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Moderate grazing has little effect on global warming potential in the temperate steppes of northern China

Longyu Hou[a,1], Yang Li[b,1], Huiqiu Shi[a], Dashuan Tian[c], Bingxue Wang[c], Linghao Li[a,*], Lihua Zhang[a,**]

[a] State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing, 100093, China
[b] Xi'an Botanical Garden of Shaanxi Province, Institute of Botany of Shaanxi Province, Xi'an, 710061, China
[c] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China

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ABSTRACT

Grazing has been reported to significantly affect the flux of three greenhouse gases (GHGs: CO_2, CH_4 and N_2O) in grasslands, but its effect on total global warming potential (GWP) is still unclear. To assess the effect of grazing on GWP, we simultaneously measured the flux of these three GHGs using static chambers in meadow, typical, and desert steppes under no grazing (NG) and summer grazing (SG) conditions during the 2012-14 growing seasons. We aimed to examine the impact of grazing on total GWP across different steppes and to assess the relative contribution of different environmental factors to changes in GWP. Our results showed that total GWP values were almost entirely negative in all steppe environments and displayed high spatio-temporal variability. Net ecosystem exchange was the most important predictor of total GWP in all three steppes, and the positive GWP induced by N_2O emission was approximately equal to the negative GWP induced by CH_4 uptake. Steppe type and sampling year—but not grazing treatment—were found to affect GWP. Air temperature and precipitation were the major factors driving total GWP change under the no grazing treatment. In contrast, soil temperature, soil moisture, and precipitation explained a significant percentage of variation in total GWP under the summer grazing treatment. Our study suggests that moderate grazing does not change the role of temperate steppe's function in mitigating climate change; however, multi-year GWP data are necessary for extrapolation to a regional scale.

1. Introduction

The increased atmospheric concentration of greenhouse gases (GHGs) plays a dominant role in climate change and global warming (Mu et al., 2013; IPCC, 2013). Since 1990, the Intergovernmental Panel on Climate Change (IPCC) has used Global Warming Potential (GWP) as an index to integrate the potential impact of the fluxes of different GHGs on climate (IPCC, 2013). Carbon dioxide (CO_2), methane (CH_4), and nitrogen oxide (N_2O) are the three most important greenhouse gases (GHGs), and contribute 64, 17, and 6%, respectively, of the total global warming potential of all GHGs (IPCC, 2013). Total GWP was determined as the total of all potential tradeoffs and/or synergisms of all GHG fluxes. Therefore, understanding changes in total GWP due to different land use regimes is important to evaluate whether differences in ecosystem usage contribute to global climate change.

GHG fluxes and their respective contributions to total GWP vary among different ecosystems and soils (Mosier et al., 2005; Wang et al., 2011; Mu et al., 2013), as do the particular contributions of each GHG to total GWP (Mosier et al., 2005). For instance, the main contributors to total GWP in paddy soils, intensively managed grasslands in Switzerland, and vegetable croplands in south China were CH_4, N_2O, and CO_2, respectively (Mu et al., 2013; Xu et al., 2017). Moreover, even within the same ecosystem or soil type, the production or uptake of different GHGs can be determined by different environmental factors (Yao et al., 2010; Shi et al., 2017). Any single environmental factor can induce different—and even opposite—effects on GHG flux. For example, soil moisture has been shown to have opposing effects on soil CH_4 uptake and soil respiration (Morgan et al., 2011; Dijkstra et al.,

* Corresponding author.
** Corresponding author.
E-mail addresses: llinghao@ibcas.ac.cn (L. Li), zhanglihua@ibcas.ac.cn (L. Zhang).
[1] These authors contributed equally to this study.

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2013). Different GHG fluxes also have interactive effects on global warming potential. For example, N_2O and CO_2 fluxes have been shown to produce significant interactions in meadow steppe (Holst et al., 2008; Yao et al., 2010; Shi et al., 2017). In addition, the mechanisms that regulate the relationship between CH_4 uptake and N_2O emission have been shown to be different among steppe types (Shi et al., 2017). Thus, evaluating total GWP and how it changes with various environmental factors in a specific ecosystem will advance our understanding of how feedback in that ecosystem may contribute to climate change.

Grasslands cover about 20 percent of the temperate land surface of the Earth and are widely used as pastures (Wolf et al., 2010). Previous studies have shown that changes in CO_2, CH_4, and N_2O fluxes depend on grazing intensity and steppe type (Buchmann et al., 2011; Imer et al., 2013; Hou et al., 2016). These studies also identified different factors causing the production and consumption of different greenhouse gases (Merbold et al., 2014; Li et al., 2015). However, these studies only focused on individual GHG fluxes without quantifying the total GWP. To assess the total potential impact on climate change, it is necessary to simultaneously investigate the contributions of each of the GHGs over a long (i.e. multiple-year) time scale.

In this study, we obtained measurements of CO_2, CH_4, and N_2O fluxes in 3 years at three temperate steppe sites (i.e. meadow, typical, and desert steppes) with both no grazing and summer grazing treatments. From these data, the total GWP was calculated using the calculation method specified by the IPCC (2013). The objectives of this study were (1) to test the effects of grazing and steppe type on total GWP across years, and (2) to analyze the relative contributions of different environmental factors in driving changes in GWP by studying interannual and spatial variations in these factors as well as in total GWP.

2. Materials and methods

2.1. Site and experimental description

Temperate steppe is one of the largest terrestrial biomes worldwide, and is widely used for grazing and other economic activities related to livestock production. The Inner Mongolian steppe is part of a continuous expanse of approximately 12.5 million km^2 of temperate grasslands that make up more than 8% of the earth's land surface area (Tang et al., 2013). This steppe has a temperate continental monsoon climate, and the growing season starts in early May and ends in late September (Hou et al., 2016). In 2011, we created east-west transects of the Inner Mongolia grassland, and identified meadow steppe, typical steppe, and desert steppe environments. These three steppe types were defined based on the humidity of the steppe climate. The meadow steppe site receives 350–500 mm of annual precipitation, has a mean annual temperature of 1–4 °C, and *Stipa baicalensis* is the dominant species. The typical steppe site was characterized by having 300–400 mm of annual precipitation range, a mean annual temperature between −2.3 and 5 °C, and *Stipa grandis* and *Stipa krylovii* as dominant species. The desert steppe site receives only 135–311 mm of annual precipitation, has an annual temperature of 0.8–5.3 °C, and contains the dominant species *Stipa klemenzii*, *Stipa breviflora*, and *Stipa glareosa* (Miao et al., 2016). The typical steppe site for this experiment is located at the Inner Mongolia Grassland Ecosystem Research Station of the Chinese Academy of Sciences. The desert steppe site was at the Siziwang Experimental Station of the Inner Mongolia Academy of Agricultural and Animal Husbandry Sciences. The meadow steppe also determined after comparing a huge of meadow steppe. The characteristics of the experimental sites are shown in Table 1. The basic properties of the soil were measured in May 2012 and are described in detail in a previous study (Hou et al., 2016).

First, summer grazing plots were 1 ha (100 m × 100 m) and were stocked at a rate of 0.5 sheep per ha during the growing season, which approximated the grazing intensity of the Inner Mongolian grasslands

Table 1
Site specific characteristics and climates in the meadow, typical, and desert steppe sites.

Parameter	Meadow steppe		Typical steppe		Desert steppe	
	NG	SG	NG	SG	NG	SG
Latitude/Longitude	120.3° N, 45.1° E		116.7° N, 43.6° E		111.9° N, 41.8° E	
Altitude (m)	656		1268		1428	
Soil type	Typical Kastanozem		Calcia Chernozem		Light-colored Chernozemic	
MAP (1971-2000) (mm)	395		293		175	
MAT (1971-2000) (°C)	2.1		−0.3		3.1	
Grazing density (sheep hm^{-2})		0.5		0.5		0.5
Areas (hm^2)	1	1	1	1	1	1
Grazing period		Jun-Sep		Jun-Sep		Jun-Sep
Air temperature (°C)						
2012	20.8		17.3		19.7	
2013	21.5		18.0		19.2	
2014	21.0		17.6		19.6	
Relative humidity						
2012	61.6		54.8		54.8	
2013	58.2		49.6		55.6	
2014	59.7		51.3		50.1	
Soil temperature (°C)						
2012	22.5	23.7	16.6	16.5	20.4	21.4
2013	20.0	20.3	15.8	17.0	22.0	22.6
2014	18.3	18.9	17.0	17.5	23.8	24.4
Soil moisture (v/v%)						
2012	56.8	46.3	33.3	31.5	24.6	25.4
2013	47.8	33.0	19.2	22.0	19.8	18.6
2014	39.6	29.5	17.3	19.3	11.3	12.3

MAP and MAT are the means from 1971 to 2000.
Air temperature and relative humidity values listed are the means of May to September and were supplied by the local meteorological station.
Soil temperature and moisture values are the means of May to September measured in this study.

(0.38–0.75 sheep per ha) (Hou et al., 2015). Second, the plots were grazed by one sheep from Jun to September but the sheep was fed by foraging for other foods during the non-growing season. Third, more than 90% of the grassland was degraded in Inner Mongolia, and this grazing intensity is therefore widely used for sustainable management of grassland in this area (Tang et al., 2013).

In 2012, we established paired summer grazing (SG) and no grazing (NG) treatment plots in each of the three steppe types to measure the net ecosystem exchange (NEE, CO_2 flux), CH_4 and N_2O fluxes. The NG plots had been enclosed for more than 15 years. At each site, six bases (0.5 m × 0.5 m) for each treatment (SG vs NG) were installed in the soil at a depth of 10 cm ten days prior to GHG measurement. Of these, three bases were used for NEE measurement and the other three for the measurement of CH_4 and N_2O fluxes.

2.2. GHG sampling and analysis

NEE, CH_4 and N_2O fluxes were measured every ten days from May to September in 2012 and monthly in 2013 and 2014. NEE was measured by transparent chambers (length × width × height = 0.5 m × 0.5 m × 0.4 m), and CH_4 and N_2O were measured by opaque chambers (length × width × height = 0.5 m × 0.5 m × 0.25 m). A detailed account of the transparent and opaque chamber method has been presented in previous studies (i.e. Zhang et al. (2014) and Hou et al. (2012)). GHGs were collected using 100-ml air-tight plastic syringes at 0-, 1-, 2- and 3-min intervals for transparent chambers and at 0-, 10-, 20- and 30-min for opaque chambers after manually closing the chamber (Zhang et al., 2014; Hou et al., 2012). The gas samples were

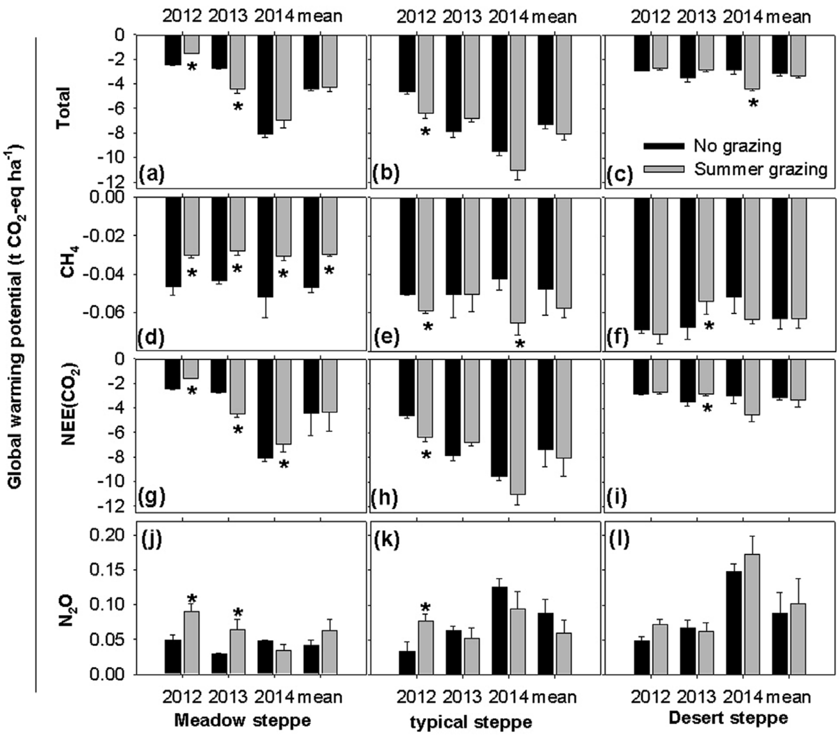

Fig. 1. Global warming potential during growing seasons (May to September, 153 days) under no grazing and summer grazing at the meadow (a, d, g, j), typical (b, e, h, k) and desert steppe sites (c, f, i, l). Data are presented as means + standard error. * indicates a significant difference between grazing and no grazing treatments at $p < 0.05$.

then transferred into 100-ml sealed airbags, which were transported to the lab within two days for gas measurement using a Hewlett-Packard 5890 series II gas chromatograph (GC) fitted with aflame ionization detector (FID). Certified CH_4, CO_2, and N_2O standards with concentrations of 1.92 $\mu l\, l^{-1}$, 348 $\mu l\, l^{-1}$, and 0.338 $\mu l\, l^{-1}$, respectively, were used for calibration. The GHG fluxes were calculated using linear regression of the gas concentration against time (Dijkstra et al., 2013). The cumulative (growing season of each year) flux per hectare were calculated by multiplying the average values by 153 days (i.e. the number of days between 1-May to 30-September).

2.3. Measurements of environmental factors

At the same time, we measured soil temperature (10 cm depth, portable digital thermometer) and moisture (0–20 cm depth, TDR300) for each gas sample. Above-ground biomass (AGB) was measured by clipping the canopy biomass of 3–6 1 × 1 m quadrats to the ground at each experiment site in Mid-August of each year. Belowground biomass (BGB) was sampled using a stainless steel corer (7.0 cm in diameter) in each quadrat and put in root bags. After being rinsed, BGB and AGB samples were oven-dried at 65 °C to a constant weight (about 48 h of total drying). Precipitation and relative humidity were provided by local meteorological observations.

2.4. Total global warming potential (GWP) calculation

The global warming potential (GWP), a simplified index based upon radiative forcing, was introduced to estimate the potential future impact of fluxes of different gases upon the climate (Lashof and Ahuja, 1990). When reliable data characterizing GHG flux over a growing season or year is obtained, the GWP of an ecosystem can be calculated in terms of CO_2 equivalent (Robertson et al., 2000; Kim et al., 2012). CO_2 is generally used as the reference gas for GWP estimation, and an increase or reduction in emission of CH_4 and N_2O is converted into "CO_2-equivalents" based on their GWPs (IPCC, 2013; Kim et al., 2012). GWP equivalent ratios are 1 for CO_2, 28 for CH_4, and 265 for N_2O; thus at a 100-year time scale the total GWP is calculated as follows (IPCC, 2013):

$$\text{GWP } (CO_2 \text{ equivalent}) = CO_2 \text{ (NEE)} + 28(CH_4) + 265(N_2O)$$

A negative GWP indicates GHG uptake from the atmosphere and a potential climate cooling effect, while a positive GWP indicates GHG release to the atmosphere and a potential climate warming effect (Tian et al., 2015). Recently, net GWP has been estimated to improve our understanding of agricultural impacts on radiative forcing (Mosier et al., 2005; Kim et al., 2012; Mu et al., 2013).

2.5. Statistical analysis

Independent-samples *t*-tests were used to determine the statistical significance of net GWP values between no grazing and summer grazing treatments of each steppe type. Multivariate analysis was used to analyze the effects of steppe type, use regime (NG, SG), and year on total GWP. Scatterplots with trendlines were used to show the effects of GHG flux and environmental factors on GWP. Statistical analyses were performed using SPSS Statistics version 21 (IBM SPSS, Chicago, USA), and Sigma Plot 10.0 was used to construct figures. Moreover, to avoid the influence of autocorrelation among environmental factors when determining net GWP, we used structural equation modelling (SEM) to analyze pathways of environmental factor effects on GWP under different grazing treatments. Amos version 17.0.2 (Amos Development Corporation, Chicago, USA) was used to parameterize the SEM model.

3. Results

3.1. Total global warming potential under different grazing regimes

Grazing significantly reduced total GWP in 2012 at the meadow steppe site, but increased it in 2012 at the typical steppe site, in 2013 at the meadow steppe site, and in 2014 at the desert steppe site (Fig. 1a–c). No significant difference in mean GWP over 2012-2014 was found between the no grazing and summer grazing treatments for the three steppe ecosystems (Fig. 1a–c). When by each GHG was considered separately, grazing significantly decreased GWP induced by CH_4 fluxes in all 3 years at the meadow steppe site (Fig. 1d), and at the desert steppe site in 2013. Grazing significantly reduced GWP induced by CH_4

Table 2
Relative contribution (R^2) of steppe type (meadow, typical, and desert steppe), use regime (no grazing, summer grazing) and year (2012-2014) to spatio-temporal variances of global warming potential across growing seasons (May to september, 153 days).

Factor	R^2	Cumulative R^2	Sig.
Steppe type	0.490	0.490	< 0.001
Use regime	0.003	0.493	0.408
Year	0.322	0.815	< 0.001

flux at the typical steppe site in 2012 and 2014 (Fig. 1 d–f). The effect of grazing on GWP induced by NEE and N_2O flux was also steppe type-dependent and year-dependent (Fig. 1g–l).

Regardless of grazing, the three steppe ecosystems had negative total GWP over the three growing seasons, suggesting the presence of an ongoing cooling effect on the global climate (Fig. 1a–c). The mean of total GWP of 2012–2014 at the typical steppe site (−7.3 t CO_2-eq hm^{-2}) was higher than that at the meadow steppe site (−4.4 t CO_2-eq hm^{-2}) or the desert steppe site (−3.1 t CO_2-eq hm^{-2}) (Fig. 1a–c).

The order of CVs (inter-annual variances) of the total GWPs by site was: meadow steppe (72.2%) > typical steppe (69.0%) > desert steppe (7.1%). Comparisons between these sites showed significantly increased effects of grazing on CV for the desert steppe (28.7%) but with opposite effects for the meadow steppe (63.0%) and typical steppe (38.5%). Multivariance analysis showed that steppe type and year had significant effects on GWP, but that grassland use (i.e. grazing) regime did not (Table 2).

3.2. Relative contribution of GHGs to total GWP

NEE was the largest contributor to total GWP with a range of 100%–103.9% for the summer grazing treatment and 99.3%–103.4% for the no grazing treatment (Table 3). However, CH_4 flux contributed no more than 3%, with the mean of 2012–2014 being 1.1, 0.9, and 2.0% for the no grazing treatment and 0.7, 0.7, and 1.9% for the summer grazing treatment for the meadow, typical, and desert steppe sites, respectively (Table 3). The contribution of N_2O flux to total GWP was within the range of −5.9%∼-0.5%, under both the no grazing and summer grazing treatments (Table 3). The positive GWP caused by N_2O emission was approximately equal to the negative GWP by CH_4 uptake (Table 3).

3.3. Relationship between GHGs and GWP

Regardless of grazing or not, a significantly positive correlation was found between total GWP and NEE (Fig. 2b; $R^2 = 1$, N = 27, $P < 0.001$), showing that the variability in total GWP was mainly determined by NEE (Fig. 2b). Neither CH_4 nor N_2O flux was correlated with GWP regardless of grazing treatment (Fig. 2a, c).

3.4. Relationship between environmental factors and GWP

Under the no grazing treatment, total GWP was significantly linearly related to soil temperature ($R^2 = 0.575$, $P < 0.001$), precipitation ($R^2 = 0.349$, P = 0.001), and air temperature ($R^2 = 0.195$, P = 0.021) (Fig. 3a–c). The effects of air temperature ($R^2 = 0.284$, P = 0.004), relative humidity ($R^2 = 0.206$, P = 0.02), and soil moisture ($R^2 = 0.145$, P = 0.05) on total GWP were more pronounced under the grazing treatment (Fig. 3a, d, e). The optimum SEM for the no grazing treatment was significant (Fig. 5a; $\chi^2 = 13.369$, P = 0.1, d. f. = 8). Environmental factors explained 97% of the variance in GWP ($R^2 = 0.97$), and air temperature (Path coefficient = 0.77, $P < 0.05$), precipitation (Path coefficient = 0.61, $P < 0.05$) had significant direct effects on GWP (Fig. 4a). Under the summer grazing treatment, the optimized SEM was also significant (Fig. 5b; $\chi^2 = 7.089$, P = 0.214, d. f. = 5). The variance of total GWP explained by environmental factors decreased to 85% ($R^2 = 0.85$), with significant direct effects of soil temperature (Path coefficient = 0.63, $P < 0.05$), precipitation (Path coefficient = 0.37, $P < 0.05$), and soil moisture (Path coefficient = 0.33, $P < 0.05$) on GWP (Fig. 4b).

3.5. Relations between plant biomass and GWP

No significant linear relations were found between above-ground biomass, below-ground biomass and GWP (Fig. 5).

4. Discussion

4.1. Effect of summer grazing on total GWP

The effect of grazing on GWP depended on time (year) and steppe type (Fig. 1). Previous studies have found GHG tradeoffs associated with grazing intensity and stage, and these changes varied for each GHG (Liebig et al., 2010; Shi et al., 2017). However, to date few studies have focused on the effect of grazing on total GWP in grasslands. Based on our SEM models, environmental factors accounted for 97% and 85% of the variance in GWP in the no grazing and summer gazing regimes, respectively (Fig. 4). The pathways by which environmental factors, vegetation type, soil properties, and their interaction effects affect total GWP should be investigated further in additional grazing experiments in the future.

Though summer grazing had significant effect on GWP in some experiment years, the mean GWP values for the three years of data

Table 3
Relative contributions (%) of net ecosystem exchange (NEE), CH_4, and N_2O to global warming potential under no grazing and summer grazing treatments at meadow (MS), typical (TS), and desert steppe (DS) sites. Data are shown as mean + standard error.

		CH_4 contribution (%)		NEE contribution (%)		N_2O contribution (%)	
		NG	SG	NG	SG	NG	SG
MS	2012	1.9 ± 0.2	2.0 ± 0.1	100.1 ± 0.3	103.9 ± 0.9	−2.0 ± 0.3	−5.9 ± 0.9
	2013	1.6 ± 0.1	0.6 ± 0.1	99.5 ± 0.1	100.8 ± 0.4	−1.1 ± 0.1	−1.4 ± 0.4
	2014	0.6 ± 0.1	0.4 ± 0.1	100.0 ± 0.1	100.1 ± 0.1	−0.6 ± 0.0	−0.5 ± 0.1
	mean	1.1 ± 0.1	0.7 ± 0.1	99.9 ± 0.1	100.8 ± 0.4	−1.0 ± 0.1	−1.5 ± 0.5
TS	2012	1.1 ± 0.1	0.9 ± 0.1	99.6 ± 0.3	100.3 ± 0.2	−0.7 ± 0.3	−1.2 ± 0.1
	2013	0.6 ± 0.2	0.7 ± 0.1	100.2 ± 0.2	100.0 ± 0.3	−0.8 ± 0.1	−0.8 ± 0.2
	2014	0.4 ± 0.1	0.6 ± 0.1	100.9 ± 0.1	100.3 ± 0.0	−1.3 ± 0.2	−0.9 ± 0.2
	mean	0.9 ± 0.1	0.7 ± 0.1	100.3 ± 0.2	100.0 ± 0.2	−1.2 ± 0.2	−0.7 ± 0.2
DS	2012	2.4 ± 0.1	2.6 ± 0.1	99.3 ± 0.2	100.0 ± 0.4	−1.7 ± 0.2	−2.7 ± 0.4
	2013	1.9 ± 0.3	1.9 ± 0.4	100.0 ± 0.5	100.3 ± 0.6	−1.9 ± 0.3	−2.2 ± 0.3
	2014	1.8 ± 0.5	1.4 ± 0.1	103.4 ± 0.4	102.5 ± 0.7	−5.2 ± 0.3	−3.9 ± 0.7
	mean	2.0 ± 0.3	1.9 ± 0.2	100.8 ± 0.3	101.2 ± 0.6	−2.9 ± 0.2	−3.1 ± 0.5

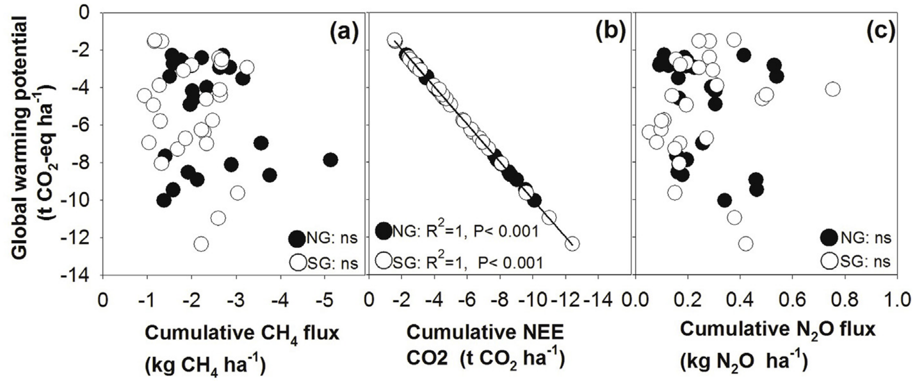

Fig. 2. Relationships between global warming potential and cumulative GHG fluxes [CH_4 (a), Net ecosystem exchange (b), and N2O (c)] under no grazing (NG) and summer grazing (SG) conditions.

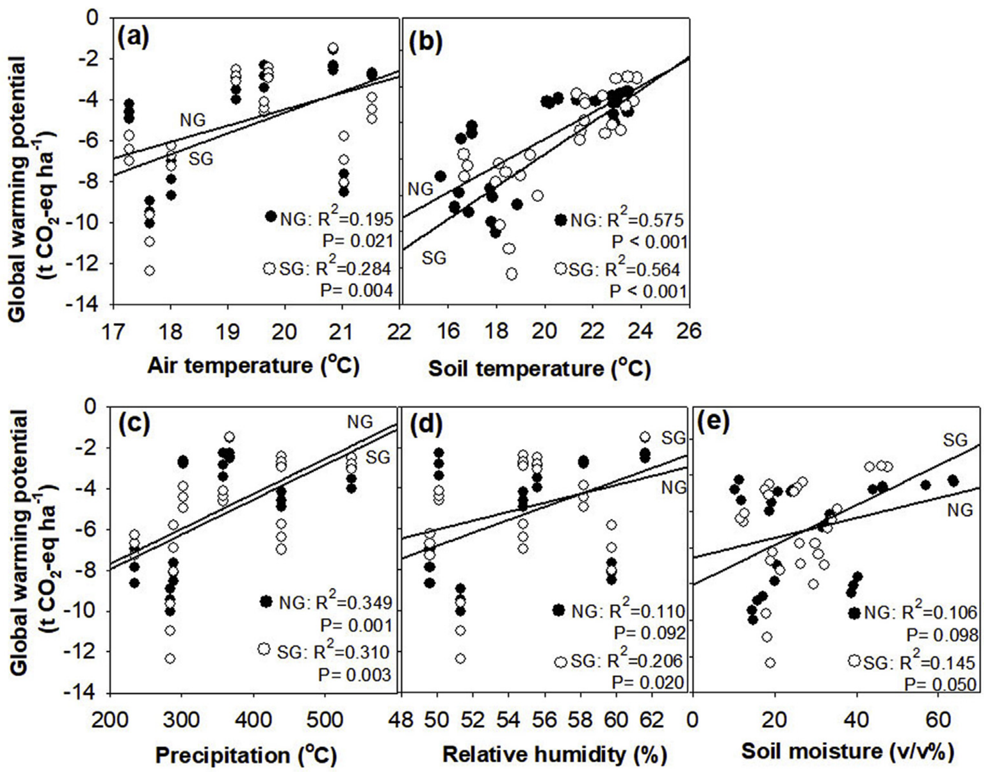

Fig. 3. Effects of environmental factors on global warming potential under no grazing (NG) and summer grazing (SG) treatments.

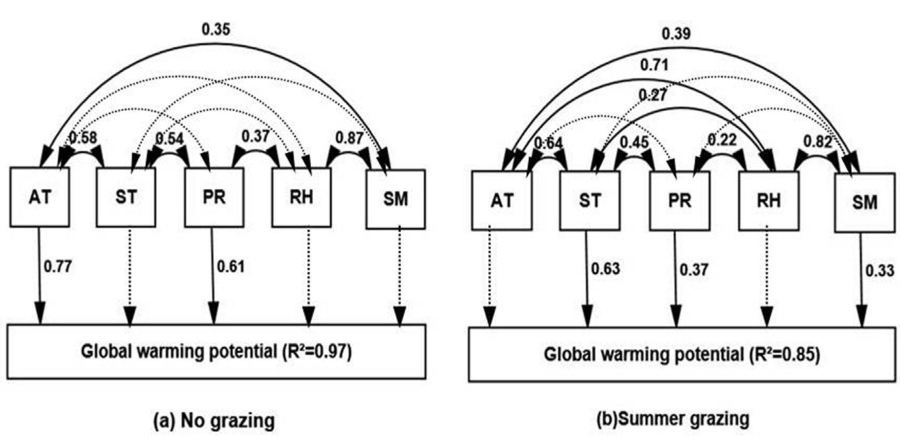

Fig. 4. Structural equation models (SEMs) of global warming potential via pathways of air temperature (AT), soil temperature (ST), precipitation (PR), relative humidity (RH), soil moisture (SM)] under no grazing (a) and summer grazing (b) treatments. Results of model fitting: (a: χ^2 = 13.369, P = 0.1, d. f. = 8; b: χ^2 = 7.089, P = 0.214, d. f. = 5). Solid arrows and dashed arrows denote significant (P < 0.05) and non-significant effects (P > 0.05); Values associated with single-headed arrows are the direct path coefficients between the factor and global warming potential. Values associated with double-headed arrows indicate the correlation coefficients between two environmental factors.

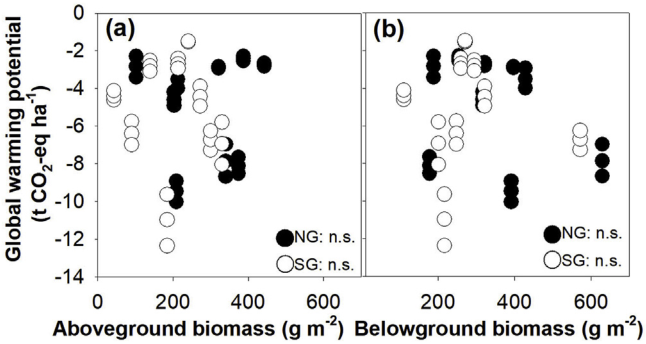

Fig. 5. Effects of above-ground biomass (a) and below-ground biomass (b) on global warming potential under no grazing (NG) and summer grazing treatment (SG).

collected in this study were significantly different (Fig. 1). This indicates that over many years, summer grazing may have little effect on total GWP. In a laboratory experiment modelled after alpine grassland, application of dung by grazing animals and a 15-day incubation considerably increased total GWP (Cai et al., 2013). There are three reasons that may account for the difference between the findings of Cai et al. and ours. First, the Cai et al. (2013) studied soil qualities, whereas we studied the whole ecosystem. That is, in our experiment, we also recorded the size of the above-ground biomass. Second, the effect of grazing on the ecosystem is complex, and involves both changing plant biomass by growth and changing soil properties directly (Hou et al., 2016). In contrast, application of dung alone changed only the chemical properties of the soil. Third, environmental factors (i.e. air temperature and humidity) changed under grazing, while these factors were controlled for in the laboratory study. In a long-term evaluation of grassland ecosystems in the northern Great Plains of North America, Liebig et al. (2010) indicated that moderate stocking rates can promote soil organic carbon accumulation and potentially reduce global warming by decreasing total GWP. Thus, we speculate that from a management point of view moderate grazing can be a sustainable land use regime for grasslands.

Summer grazing increased the effect of soil moisture on total GWP (Fig. 3). The SEM model indicated that the major factors affecting total GWP were air temperature and precipitation under the no grazing treatment, and soil temperature, soil moisture, and precipitation under the summer grazing treatment (Fig. 4). This may be due to the fact that grazing decreases canopy biomass and changes the properties of the soil by trampling and nutrition return (Hou et al., 2016).

4.2. Total GWP mostly determined by NEE

NEE was the largest contributor to total GWP in temperate grassland sites studied here (Table 3). Similar results have also found at Auchencorth Moss and Easter Bush (Skiba et al., 2013). In our experiment, the main reason why NEE was the largest contributor was that the positive GWP induced by N_2O flux was nearly equal to the negative GWP induced by CH_4 flux (Fig. 1, Table 3). Other studies have shown that the directions of CH_4 and N_2O flux are opposed in Inner Mongolian steppe sites (e.g. Yao et al., 2010; Zhang et al., 2014; Shi et al., 2017). In a study by Skiba et al. (2013), GWP was induced by both N_2O and CH_4 emissions, but this counteracted the NEE sink strength by 0.3% and 2.8%, respectively. However, in our study we found that NEE contributed a very high proportion of total GWP.

The contribution of each GHG to total GWP has been shown to vary in different ecosystems or soils. In paddy soils, CH_4 accounted for 79–81% of the total GWP. In peat bog, the contributions of CH_4 and N_2O to total GWP were very small (Beetz et al., 2013). These differences can be attributed to differences in environmental factors, vegetation characteristics, and soil properties in different ecosystems (Mosier et al., 2005; Drewer et al., 2012; Beetz et al., 2013; Tian et al., 2015). Because the individual contributions of any one GHG can vary, total GWP is a better estimate of the feedback of one ecosystem to global warming. Further study of the mechanisms responsible for these changes should be performed in multiple ecosystems in multi-year experiments.

4.3. Spatial and temporal variation of GWP

All three steppe environments had cooling effects over the growing season (i.e. showed negative GWP values), which implies that grassland ecosystems play a positive role in mitigating global warming, which is supported by previous studies of European grasslands (Soussana et al., 2009; Schulze et al., 2009; Imer et al., 2013).

There were significant differences in total GWP among steppe types (Fig. 1; Table 2). The typical steppe showed the largest cooling effects, suggesting that this ecosystem is the most effective at in mitigating global warming. In our experiment, NEE was the most important component of total GWP (Table 3). NEE represents the tradeoff balance between fixing carbon via photosynthesis and releasing carbon via respiration (Beetz et al., 2013; Hou et al., 2016). A previous study has shown that soil and plant canopy respiration is significantly higher in meadow steppe than in typical steppe ecosystems (Hou et al., 2016). Moreover, this result was confirmed by Cai et al. (2013) in a laboratory experiment using alpine grassland soil. There, soil moisture was found to be significantly and positively related to soil respiration (Cai et al., 2013; Hou et al., 2016), and the soil moisture in the meadow steppe ecosystem was significantly higher than in the typical steppe ecosystem (Hou et al., 2016).

We also found that total GWP varied greatly among years, which is similar to the results in semiarid grasslands and other ecosystems (Dijkstra et al., 2013; Beetz et al., 2013; Drewer et al., 2012). This variation is due to the fact that the most important factor in GWP (i.e. NEE) showed significant differences among years (Fig. 1, Liebig et al., 2010); this is evident from the significant linear relationship between NEE and total GWP (Fig. 2b). Both air temperature and precipitation were important factors determining total GWP (Fig. 4a), and these also varied among years. In other ecosystems, changes in environmental factors among years induced corresponding variation in plant components, growth, and soil chemistry. Each of these factors can affect GHG flux and thereby affect total GWP (Dijkstra et al., 2013; Beetz et al., 2013; Drewer et al., 2012). In addition, we also found that the factors determining total GWP varied among the different ecosystems we examined. However, future studies examining these relationships are required. We therefore suggest that such studies should use multi-year field data to obtain accurate estimates of total annual GWP.

4.4. Limitations

Despite the inclusion of whole growing season measurements taken on the same days of the year to estimate the effects of steppe types and grazing conditions on GWP, there are limitations regarding our results. First, GWP was calculated only during growing season, meaning that we do not report GWP values for the non-growing season, which may influence the carbon balance in these regions. Second, the accumulation of CO_2 and CH_4 flux may be important during the growing season, but the accumulation of N_2O flux during spring thaw can also be important (Wolf et al., 2010; Merbold et al., 2014). In a previous study of grassland ecosystems in North America, Liebig et al. (2010) reported that the positive GWP induced by N_2O emissions was about eightfold that of the negative GWP induced by CH_4 uptake (Liebig et al., 2010). Third, although we chose an area of $100 \times 100\ m^{-2}$ to study differences among steppe types, spatial heterogeneity also added uncertainty to the estimated total GWP for each steppe type (Cheng et al., 2014; Tian et al., 2015).

In our experiment, using three typical steppes, we term the differences in GWP as the spatial variation of GWP, some uncertainties need to considered. The experimental sites in our experiment are all typical representative, but to quantitatively discuss the spatial variation of GWP is still a series of typical sites.

5. Conclusion

Measured differences in total GWP during growing season was almost entirely due to NEE. In addition, the negative GWP induced by CH_4 uptake was nearly equal to the positive GWP induced by N_2O emissions. After analyzing data from several years, we found that moderate grazing did not significantly change the direction or magnitude of total GWP in temperate steppe. Both air temperature and precipitation were strong predictors of variation in GWP ($R^2 = 0.97$) in the no grazing treatment. In contrast, soil moisture and temperature were stronger predictors of total GWP in the summer grazing treatment.

Author contributions

L.H.Z., L.H.L and L.Y.H designed the study, L.Y.H., H.Q.S. and Y.L. conducted the study, and L.Y.H., Y.L., D.S.T, and B.X.W wrote the paper.

Additional information

Competing financial interests: The authors declare no competing financial interests.

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