland soils [45].

Previous studies [46, 47] have shown that the concentration of N_2O in various soils, derived from nitrification and denitrification, is positively correlated with SOC and TN. Thus, soils with high SOC and TN contents generally show high N_2O fluxes. We have found similarly for the semiarid grasslands in northern China in that the relationship of N_2O flux with SOC and TN had correlation coefficients of 0.752 ($P = 0.031$) and 0.781 ($P = 0.022$), respectively (Table 4, Fig. 6). Since for many surface soils SOC is proportional to TN, the relationship between N_2O flux and SOC is very similar to that between N_2O flux and TN. Our measurements indicate that soil organic matter is very important in determining the magnitude of the spatial N_2O flux, at least in the semiarid steppe.

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