Atmospheric Environment 67 (2013) 170–176

Contents lists available at SciVerse ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Contribution of grazing to soil atmosphere CH_4 exchange during the growing season in a continental steppe

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HIGHLIGHTS

► Soil CH_4 uptakes during the growing season were affected by the types of steppe.
► Overgrazing has exerted a considerable negative impact on CH_4 uptake.
► CH_4 uptakes were mainly driven by stocking rate, soil temperature and moisture.

ARTICLE INFO

Article history:
Received 29 February 2012
Received in revised form
14 October 2012
Accepted 26 October 2012

Keywords:
Methane uptake
Stocking rate
Growing season
Continental steppe
Inner Mongolia

ABSTRACT

Degradation of steppes induced by overgrazing may affect the uptake of atmospheric methane (CH_4) by soil sinks. However, uncertainty is associated with the very limited knowledge of gas fluxes in rapidly degrading steppe. In this study, we investigated the effects of grazing on CH_4 uptake during the growing season in three types of steppe (meadow steppe, typical steppe and desert steppe and) in Inner Mongolia, China, to quantify and compare CH_4 uptake in steppe ecosystems under different grazing management conditions. The CH_4 fluxes were measured using an automatic cavity ring-down spectrophotometer at three steppe locations that differed primarily in grazing intensity. The results indicated that steppe soils were CH_4 sinks throughout the growing season. CH_4 uptake at all sites averaged 7.98 kg CH_4-C ha^{-1} yr^{-1} (ranging from 1.53 to 18.74 kg CH_4-C ha^{-1} yr^{-1}), of which approximately 43.8% occurred in the desert steppe. CH_4 uptake in the desert steppe increased 20.4% and 51.2% compared with the typical steppe and meadow steppe, respectively. Light grazing (LG) of steppe did not significantly change CH_4 uptake compared with un-grazed (UG) steppe, but moderate and heavy grazing (MG, HG) reduced CH_4 uptake significantly (by 6.8–37.9%, $P < 0.05$). These findings imply that reducing the grazing pressure on steppe would help increase the atmospheric CH_4 sinks in steppe soils. Our results suggest that HG exerts a considerable negative impact on CH_4 uptake in a continental steppe. Further studies involving year-round, intensive measurements of CH_4 uptake are needed.

1. Introduction

Temperate steppes are one of the largest terrestrial biomes worldwide, and are widely used for grazing and economic activities related to livestock production. Chinese steppes cover 41.7% of China's land area, and are distributed mainly in Inner Mongolia, Xinjiang, Gansu, and the Qinghai-Tibet plateau (NSBC, 2002). The Inner Mongolian steppe is part of a continuous expanse of approximately 12.5 million km^2 of temperate grasslands, which is more than 8% of the earth's land surface area. Human activities (e.g. reclamation, collecting herbs, overgrazing) led to a strong reduction in the extent of temperate steppe in areas that traditionally (i.e. decades ago) hosted extensive livestock production (Steinfeld et al., 2006).

Approximately 28% of the Eurasian steppe and 91% of the North American prairies (the two historically dominant temperate grassland ecosystems) have already been converted to arable land or is used for other purposes (White et al., 2000), such as grazing. Much of the remaining steppe is threatened by increased grazing

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http://dx.doi.org/10.1016/j.atmosenv.2012.10.037

pressure due to rising demand for livestock products. The number of total livestock grew nearly 12-fold from 1947 to 2006 in Inner Mongolia (Bureau of Statistics of Inner Mongol, 2007). This unprecedented increase in livestock numbers has led to severe grassland degradation that involves changes in nutrient pools and fluxes (Ross et al., 1999; Augustine and Frank, 2001), vegetation cover (Paruelo et al., 2001), plant community composition (Li, 2001; Zhang and Skarpe, 1996), and in the worst case even to desertification (Li et al., 2000).

Continental steppe soils have the potential to exchange considerable amounts of methane (CH_4). Although CH_4 flux from steppe soils are usually an order of magnitude smaller than carbon dioxide (CO_2) flux, the global warming potential on a molar basis of CH_4 over a 100-year timeframe, is 25 times greater than CO_2 (IPCC, 2007). Steppes are commonly a sink of CH_4 due to their well-aerated mineral soils supporting methanotrophic activity. However, occasional CH_4 emission from semi-arid steppe have been reported during periods when CH_4 consumption was either limited or exceeded by CH_4 production from anaerobic microsites in a predominantly aerated soil (e.g. high soil humidity) or under extremely low soil moisture conditions (Wang et al., 2009; Liu et al., 2007).

Most studies of soil-atmospheric CH_4 exchange in Inner Mongolia have been conducted in typical steppe regions (Wang et al., 2005; Liu et al., 2007; Holst et al., 2008; Wang et al., 2009; Chen et al., 2011a, b). To our knowledge, few reports are available on soil-atmospheric CH_4 exchanges in the entire Inner Mongolian steppe ecosystem. Incomplete consideration of the entire steppe region in previous studies may lead to high uncertainty when the overall contribution of steppe ecosystems to the greenhouse effect is assessed. The aims of this study were to 1) investigate soil-atmosphere CH_4 exchange during the growing season in different types of steppe ecosystem in Inner Mongolia; 2) assess the effects of stocking rate on dynamic variation in CH_4 fluxes; and 3) evaluate the relationship between CH_4 uptake and soil temperature and moisture. Our hypotheses are that 1) grazing management and type of steppe affect CH_4 uptake capacity of steppe soils during the growing season, and 2) the moisture content and temperature of soil are the principal factors controlling CH_4 uptake.

2. Materials and methods

2.1. Site description

The experiment selected three types of steppe (desert steppe, typical steppe and meadow steppe) located in Inner Mongolia. These sites are the main zonal grassland types, which are used mainly as natural grazing lands providing forage for sheep in Northern China. Previously grazing was nomadic, but individual households are now settled on allocated areas of grassland under the "responsibility system". The brief descriptions of three steppes are shown as follows.

2.1.1. Desert steppe

The desert steppe is located in Siziwang Banner in the mid-west of Inner Mongolia (41° 47′ 17″ N, 111° 53′ 46″E). The site has an elevation of 1450 m and is in a temperate continental climate, characterized by a short growing season and long cold winter with a frost-free period of 175 days. The average annual precipitation is approximately 280 mm, of which nearly 75% falls during June through September. The dominant soil types are Kastanozem (FAO soil classification) or Brown Chernozem (Canadian Soil Classification) with a loamy sand texture (Li et al., 2008). The grassland is dominated by *Stipa breviflora* Griseb., *Artemisia frigida* Willd., *Cleistogenes songorica* (Roshev.) Ohwi, and accompanied by *Convolvulus ammannii* Desr., *Heteropappus altaicus* (Willd.) Novopokr., *Neopallasia petinata* (Pall.) Poljak., *Bassia prostrate* (L.) A.J. Scott, *Caragana stenophylla* Pojark., *Leymus chinensis* (Trin.) Tzvelev. The ground coverage of vegetation is 18–25%.

2.1.2. Typical steppe

The typical steppe is located in the Xilingol of Inner Mongolia (43°11′–43°27′N, 116°22′–117°00′E). The site has an elevation of 1000 m and the climate is the temperate continental and semi-arid. The growing season starts in early May and ends in late September. The annual average temperature is 0.7 °C with a frost-free period of 98 days (Liu et al., 2007). Annual mean precipitation is 330 mm with 60–80% falling as rain between June and August. Soil type is Kastanozem (FAO soil classification). The constructive species is *L. chinensis* and *Stipa grandis*. The ground coverage of vegetation is 50–60%.

2.1.3. Meadow steppe

The meadow steppe is located in the northeastern of Xilingol of Inner Mongolia (43°57′–45°23′N, 116°21′–119°51′E). The site has an elevation of 1000 m and the climate is the temperate continental. The mean annual temperature is 1.2 °C with frost-free period 106d. The average annual precipitation is 370 mm, and mostly concentrated in 7–8 months. The soil type is mainly typical kastanozems. The grassland is dominated by *L. chinensis* (Trin.) Tzvel., *Stipa baicalensis* Roshev., and *Filifolium sibiricum* (L.) Kitam. with other species, such as *Achnatherum sibiricum* (L.) Keng., *Thymus serphyllum* L., *Allium tenuissimum* L., *Leontopodium lenontopodioides* (Willd.) Beauv., *Stellera chamaejasme* L., *Artemisia pubescens* Ledeb., and *Melilotoides ruthenica* (L.) Sojak. The ground coverage of vegetation is 60–75%.

2.2. Experimental design

The design of our grazing study was modeled after a piosphere where grazing impacts radiate in a diminishing response away from the centre, which was the location of the holding pen and water source (Fig. 1). The piosphere grazing gradient was sampled along three replicate transects radiating from the center. The boundaries of the three grazing intensity zones (light grazing, LG; moderate grazing, MG; heavy grazing, HG) were defined along each transect and un-grazed (UG) zone was fenced (Han et al., 2008). The zones and their boundaries were defined by sampling species composition and vegetation coverage along the transects at 50 m intervals, using a single 20 cm × 50 cm quadrat, and grouping the plots into one of the three grazed zones using cluster analyses. The boundaries' distances of grazing intensity in HG, MG and LG are 180 m, 300 m and 420 m in the desert steppe, respectively; 600 m, 1700 m and 2400 m in the typical steppe, respectively, and 240 m, 520 m and 740 m in the meadow steppe, respectively. The grazing densities were quantified based on the percentage of forage utilization. The percentage of forage utilization in HG, MG and LG was 65–70%, 40–44% and 24–30% in the three steppes, respectively.

Three replicate sampling sites of each grazing density were selected along the transects. Marking the centre of each grazing zones along the transect, the three replicate points were designed with a transect bearing of either 120°, 240° or 360°. Each sampling site was located at 10 m apart from the centre.

2.3. CH_4 flux measurements

The field experiment was conducted along three replicate transects radiating from the center of each steppe from May to October in 2010. CH_4 fluxes at an interval of two weeks at each

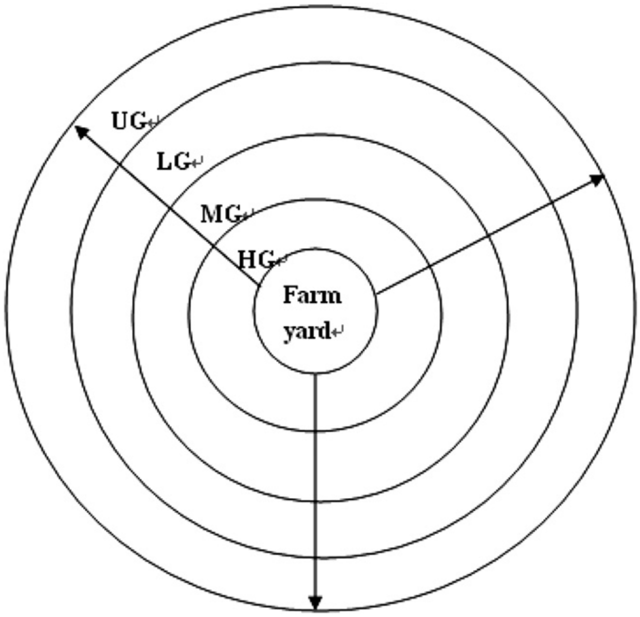

Fig. 1. Schematic diagram of the grazing system. The gradients were divided into heavy grazing (HG), moderate grazing (MG), light grazing (LG) and un-grazed (UG) (Han et al., 2008). The UG sites were fenced. Stocking rate decreases along the direction of the arrow. The boundaries' distance of grazing intensity in HG, MG and LG is 180 m, 300 m and 420 m, respectively in the desert steppe, 600 m, 1700 m and 2400 m, respectively in the typical steppe, and 240 m, 520 m and 740 m, respectively in the meadow steppe.

site were measured using an automatic cavity ring-down spectrophotometer (Picarro G1301, Santa Clara, CA, USA. a portable instrument) during 9:00–10:00 in the morning and 16:00–17:00 in the afternoon, which are times that are representative of the average rate of CH_4 flux over a 24-h cycle (Wang et al., 2005; Tang et al., 2006). CH_4 flux was measured at one site in the morning and the same site in the afternoon for the next time. The measurement method is based on wavelength scanning optical cavity ring-down spectroscopy (WS-CRDS) technology, a time-based measurement utilizing a near-infrared laser to measure a spectral signature of the molecule. A stainless steel chamber (21 cm internal diameter and 10.5 cm height) with thick wall attached to G1301 by two vent tubes at the top of chamber. One tube is for sampling, another for vent. The chamber was put on each point for 2 min and then moved to the next point. The data are presented with an interval of 5 s on a transportable. The chamber was gently rotated to ensure close the ground and prevent leak of gas before the measurement. The direct current of the charged battery groups (48 V) was converted to alternating current (220 V) using a commutator in the filed. CH_4 fluxes were calculated according to the following equation:

$$F = \rho \cdot \frac{V}{A} \cdot \frac{\Delta C}{\Delta T}$$

where F is the flux ($\mu g\ m^{-2}\ h^{-1}$) of gas; ρ is the density of gas; $\Delta C/\Delta T$ is the slope of the linear regression for gas concentration gradient through time; V and A are volume (m^3) and the chamber base area (m^2), respectively.

2.4. Auxiliary measurements

Soil temperature (5 cm depth) and moisture (0–5 cm) were measured by thermocouples and a hand-held reader (HH-25TC, OMEGA Engineering Inc., Stamford, CT) and a portable TDR probe (HH2, Delta-T Devices, Cambridge, UK). Daily precipitation and air temperature were obtained from the local meteorological station. Growing season air temperature, soil temperature (5 cm) and precipitation at three steppe sites were presented in Figs. 2a and 3a and 4a.

Soil was sampled in August, 2010. The soil was sampled along the three transect lines within each zone of grazing intensity. Soil cores (3.5 cm diameter) at the depth of 0–20 cm were collected using soil auger in each sampling site to measure bulk density, soil organic matter and total N. The contents of soil organic matter and total N were determined by oxidation with potassium dichromate

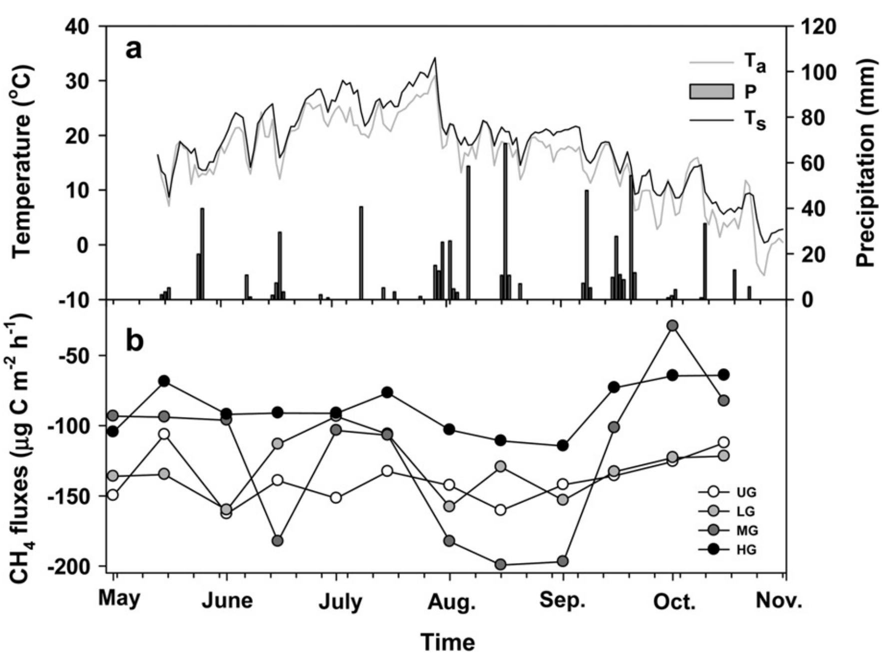

Fig. 2. Dynamics of air temperature (Ta), soil (5 cm) temperature (Ts), precipitation (P) (a), and methane (CH_4) flux at the desert steppe (b) site during the 2010 growing season. CH_4 fluxes are daily mean values, representing measurements with three replicates (nine flux measurements per day).

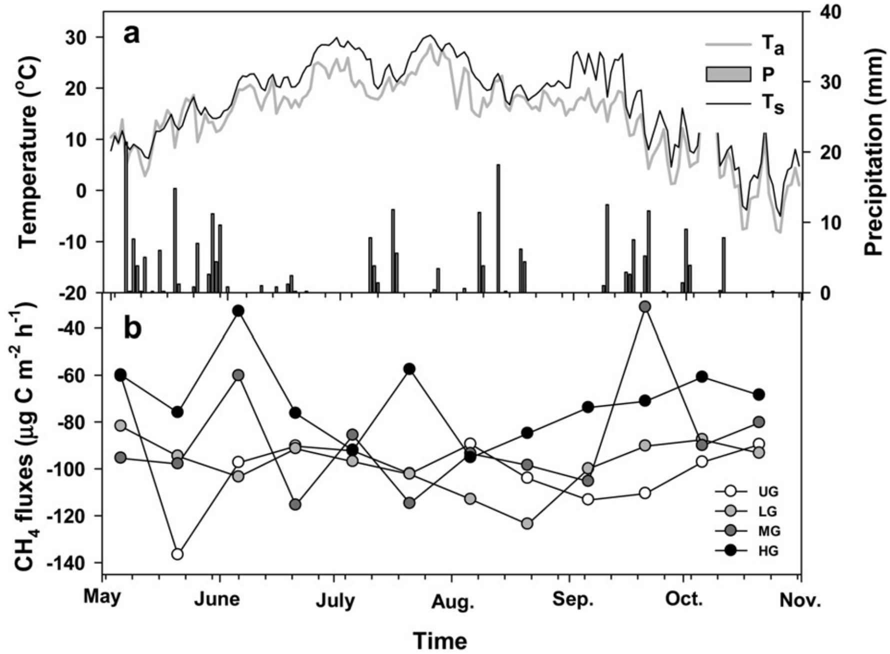

Fig. 3. Dynamics of air temperature (Ta), soil (5 cm) temperature (Ts), precipitation (P) (a), and methane (CH_4) flux at the typical steppe (b) site during the 2010 growing season. CH_4 fluxes are daily mean values, representing measurements with three replicates (nine flux measurements per day).

and Kjeldahl digestion, respectively (Bao, 2000). Information on soils at each site is presented in Table 1.

2.5. Statistical analyses

CH_4 fluxes were analyzed using MIXED procedure of the Statistical Package for Social Science (SPSS 13.0 for Windows, 2003), to test experimental differences in CH_4 fluxes. Replicate flux measurements were averaged by the sampling point for each grazing plot. The type of steppe, stocking rate and all possible interactions were treated as fixed effects, grazing plot of each stocking rate as random effect, and sampling date as repeated measure with grazing plot as subject. The best fit covariance structure was compound symmetry. The data were examined for homogeneity of variances and for normal distribution before analysis. If necessary, data were adjusted using log transformation. Paired means of significant differences in treatments were determined using the least significant difference (LSD) statistic. Pearson correlation analysis was performed between CH_4 fluxes and soil temperature and moisture.

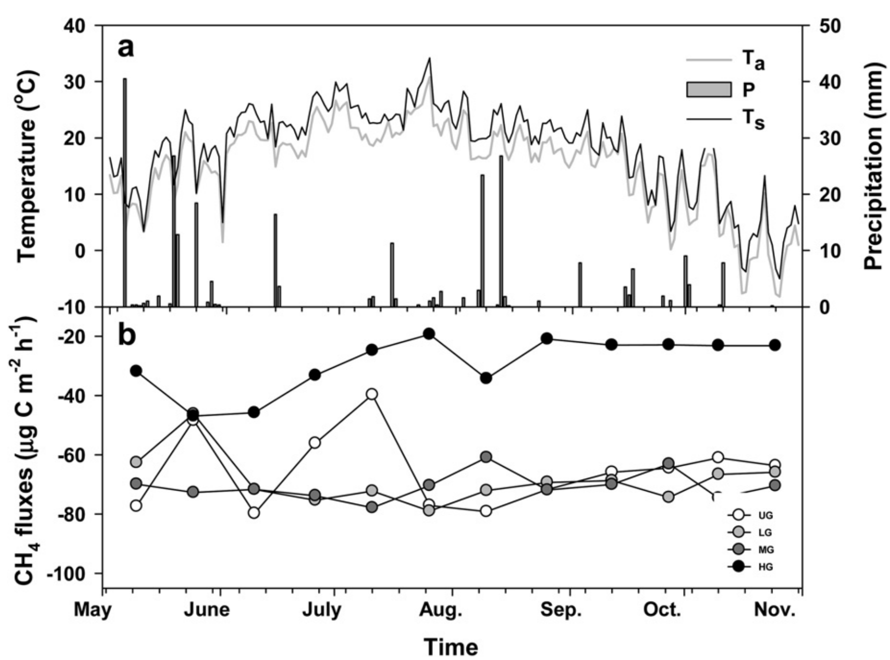

Fig. 4. Dynamics of air temperature (Ta), soil (5 cm) temperature (Ts), precipitation (P) (a), and methane (CH_4) flux at the meadow steppe (b) site during the 2010 growing season. CH_4 fluxes are daily mean values, representing measurements with three replicates (nine flux measurements per day).

Table 1
Soil properties of the depth of 0–20 cm at study sites.

Steppe type	Grazing treatment	Soil moisture (vol. %)	Bulk density (g cm^{-3})	Organic matter (g kg^{-1})	Total N (g kg^{-1})	C:N ratio
Desert steppe	UG	6.9 ± 1.1^{b}	1.29 ± 0.03^{b}	35.62 ± 0.67^{c}	1.87 ± 0.13^{bc}	11.05
	LG	7.8 ± 0.8^{a}	1.24 ± 0.03^{b}	50.58 ± 1.40^{a}	2.65 ± 0.11^{a}	11.07
	MG	6.1 ± 0.4^{b}	1.36 ± 0.02^{a}	36.17 ± 3.13^{c}	1.72 ± 0.08^{c}	12.20
	HG	4.1 ± 0.7^{c}	1.39 ± 0.03^{a}	41.20 ± 2.18^{b}	1.95 ± 0.16^{b}	12.25
Typical steppe	UG	13.7 ± 0.8^{b}	1.03 ± 0.04^{b}	17.06 ± 4.78^{c}	1.30 ± 0.16^{c}	7.61
	LG	14.5 ± 0.7^{a}	1.04 ± 0.02^{b}	18.29 ± 2.60^{c}	1.28 ± 0.14^{c}	8.28
	MG	12.0 ± 0.4^{c}	1.24 ± 0.02^{a}	24.81 ± 4.32^{b}	1.55 ± 0.08^{b}	9.28
	HG	9.1 ± 0.4^{d}	1.27 ± 0.02^{a}	36.24 ± 5.81^{a}	1.87 ± 0.16^{a}	11.24
Meadow steppe	UG	15.8 ± 0.1^{a}	1.06 ± 0.08^{d}	22.56 ± 7.98^{a}	1.69 ± 0.09^{a}	7.74
	LG	14.7 ± 0.4^{b}	1.16 ± 0.05^{c}	22.26 ± 7.53^{a}	1.65 ± 0.03^{a}	7.83
	MG	14.8 ± 0.3^{b}	1.63 ± 0.05^{b}	21.64 ± 12.42^{a}	1.62 ± 0.11^{a}	7.75
	HG	13.9 ± 0.7^{c}	1.91 ± 0.02^{a}	22.44 ± 7.12^{a}	1.71 ± 0.15^{a}	7.61

UG: un-grazed; LG: light grazing; MG: moderate grazing; HG: heavy grazing.
The given data represent the mean ± standard error.
Different lowercase letters indicate significant differences among treatments of the same steppe at $P < 0.05$.

3. Results

3.1. Soil-atmosphere CH_4 exchange in different types of steppe

Soil CH_4 uptakes during the growing season were affected ($P < 0.01$) by the different types of steppe (Fig. 5b), following the order desert steppe > typical steppe > meadow steppe. Soil CH_4 flux in the desert steppe ranged from −56.35 to −213.89 μg CH_4-C m^{-2} h^{-1} with a mean of −119.67 μg CH_4-C m^{-2} h^{-1}, and showed the greatest CH_4 uptake rate of the three steppe ecosystems (Figs. 2 and 5). In the typical steppe, CH_4 flux ranged from −30.43 to −142.37 μg CH_4-C m^{-2} h^{-1} with a mean of −95.24 μg CH_4-C m^{-2} h^{-1} (Fig. 3). Soil CH_4 flux in the meadow steppe ranged from −17.48 to −82.33 μg CH_4-C m^{-2} h^{-1}, with an overall mean flux of −58.40 μg CH_4-C m^{-2} h^{-1}, being the smallest uptake rate of the three steppe ecosystems (Figs. 4 and 5). CH_4 uptake in the desert steppe was 20.4% and 51.2% larger than from the typical steppe and meadow steppe, respectively.

3.2. Influence of stocking rates on CH_4 exchange

Soil CH_4 fluxes were affected ($P < 0.05$) by different stocking rates (Table 2, Fig. 5a). The CH_4 uptake at all sites ranged from 17.48 to 213.89 (91.10 on average) μg CH_4-C m^{-2} h^{-1} during the growing season. The measured mean CH_4 fluxes for UG, LG, MG and HG areas during the growing season were −100.78 μg CH_4-C m^{-2} h^{-1}, −98.97 μg CH_4-C m^{-2} h^{-1}, −93.96 μg CH_4-C m^{-2} h^{-1} and −62.55 μg CH_4-C m^{-2} h^{-1}, respectively (Table 2). The results indicate that the grazed areas were a CH_4 sink during the entire measurement period, and the strength of soil-atmospheric CH_4 uptake decreased ($P < 0.05$) with an increase in stocking rate. Compared with their respective UG sites, MG and HG sites showed a significantly lower CH_4 uptake. However, LG did not change CH_4 uptake significantly compared with UG sites. Effects of interaction between the stocking rate and the type of steppe were observed in our study (Table 2).

3.3. Relationship between CH_4 fluxes and environmental factors

The relationships between CH_4 uptake and soil temperature and moisture were shown in Table 3. The measured CH_4 fluxes in the different types of steppe were positively correlated ($P < 0.05$) with topsoil (5 cm) temperature at each site. Changes in mean soil temperature could explain 21.3–59.6% of the variation in CH_4 fluxes in three types of steppe. The correlation coefficients indicate that CH_4 fluxes were significantly affected ($P < 0.01$, negative) by soil (0–5 cm) moisture (vol. %) at all measured sites.

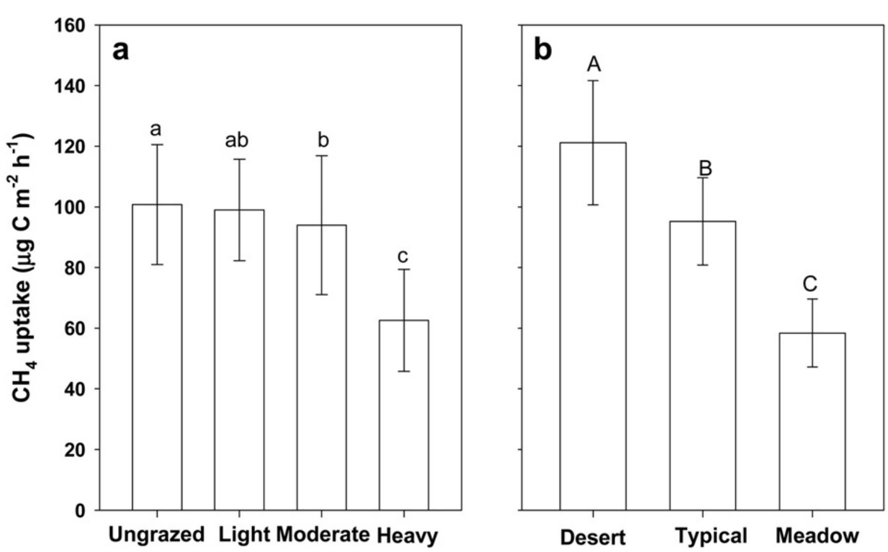

Fig. 5. Effects of grazing and grassland type on CH_4 uptake during the growing season. The data were shown in (a) represent the mean values of different stocking rates. The data illustrated in (b) represent the mean values of different types of grassland. Different uppercase and lowercase letters and capital letters indicate significant differences among groups at $P < 0.05$ and $P < 0.01$, respectively.

Table 2
Comparison of CH_4 fluxes (μg C m^{-2} h^{-1}) in three types of grassland under different stocking rates.

Type of steppe	CH_4 fluxes				SEM	P value		
	UG	LG	MG	HG		S	T	S × T
Desert	−138.43 ± 10.65	−130.22 ± 12.07	−122.32 ± 36.24	−87.80 ± 11.01	2.075	0.021	<0.0001	0.004
Typical	−98.59 ± 10.40	−98.14 ± 6.66	−89.01 ± 20.65	−70.79 ± 9.6	2.075			
Meadow	−65.33 ± 7.29	−68.63 ± 4.89	−70.57 ± 2.84	−58.40 ± 5.39	2.075			

UG: un-grazed; LG: light grazing; MG: moderate grazing; HG: heavy grazing; SEM: standard error of mean; S: Stocking rate; P: probability value; T: Type of steppe; S × T: interaction of stocking rate and type of steppe.

4. Discussion

4.1. Soil-atmosphere CH_4 exchange in continental steppe

Natural steppe soil where methanotrophic activity occurs is an important natural sink for CH_4. The mean CH_4 uptake rate in three types of steppe during the growing season was 91.10 μg CH_4-C m^{-2} h^{-1} (7.98 kg C ha^{-1} yr^{-1}). CH_4 uptake rates were the highest in desert steppe soils, intermediate for typical steppe soils, and lowest for meadow steppe soils. CH_4 uptake in the meadow steppe was 48.8% and 61.3% of the uptake in desert and typical steppe, respectively. These findings suggest that the global warming potential of continental steppe ecosystems could be over-estimated or under-estimated if only data from a single type of steppe is considered. The difference between uptake rates in different types of steppe may be attributed to differences in soil characteristics, water content and different types of methanotrophic communities in their soils. Singh and Tate (2007) reported that type II methanotrophs dominate pine plantations while type I methanotrophs dominate in pasture soils. There is often a strong relationship between grassland or pasture CH_4 flux and soil water status (Steudler et al., 1996; Liu et al., 2007; Chen et al., 2011a) but not always (Livesley et al., 2009). Where soil pore spaces are filled by water, anoxic conditions increase and CH_4 diffusion to the methanotrophs in the subsurface is restricted (Ball et al., 1997). Although some studies reported a positive correlation of CH_4 uptake with soil temperature (Wang et al., 2005), in agreement with our findings most studies found this relationship to be of limited significance (Holst et al., 2008), with controls on gas diffusivity, such as soil texture, bulk density, and soil moisture, attaining more importance (Holst et al., 2008; Smith et al., 2003).

Grazing is a complex event in the Inner Mongolian steppe. A range of specific factors, such as fecal and urine deposition, shifts in plant rhizosphere exudation, shifts in plant species, and changes in soil structure and aerobicity can change soil characteristics (Clegg, 2006). CH_4 exchange is dependent on a number of parameters that may affect gas diffusivity and soil aeration, such as bulk density, soil moisture and litter layer characteristics, substrate control and so on (Smith et al., 2003; Holst et al., 2008; Liu et al., 2007). Furthermore, the exchange of terrestrial CH_4 is regulated by internal N cycling in soils (Aronson and Helliker, 2010). These controls may exert differential effects on the production and consumption of CH_4. In our study, there was little variation in total N in the soils of three types of steppe under different stocking rates (Table 1), so soil N is unlikely to have contributed to the observed differences in CH_4 flux. Pol-van Dasselaar et al. (1998) reported that CH_4 uptake may be promoted by reduced inorganic N content. Aronson and Helliker, 2010 also reported that smaller amounts of N tended to stimulate CH_4 uptake while larger amounts tended to inhibit uptake by soil. Our explanation that N may be factor to constrain CH_4 uptake, however, requires further investigation, such as studying the influence of rate and type of N added, duration of N addition, and previous land use.

Table 3
Correlation coefficients between mean CH_4 flux (μg C m^{-2} h^{-1}) (± SE) measured over a 6-month period (12 times, an interval of two weeks) in 2010 and environmental variables in the desert, typical and meadow steppe.

	Desert steppe	Typical steppe	Meadow steppe
CH_4 flux (μg C m^{-2} h^{-1})	−119.67 ± 23.22 $n = 432$	−95.24 ± 14.38 $n = 432$	−58.40 ± 11.20 $n = 432$
Air temperature (°C)	−0.459 *	−0.455 *	−0.372 *
Soil temperature 5 cm (°C)	−0.596 *	−0.560 **	−0.231 *
Soil moisture (vol. %)	0.674 **	0.659 **	0.193 *

Significant correlations are indicated by * and ** at the 0.05 and 0.01 level, respectively.

4.2. Influence of stocking rates on CH_4 exchange

Previous studies reported inconsistent effects of grazing on CH_4 uptake by steppes (Wang et al., 2005; Liu et al., 2007; Saggar et al., 2007; Chen et al., 2011a, b). In temperate semiarid steppes, Wang et al. (2005) did not detect significant differences in CH_4 uptake between grazed and UG steppes. Liu et al. (2007) reported that winter-grazing significantly reduced steppe CH_4 uptake during the growing season by 47%, and Chen et al., (2011a, b) suggested that HG reduced annual CH_4 uptake by 21–34%. In our study, HG reduced CH_4 uptake significantly by 37.9% compared with UG steppes. However, uncertainty associated with the limited number of observations (e.g. a single type of steppe under specific soil and climatic conditions), measurement (e.g. transport of samples to the laboratory), and the diversity of grazing practices in various studies may limit the conclusiveness of studies of grazing effects on CH_4 uptake.

Based on our study, LG would be the recommended practice because this grazing intensity did not significantly change CH_4 uptake. With a 6.8–37.9% reduction of CH_4 uptake, MG to HG ought to be discouraged during the growing season. Three mechanisms may collectively or independently contribute to a significant reduction in CH_4 uptake in heavily grazed steppe. First, animal trampling disturbs the topsoil and decreases the diffusion of CH_4 and oxygen (both substrates for methanotrophs) from the atmosphere into the soil profile (Liu et al., 2007). This explanation was supported by Chen et al. (2011a, b) who showed a significant linear dependence of topsoil air permeability (AP, cm s^{-1}) on stocking rates (SR, sheep ha^{-1} yr^{-1}; i.e., $AP = -1.46SR + 4.45$). Second, fresh animal feces deposited on grazed sites are hotspot sources of CH_4 (Jiang et al., 2012; Chen et al., 2011a, b). During the grazing season, animal feces were usually found in the soil surface. Although the most intensively grazed steppes was a net CH_4 uptake, the higher fecal and urine deposition for feces-originated CH_4 emissions in heavily grazed sites could offset more CH_4 uptake than in other sites. Third, as has been shown in other studies from a typical steppe in Inner Mongolia (Zhou et al., 2008), grazing changes the community of soil methanotrophs. Zhou et al. (2008) found that populations of the two types of soil (0–5 cm) methanotrophs (Type I and Type II) were higher in LG and MG sites compared with UG and HG sites.

5. Conclusions

The magnitude of CH_4 uptake in the desert steppe was found to be significantly higher compared with the typical steppe and humid meadow steppe. In addition to the type of steppe, CH_4 uptake was mainly driven by stocking rate, soil temperature and moisture. Considering the increase in grazing intensity in Inner Mongolia steppes reported in recent decades, one may hypothesize that overgrazing has exerted a considerable negative impact on CH_4 uptake. However, intensive measurements of CH_4 uptake during an entire dormant season are still missing, and, thus, limit our ability to accurately quantify annual CH_4 uptake by steppe in the region.

Acknowledgments

This research was funded by the Inner Mongolia Palmary Youth Project (2010JQ04), Chinese National Natural Science Foundation (31160109, 30960072, 31070413), National Commonweal Project (201003019, 200903060), Inner Mongolia Agricultural University Innovation Group (NDTD2010-5), and Management and Policy Support to Combat Land Degradation Project: PRC-GEF Partnership on Land Degradation in Dryland Ecosystems. The authors gratefully acknowledge staff of Inner Mongolia Academy of Agriculture and Animal Husbandry Research Station and Inner Mongolia Grassland Ecosystem Research Station for their assistance in gas sample collection.

References

Aronson, E.L., Helliker, B.R., 2010. Methane flux in non-wetland soils in response to nitrogen addition: a meta-analysis. Ecology 91, 3242–3251.
Augustine, D.J., Frank, D.A., 2001. Effects of migratory grazers on spatial heterogeneity of soil N properties in a grassland ecosystem. Ecology 82, 3149–3162.
Ball, B.C., Dobbie, K.E., Parker, J.P., Smith, K.A., 1997. The influence of gas transport and porosity on methane oxidation in soils. Journal of Geophysical Research 102, 23301–23308.
Bao, S.D., 2000. Soil and Agricultural Chemistry Analysis. China Agriculture Press, Beijing (in Chinese).
Bureau of Statistics of Inner Mongol, 2007. Inner Mongolia Yearbook 2007. China Statistic Press, Beijing.
Chen, W.W., Wolf, B., Brüggemann, N., Butterbach-Bahl, K., Zheng, X.H., 2011a. Annual emission of greenhouse gases from sheepfolds in Inner Mongolia. Plant and Soil 340, 291–301.
Chen, W.W., Wolf, B., Zheng, X.H., Yao, Z.S., Butterbach-Bahl, K., Brüggemann, N., Liu, C.Y., Han, S.H., Han, X.G., 2011b. Annual methane uptake by temperate semiarid steppes as regulated by stocking rates, aboveground plant biomass and topsoil air permeability. Global Change Biology 17, 2803–2816.
Clegg, C.D., 2006. Impact of cattle grazing and inorganic fertilizer additions to managed grasslands on the microbial community composition of soils. Applied Soil Ecology 31, 73–82.
Han, G.D., Hao, X.Y., Zhao, M.L., Wang, M.J., Ellert, B., Willms, W., Wang, M.J., 2008. Effect of grazing intensity on carbon and nitrogen in soil and vegetation in a meadow steppe in Inner Mongolia. Agriculture, Ecosystems and Environment 125, 21–32.
Holst, J., Liu, C., Yao, Z., Brüggemann, N., Zheng, X., Giese, M., Butterbach-Bahl, K., 2008. Fluxes of nitrous oxide, methane, carbon dioxide during freezing-thawing cycles in an Inner Mongolian steppe. Plant and Soil 308, 105–117.
IPCC (Intergovernmental Panel on Climate Change), 2007. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York.
Jiang, Y.Y., Tang, S.M., Wang, C.J., Zhou, P., Tenuta, M., Han, G.D., Huang, D., 2012. Contribution of urine and dung patches from grazing sheep to methane and carbon dioxide fluxes in an Inner Mongolian desert grassland. Asian-Australasian Journal Animal Science 25, 207–212.
Li, C.L., Hao, X.Y., Zhao, M.L., Han, G.D., Willms, W.D., 2008. Influence of historic sheep grazing on vegetation and soil properties of a Desert Steppe in Inner Mongolia. Agriculture, Ecosystems and Environment 128, 109–116.
Li, S.G., Harazono, Y., Oikawa, T., Zhao, H.L., He, Z.Y., Chang, X.L., 2000. Grassland desertification by grazing and the resulting micrometeorological changes in Inner Mongolia. Agricultural and Forest Meteorology 102, 125–137.
Li, X.R., 2001. Study on shrub community diversity of Ordos Plateau, Inner Mongolia, Northern China. Journal of Arid Environments 47, 271–279.
Liu, C., Holst, J., Brüggemann, N., Butterbach-Bahl, K., Yao, Z., Yue, J., Han, S., Han, X., Krümmelbein, J., Horn, R., Zheng, X., 2007. Winter-grazing reduces methane uptake by soils of a typical semi-arid steppe in Inner Mongolia, China. Atmospheric Environment 41, 5948–5958.
Livesley, S.J., Kiese, R., Miehle, P., Weston, C.J., Butterbach-Bahl, K., Arndt, S.K., 2009. Soil-atmosphere exchange of greenhouse gases in a *Eucalyptus marginata* woodland, a clover-grass pasture, and *Pinus radiata* and *Eucalyptus globulus* plantations. Global Change Biology 15, 425–440.
NSBC (National Statistics Bureau of China), 2002. China Statistics Yearbook 2002 (in Chinese). Chinese Statistics Press, Beijing, China. p.6.
Paruelo, J.M., Burke, I.C., Lauenroth, W.K., 2001. Land-use impact on ecosystem functioning in eastern Colorado, USA. Global Change Biology 7, 631–639.
Pol-van Dasselaar, A., Beusichem, A.M.L., Oenema, O., 1998. Effects of soil moisture content and temperature on methane uptake by grasslands on sandy soils. Plant and Soil 204, 213–222.
Ross, D.J., Tate, K.R., Scott, N.A., Teltham, C.W., 1999. Land-use change: effects on soil carbon, nitrogen and phosphorus pools and fluxes in three adjacent ecosystems. Soil Biology and Biochemistry 31, 803–813.
Saggar, S., Hedley, C.B., Giltrap, D.L., lambie, S.M., 2007. Measured and modeled estimates of nitrous oxide emission and methane consumption from a sheep-grazed pasture. Agriculture, Ecosystems and Environment 122, 357–365.
Singh, B.K., Tate, K., 2007. Biochemical and molecular characterization of methanotrophs in soil from a pristine New Zealand beech forest. FEMS Microbiology Letters 275, 89–97.
Smith, K.A., Ball, T., Conen, F., Dobble, K.E., Massheder, J., Rey, A., 2003. Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. European Journal of Soil Science 54, 779–791.
SPSS (Statistical Package for Social Science) for Windows XP, 2003. Release 16.0, Copyright. SPSS Inc.
Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C., 2006. Livestock's Long Shadow. Environmental Issue and Options. Food and Agriculture Organization of the United Nations, Rome.
Steudler, P.A., Melillo, J.M., Feigl, B.J., Neill, C., Piccolo, M.C., Cerri, C.C., 1996. Consequence of forest-to-pasture conversion on CH_4 fluxes in the Brazilian Amazon Basin. Journal Geophysical Research 101, 18547–18554.
Tang, X.L., Liu, S.G., Zhou, G.Y., Zhang, D.Q., Zhou, C.Y., 2006. Soil-atmospheric exchange of CO_2, CH_4, and N_2O in three subtropical forest ecosystems in southern China. Global Change Biology 12, 546–560.
Wang, Y.S., Xue, M., Zheng, X.H., Ji, B.M., Du, R., Wang, Y.F., 2005. Effects of environmental factors on N_2O emission form and CH_4 uptake by the typical grasslands in the Inner Mongolia. Chemosphere 58, 205–215.
Wang, Z.P., Han, X.G., Li, L.H., Chen, Q.S., Duan, Y., Cheng, W.X., 2005. Methane emission from small wetlands and implications for semiarid region budgets. Journal of Geophysical Research 110, D13304. http://dx.doi.org/10.1029/2004JD005548.
Wang, Z.P., Song, Y., Gulledge, J., Yu, Q., Liu, H.S., Han, X.G., 2009. China's grazed temperate grasslands are a net source of atmospheric methane. Atmospheric Environment 43, 2148–2153.
White, R.P., Murray, S., Rohweder, M., 2000. Pilot Analysis of Global Ecosystem: Grassland Ecosystems. World Resource Institute, Washington, DC.
Zhang, W., Skarpe, C., 1996. Small-scale vegetation dynamics in semi-arid steppe in Inner Mongolia. Journal of Arid Environments 34, 421–439.
Zhou, X.Q., Wang, Y.F., Huang, X.Z., Tian, J.Q., Hao, Y.B., 2008. Effect of grazing intensities on the activity and community structure of methane-oxidizing bacteria of grassland soil in Inner Mongolia. Nutrient Cycling in Agroecosystems 80, 145–152.