Long-term grazing effects on soil-atmosphere exchanges of CO$_2$, CH$_4$ and N$_2$O at different grasslands in Inner Mongolia: A soil core study

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**ABSTRACT**

Regional greenhouse gas (GHG) budgets in vast grasslands may be changing due to overgrazing and grassland types. However, the comprehensive effects of grazing patterns, environmental factors and grassland types on soil carbon dioxide (CO$_2$), methane (CH$_4$) and nitrous oxide (N$_2$O) exchanges have been poorly studied. This study investigates the effects of long-term grazing on the soil-atmosphere exchanges of CO$_2$, CH$_4$ and N$_2$O in important processes within different grasslands in Inner Mongolia, China. Using manual static chamber and gas chromatography, we measured the fluxes of CO$_2$, CH$_4$ and N$_2$O from intact soil cores of paired grazed/ungrazed sites collected from two typical steppes (Stipa grandis and Leymus chinensis): one wetland in a flood plain and one desert steppe in the region of the Xilin River catchment, Inner Mongolia. Soil gas flux and concentration measurements were conducted in four simulated conditions (i.e., drought, dry-wet, intense rainfall and freeze-thaw), which represent important processes in annual GHG exchanges. Extreme drought significantly inhibited CO$_2$ and N$_2$O emissions in all plots but did not change the CH$_4$ uptake by typical steppes. Dry-wet transition and intense rainfall could remarkably promote soil CO$_2$ emission pulses at different types, significantly decrease CH$_4$ uptake by typical steppes, and arouse N$_2$O emission pulses at all plots with different times of occurrence. During the freeze-thaw simulation, temperature-induced soil CO$_2$ emission and CH$_4$ uptake/emission presented a clear alternative variation, while soil thaw only slightly increased (< 15 μg N m$^{-2}$ h$^{-1}$) in the steppes and sand dunes and was significantly higher in the wetland (11–96 μg N m$^{-2}$ h$^{-1}$). Long-term grazing significantly inhibited soil respiration rates at all grassland types, significantly decreased CH$_4$ uptake by the Leymus chinensis steppes, and did not show significant influence on N$_2$O emission due to large spatial variations for all types. Compared to the ungrazed $L_e$ymus steppes, $S_t$ipa steppes, sand dune and wetland, continuously grazed sites were significantly reduced by 22%, 38%, 48% and 47% in total GHG emissions, respectively. Our results indicate that the potential of the steppe soil CH$_4$ sink function can be offset by N$_2$O emission, especially in over-grazed plots. Furthermore, N$_2$O emissions should be considered in wetland rangelands with significantly higher N$_2$O emission potential (range: 0–343 μg N m$^{-2}$ h$^{-1}$) more than steppes (range: 0–132 μg N m$^{-2}$ h$^{-1}$) and sand dunes (range: 0–49 μg N m$^{-2}$ h$^{-1}$). Nevertheless, comprehensive evaluation of the grazing effect on ecosystem GHG emissions merits consider in both field observation and incubation experiments because soil properties and environmental factors could be changed by vegetation growth in different grazing practices.

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Semiarid grassland 
Grazing 
Freeze-thaw 
Dry-wet 
Intense rainfall 
Inner Mongolia

1. Introduction

Temperate steppes, covering approximately one-tenth of the earth’s land surface, play important roles in greenhouse gas (GHG) emissions or uptake (Sutie et al., 2005). In general, steppe soils serve as a reservoir for large amounts of organic carbon and a sink or source of carbon dioxide (CO$_2$), methane (CH$_4$) and nitrous oxide (N$_2$O) exchanges have been poorly studied. This study investigates the effects of long-term grazing on the soil-atmosphere exchanges of CO$_2$, CH$_4$ and N$_2$O in important processes within different grasslands in Inner Mongolia, China. Using manual static chamber and gas chromatography, we measured the fluxes of CO$_2$, CH$_4$ and N$_2$O from intact soil cores of paired grazed/ungrazed sites collected from two typical steppes (Stipa grandis and Leymus chinensis): one wetland in a flood plain and one desert steppe in the region of the Xilin River catchment, Inner Mongolia. Soil gas flux and concentration measurements were conducted in four simulated conditions (i.e., drought, dry-wet, intense rainfall and freeze-thaw), which represent important processes in annual GHG exchanges. Extreme drought significantly inhibited CO$_2$ and N$_2$O emissions in all plots but did not change the CH$_4$ uptake by typical steppes. Dry-wet transition and intense rainfall could remarkably promote soil CO$_2$ emission pulses at different types, significantly decrease CH$_4$ uptake by typical steppes, and arouse N$_2$O emission pulses at all plots with different times of occurrence. During the freeze-thaw simulation, temperature-induced soil CO$_2$ emission and CH$_4$ uptake/emission presented a clear alternative variation, while soil thaw only slightly increased (< 15 μg N m$^{-2}$ h$^{-1}$) in the steppes and sand dunes and was significantly higher in the wetland (11–96 μg N m$^{-2}$ h$^{-1}$). Long-term grazing significantly inhibited soil respiration rates at all grassland types, significantly decreased CH$_4$ uptake by the Leymus chinensis steppes, and did not show significant influence on N$_2$O emission due to large spatial variations for all types. Compared to the ungrazed $L_e$ymus steppes, $S_t$ipa steppes, sand dune and wetland, continuously grazed sites were significantly reduced by 22%, 38%, 48% and 47% in total GHG emissions, respectively. Our results indicate that the potential of the steppe soil CH$_4$ sink function can be offset by N$_2$O emission, especially in over-grazed plots. Furthermore, N$_2$O emissions should be considered in wetland rangelands with significantly higher N$_2$O emission potential (range: 0–343 μg N m$^{-2}$ h$^{-1}$) more than steppes (range: 0–132 μg N m$^{-2}$ h$^{-1}$) and sand dunes (range: 0–49 μg N m$^{-2}$ h$^{-1}$). Nevertheless, comprehensive evaluation of the grazing effect on ecosystem GHG emissions merits consider in both field observation and incubation experiments because soil properties and environmental factors could be changed by vegetation growth in different grazing practices.

**References:**

Sutie et al., 2005.
methane (CH$_4$) and nitrous oxide (N$_2$O) (Soussana et al., 2007). The size of sinks or sources in steppe soils is strongly controlled by the physical factors of soil (e.g., texture, organic matter and soil temperature moisture) but also by land uses (e.g., grazing and reclaiming) and climate change (e.g., rainfall and air temperature) (Galbally et al., 2008). Due to the large area and the mitigation potential, clarification of soil-atmosphere exchanges of GHG in temperate steppes is crucial to our understanding of the global C/N cycle and mitigation options.

The GHGs (e.g., CO$_2$, CH$_4$ and N$_2$O) are produced or consumed as a result of microbial processes in the soil (Galbally et al., 2008). The soil-atmosphere fluxes of GHGs heavily depend on the physical factors of soil, which affects the microbial processes of production, consumption and gas transport in the soil (Smith et al., 2003). Soil temperature and water content have been reported to be the two most important factors linked to soil GHG fluxes (e.g., Wang et al., 2005; Wang and Fang, 2010). They directly affect production and consumption of GHGs through their effects on microorganisms and root activity. In addition, gas diffusivity, which depends on air-filled porosity (and thus varies inversely with water content), controls the movement of the gases to and from the atmosphere and indirectly controls the capacity of microbial processes by affecting soil aeration. Studies have shown that a large amount of water input during periods of freeze-thaw, dry-wet and intense rainfall could contribute greatly to annual GHG budgets (e.g., Hao et al., 2010; Wolf et al., 2010; Yao et al., 2010). Wolf et al. (2010) found that the N$_2$O pulses during spring thaw dominate the annual N$_2$O emission in a typical steppe. The function of a carbon sink in the grassland ecosystem may change to the source during extreme dry years (Hao et al., 2010). Soil CH$_4$ uptake in grasslands have been reported to be sensitive to soil temperature and water content at the seasonal and annual scales (Chen et al., 2011). These studies have suggested these temperature- or water-related periods are important in affecting the greenhouse gas exchange mechanisms and regional GHG budgets.

At present, most of the grasslands suffer from degradation due to overgrazing and poor management, especially arid and semiarid grassland, where 73% of rangeland is degraded (Steinfeld et al., 2006). Inner Mongolian steppes (approximately 87 million hectare), covering more than 20% of the total grassland area in China, are characterized by a typical temperate semiarid climate (Wang et al., 2005). As a major base of animal husbandry, livestock numbers have increased significantly in the past few decades and most natural steppe have been facing the accelerating threats from overgrazing (Tong et al., 2004). Overgrazing has resulted in widespread rangeland degradation or desertification of steppes, associated with changes in soil properties (Kang et al., 2007), plant diversity and productivity (Gao et al., 2011) or activities of soil microorganisms (Su et al., 2005). Recently, it was shown that the potential of soils to acts as a sink or source of atmospheric CH$_4$ or N$_2$O in steppes may have been reduced significantly if heavily grazed continuously for three years (Wolf et al., 2010; Chen et al., 2011). This indicates that greenhouse gas exchange in steppe ecosystems might have changed significantly with the expansion of degraded grasslands and global warming. Furthermore, these steppe types are characterized by a typical temperate semiarid climate with a significant inter-annual variability (Liu et al., 2008). However, the comprehensive estimate of grazing practices and environmental factor effects on total GHG exchanges during freeze-thaw, dry-wet and intense rainfall periods have been rare until now. In addition to typical steppes, wetland rangelands (e.g., flood plain and river valley meadows) and sand dune rangelands are very valuable grazing places due to plentiful water supply, rich vegetation, special water storage performance or leeward side for winter grazing. However, the grazing effect on GHG emissions from these two types of rangeland has been poorly studied. Thus, both aspects indicate the large uncertainties of these important parameters for regional GHG budgets.

The objective of this study is to understand the effects of steppe types, grazing practices and environmental factors on the potential of soil GHG exchanges. Using soil core incubation and gas chromatography methods, we determined the fluxes of CO$_2$, CH$_4$ and N$_2$O from intact soil cores of paired grazed/ungrazed sites collected from two typical steppes (Stipa grandis and Leymus chinensis), one wetland in a flood plain and one desert steppe in the region of the Xilin River catchment of Inner Mongolia. The flux measurements were conducted in four simulated conditions (i.e., dry, dry-wet, intense rainfall and freeze-thaw), which represent important processes in annual GHG exchanges. In addition, soil GHG concentrations at four depths (5, 10, 20 and 30 cm) were selectively measured to further understand soil-atmospheric GHG exchanges. The differences of GHG exchange rates under various combined conditions and possible mechanisms are estimated and discussed.

2. Materials and methods

2.1. Study region

The study was conducted in different grassland ecosystems located in the Xilin River catchment near the Inner Mongolia Grassland Ecosystem Research Station (IMGERS, 43°38' N, 116°42' E; 1100 m a.s.l.) of the Chinese Ecosystem Research Network. The local climate is characterized as a temperate continental climate. In this region, the growing season usually starts in early May and ends in late September, and the remaining seven months are the non-growing season, when grass vegetation and roots are dormant. The 25-year mean annual air temperature (1982–2007) recorded by IMGERS was 0.7 °C, with a mean January temperature of ~21 °C and a July mean of 19 °C. The annual mean precipitation is 330 mm (range: 166–507 mm yr$^{-1}$ in 1982–2007), of which 85% falls between May and September. The average air temperature and precipitation values (mostly in snowfall) during the non-growing season were ~8.7 °C and 52 mm.

The typical steppe covers approximately 85% of the area of the Xilin River catchment. The most common typical steppe types are communities either dominated by Stipa grandis or Leymus chinensis. The soil types of the Stipa grandis and Leymus chinensis steppes are kastanozem and chernozem, respectively. Sand dunes, occupying 6.5% of the study area, are characterized by undulating topography, where sand forms a sequence of depressions and hills. Dense vegetation, particularly Ulmus pumila and other tree genera, i.e., Betula spp., Malus spp., Prunus spp. and Populus spp. dominate north- to northwest-facing slopes, as well as in depressions. South- to southwest-facing slopes generally have sparser shrubs and grassland vegetation. Wetland covers only a tiny portion of the study area (approximately 0.4%). It borders most of the Xilin River, its tributaries and some flat areas of episodic streams. These areas are divided into two parts: dry and wet marshland. Dry marshland is frequently wet, but it becomes dry during one to three months of the summer. In contrast, wet marshland is wet all year round. However, wet marshland has also been noted to dry out during years with low summer rainfall (approximately 100 mm). The vegetation found in these areas consists mainly of marshland species such as Phragmites australis, Carex appendiculata, Iris lactea var. chinensis and Hippuris vulgaris.

2.2. Soil core sampling

Grazing practices (or stocking rate) and grassland type are indicators of soil GHG emissions or uptake in grasslands. It is crucial to consider these two indicators to find the best balance point in grassland quality and GHG emissions, and then select suitable grazing patterns for local grassland management. Paired experimental rangelands or plots under ungrazed and grazing practices in the Xilin River catchment were established by IMGERS. To determine the long-term grazing effect on the potential of soil GHG exchanges, four paired plots were chosen, including one plot that has remained ungrazed since 1979 (SUG79), and an adjacent, continuously grazed rangeland (SCG) at Stipa grandis steppe; one plot that has remained ungrazed since 1979 (LUG79) and...
Table 1
Grassland managements and soil properties at paired ungrazed and grazed grasslands in Inner Mongolia.

<table>
<thead>
<tr>
<th>Grassland type</th>
<th>Site code</th>
<th>Location</th>
<th>Management</th>
<th>Stocking rate (sheep ha(^{-1}) yr(^{-1}))</th>
<th>Bulk density (g cm(^{-3}))</th>
<th>pH</th>
<th>Total C (mg g(^{-1}))</th>
<th>Total N (mg g(^{-1}))</th>
<th>CaCO(_3) (mg g(^{-1}))</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Säpa grandis</em> steppe</td>
<td>SUG79</td>
<td>N 43°32'32&quot; E 116°40'15&quot;</td>
<td>Ungrazed since 1979</td>
<td>0</td>
<td>1.06(^{ab})</td>
<td>7.5(^{a})</td>
<td>1.54(^{d})</td>
<td>0.22(^{b})</td>
<td>0.1</td>
<td>60.3</td>
<td>31.3</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>SCG</td>
<td>N 43°32'22&quot; E 116°40'03&quot;</td>
<td>Continuously grazed</td>
<td>2.34</td>
<td>1.24(^{b})</td>
<td>6.9(^{a})</td>
<td>1.22(^{a})</td>
<td>0.17(^{a})</td>
<td>0.1</td>
<td>62.4</td>
<td>28.1</td>
<td>9.5</td>
</tr>
<tr>
<td><em>Leymus chinensis</em> steppe</td>
<td>LUG79</td>
<td>N 43°33'10&quot; E 116°40'27&quot;</td>
<td>Ungrazed since 1979</td>
<td>0</td>
<td>0.87(^{a})</td>
<td>6.9(^{a})</td>
<td>1.63(^{d})</td>
<td>0.19(^{bc})</td>
<td>0</td>
<td>73.5</td>
<td>17.3</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td>LCG</td>
<td>N 43°33'05&quot; E 116°40'54&quot;</td>
<td>Continuously grazed</td>
<td>2.05</td>
<td>1.00(^{ad})</td>
<td>6.9(^{a})</td>
<td>0.51(^{c})</td>
<td>0.07(^{a})</td>
<td>0</td>
<td>86.7</td>
<td>9.5</td>
<td>3.8</td>
</tr>
<tr>
<td>Sand dune</td>
<td>SDUG02</td>
<td>N 43°37'57&quot; E 116°42'04&quot;</td>
<td>Ungrazed since 2002</td>
<td>0</td>
<td>0.98(^{d})</td>
<td>7.4(^{a})</td>
<td>2.09(^{d})</td>
<td>0.33(^{a})</td>
<td>0.1</td>
<td>80.5</td>
<td>14.2</td>
<td>5.3</td>
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<tr>
<td></td>
<td>SDGC</td>
<td>N 43°38'01&quot; E 116°41'47&quot;</td>
<td>Continuously grazed</td>
<td>1.56</td>
<td>1.45(^{c})</td>
<td>6.9(^{a})</td>
<td>2.14(^{ab})</td>
<td>0.25(^{ab})</td>
<td>0.2</td>
<td>92.4</td>
<td>4.6</td>
<td>3.0</td>
</tr>
<tr>
<td>Wetland</td>
<td>WUG89</td>
<td>N 43°37'39&quot; E 116°41'13&quot;</td>
<td>Ungrazed since 1989</td>
<td>0</td>
<td>1.11(^{c})</td>
<td>6.9(^{a})</td>
<td>2.57(^{d})</td>
<td>0.24(^{b})</td>
<td>0.9</td>
<td>45.7</td>
<td>49.4</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>WCG</td>
<td>N 43°37'09&quot; E 116°41'12&quot;</td>
<td>Continuously grazed</td>
<td>1.32</td>
<td>1.14(^{c})</td>
<td>6.7(^{b})</td>
<td>1.90(^{ad})</td>
<td>0.16(^{b})</td>
<td>0.1</td>
<td>51.6</td>
<td>39.0</td>
<td>9.4</td>
</tr>
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</table>

The lower cases on the upper-right corner of each data indicate significant (p < 0.05) differences among each column.

an adjacent, continuously grazed rangeland (LCG) at the *Leymus chinensis* steppe; one plot that has remained ungrazed since 1989 (SUG89) and an adjacent, continuously grazed rangeland (WCG) in the Xilin river flood wetland; and one plot that has remained ungrazed since 2002 (SDUG02) and an adjacent, continuously grazed rangeland (SDGC) in a sand dune place near IMGERS. The paired plots have similar backgrounds regarding soil and vegetation characteristics. Animals (sheep and goats) could walk freely during the grazing seasons in all grazed plots. All long-term fenced plots had significantly higher values in vegetation height, coverage and plant density, compared to adjacent grazed rangelands. Detailed location, grassland managements and soil properties at paired ungrazed and grazed grasslands are shown in Table 1.

Soil core sampling at the paired plots in four types of grasslands was conducted on September 20, 2008. The grass above ground were cut off to near the ground surface before sampling. At each plot or rangeland, undisturbed soil cores at a depth of 0–40 cm were taken in quintuplicates using specialized semi-column steel pipe and were put in manual chambers. Manual chambers were made from non-transparent polyvinyl chloride (PVC) pipe (diameter, 16 cm; length, 60 cm; volume, 4.0 L; basal area, 0.02 m\(^2\)) with a twist lid and a bottom (PVC) with a butyl rubber septum and a rubber O ring to form a gas-tight seal. After drying approximately 40 days until topsoil of soil cores was completely dried.

2.3. Experimental design of soil core incubation

Gas fluxes and soil gas concentrations were measured using the sampled soil core in manual chambers and gas chromatography techniques under different stimulated dry-wet, intense rainfall, freeze and thaw cycles(Table 2). We conducted undisturbed soil core incubation and these measurements for each grassland type in sequence and the detailed steps as follows:

2.3.1. Soil activation

More than ten months in storage has resulted in completely dry soil cores, thus we activated soil cores by adding a simulated 15 mm rainfall event before starting the measurement. Standard rain mixture included 11 mg CaCl\(_2\), 24.4 mg KCl, and 18.6 mg Na\(_2\)SO\(_4\) in 1000 mL of distilled water.

2.3.2. Drought simulation

After activation, all soil cores were placed at room temperature for approximately 40 days until topsoil of soil cores was completely dried. Then, we put all soil cores in electronic controlled incubators, which can regulate air temperature, and kept the air temperature at 20 °C. Fluxes of CO\(_2\), CH\(_4\) and N\(_2\)O were measured for three days during the simulated drought condition. Hereafter, the rainfall simulation and flux measurement were conducted in the incubator at room temperature.

2.3.3. Dry-wet cycle simulation

After the flux measurement under the simulated drought condition, we added 20 mm of rainfall water solution to the simulated dry-wet process. Then, GHG fluxes were continuously measured for seven to eight days until the flux variations tended to be stable. The topsoil moisture at the end time was approximately 10%-20%, which was similar to the normal values during the growing season in the grassland (mean: 15%).

2.3.4. Intense rainfall simulation

The 20 mm simulated rainfall solution was added to the soil core to simulate an intense rainfall event, aiming to evaluate the difference between grazed and ungrazed soil affected by intense rainfall in different grassland types. Similar GHG flux measurements were continuously conducted for seven to eight days until the flux was nearly stable.

2.3.5. Freeze-thaw simulation

In the steppes and sand dune, precipitation was generally small before the winter, so the topsoil moisture during the whole freeze period was low. In the following year, during snow melt and soil thawing, melted water from snow permeated into soil with air temperature increases. Soils were frozen at low temperatures, and the freeze-thaw cycle transition occurred each day. Although soil water content mainly depends on the river flood situation, we used the same simulated condition to keep pace with other types. After completion of the second rainfall simulation and flux measurement, we removed all soil cores from incubators and kept them at room temperature until soil moisture was approximately 5%. This was to create a similar soil condition with that of the real field environment. Then, soil cores were put into freezers for 20 days to simulate the freeze period, and soil flux measurements were conducted in the end of this period. In the next step, soil cores were set into an incubator and regulated to the simulated temperature of 5 °C, which was close to the actual temperature in the beginning of the spring-thaw period. We added 20 mm of rainfall.
from the initial slope of a non-linear regression of concentration against concentration change within the chambers. The CO2 was converted to CH4 in a methanizer prior to analysis. The soil gas samples were taken from each soil core with a stainless-steel tube (inner diameter: 1 mm) near the surface of the soil cores and at 5, 10, 20, and 30 cm depth during the period of gas collection. Four hours later, we measured the GHG fluxes from soil cores during the simulated thaw period. In addition, they were then put into freezers with a temperature of −10 °C for 23–24 h, and CH4 fluxes were measured CH4 fluxes, which represented the freeze process. In the following 10–12 days, the simulation of freeze (−10 °C) and thaw (5 °C) were transformed for the GHG flux measurement every day.

2.4. Measurements of GHG fluxes and soil gas GHG concentrations

The fluxes of CO2, CH4, and N2O were measured using a static chamber method. The PVC tubes (soil cores) were sealed with stainless steel lids, enclosing a headspace of ~2 L. The lids were equipped with a circulating fan to ensure complete gas mixing. In addition, they had two freezers with a temperature of 5 °C for 23–24 h and 10 °C for 2–3 days, the simulation of freeze and thaw practices, but the CO2 fluxes showed the alternative changes (Fig. 1). All investigated plots had similar varying trends of CO2 emissions under simulated dry, dry-wet, intense rainfall and freeze-thaw periods. The wetland plots with long-term and moderate grazing did not change soil bulk density and pH but significantly reduced total carbon and nitrogen content and increased the silt content of the soil.

2.5. Statistical analysis

The significance of differences in mean GHG flux and CO2−eq. emissions among the treatments was investigated using a one-way ANOVA with Tukey’s HSD test (SPSS 11.5, SPSS Inc., Chicago, USA). All plots (line, bar and contour) were made using SigmaPlot 10.0 (SPSS Inc., Chicago, USA).

3. Results

3.1. Soil properties

At the Leymus and Stipa steppes, long-term grazing significantly reduced topsoil (0–5 cm) bulk density, the contents of total carbon, nitrogen and silt (Table 1). Although grazing duration was much less than the steppes, there were also obvious decreasing trends in bulk density, pH and silt contents at the sand dune rangelands under heavy grazing practices. The wetland plots with long-term and moderate grazing did not change soil bulk density and pH but significantly reduced total carbon and nitrogen content and increased the silt content of the soil.

3.2. Carbon dioxide fluxes and concentrations

The CO2 fluxes ranged from 0 to 92 mg C m−2 h−1 in the steppes, from 0 to 110 mg C m−2 h−1 at the sand dune rangeland and from 1 to 79 mg C m−2 h−1 at the wetland during the whole incubation period (Fig. 1). All investigated plots had similar varying trends of CO2 emissions under simulated dry, dry-wet, intense rainfall and freeze-thaw periods (Fig. 1). The weak CO2 emissions (< 10 mg C m−2 h−1) were determined at investigated plots, except WUG89 under the extreme dry period. The following two simulated rainfall events substantially promoted the CO2 fluxes in the first day after watering and gradually decreased to stable levels; the CO2 fluxes showed the alternative changes of “low-high-low” with simulated freeze and thaw practices, but the fluxes in freeze-thaw were significantly lower than those in dry-wet and intense rainfall processes.

In the steppe and sand dune rangelands, soil CO2 concentrations greatly varied during dry, dry-wet, intense rainfall, and freeze-thaw periods (Fig. 4a–c). Slightly higher soil CO2 concentrations (400–500 ppmv) than ambient CO2 concentrations during the dry period indicates low CO2 emissions, whereas two simulated rainfall events (i.e., dry-wet and intense rainfall practices) rapidly promoted soil CO2 production with high concentrations (steppe: 1000–1500 ppmv; sand dune: 5000–7000 ppmv). Although soil CO2

Table 2

<table>
<thead>
<tr>
<th>Site code</th>
<th>Dry period</th>
<th>Dry-wet period</th>
<th>Intense rainfall period</th>
<th>Freeze-thaw period</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUG79</td>
<td>7 ± 2bc</td>
<td>48 ± 2d</td>
<td>52 ± 2h</td>
<td>8 ± 5f</td>
</tr>
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<td>SUG</td>
<td>2 ± 5b</td>
<td>1 ± 1</td>
<td>24 ± 4h</td>
<td>7 ± 1h</td>
</tr>
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<td>LUG79</td>
<td>7 ± 1c</td>
<td>52 ± 1d</td>
<td>35 ± 1b</td>
<td>12 ± 1d</td>
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<tr>
<td>LUG</td>
<td>8 ± 1c</td>
<td>41 ± 3h</td>
<td>15 ± 1a</td>
<td>12 ± 1d</td>
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<tr>
<td>SDU02</td>
<td>1 ± 1d</td>
<td>9 ± 2d</td>
<td>1 ± 1</td>
<td>12 ± 1d</td>
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<tr>
<td>SDG</td>
<td>0 ± 0e</td>
<td>12 ± 3d</td>
<td>1 ± 1</td>
<td>12 ± 1d</td>
</tr>
<tr>
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<td>34 ± 1c</td>
<td>1 ± 1</td>
<td>4 ± 1</td>
<td>2 ± 1</td>
</tr>
<tr>
<td>WCG</td>
<td>10 ± 1b</td>
<td>2 ± 1</td>
<td>4 ± 1</td>
<td>2 ± 1</td>
</tr>
</tbody>
</table>

The lower cases on the upper-right corner of each data indicate significant (p < 0.05) differences among each column.
concentrations (< 1000 ppmv) were obviously lower than simulated dry-wet and intense rainfall events, the significant differences of CO2 concentrations were determined between simulated frozen and thaw periods. In contrast to other rangeland types, we observed the continuously higher soil CO2 concentrations (2000–6000 ppmv) at the depth of 20–30 cm in the wetland throughout all periods except the freeze-thaw period. Simulated rainfall increased the topsoil (5–15 cm) CO2 concentrations, but the increased ranges were far lower than other types.

Compared with the lowest soil moisture condition (i.e., 5%), the CO2 fluxes in the steppe and sand dune rangelands substantially increased under the conditions of 12.5% and 20% with no significant differences between them (Fig. 7a). At the wetland, CO2 fluxes gradually increased with the increase in soil moisture from 5% to 20% and had significant differences between 5% and 20%. In addition, the mean CO2 flux under the 10 °C condition (i.e., 20.5 mg C m⁻² h⁻¹) was approximately 3–13 times of that with −10 °C (Fig. 7d). Our results clearly exhibited that grazing practices significantly reduced soil CO2 fluxes by 25%–47% in all rangeland types (Fig. 8a). Using the data under all simulated conditions in all rangeland types, soil CO2 fluxes followed the order: wetland (28 mg C m⁻² h⁻¹) > sand dune (25 mg C m⁻² h⁻¹) > steppe (22 mg C m⁻² h⁻¹).

3.3. Methane fluxes and concentrations

All steppe and sand dune rangelands were CH4 sinks with the fluxes varying from −3 to −59 μg C m⁻² h⁻¹, while wetland rangelands were shifted between weak sinks or sources (−13 to 13 μg C m⁻² h⁻¹) of atmospheric CH4 under various conditions (Fig. 2). The CH4 exchange responses to simulated dry, dry-wet and intense rainfall were quite different among the steppe, sand dune and wetland rangelands. At Leymus and Stipa steppes, soil had the strongest CH4 uptake (−40 to −60 μg C m⁻² h⁻¹) under the extreme dry condition, a fast decrease in the first day after simulated rainfall and gradually increased to a similar level as the dry period in the following days. Compared with steppes, the variation range of CH4 fluxes (−2 to −25 μg C m⁻² h⁻¹) in the sand dune were smaller and the maximum of CH4 uptake occurred at the end of simulated intense rainfall. At the wetland rangelands, soils were very weak CH4 sinks (−1 to −4 μg C m⁻² h⁻¹) under dry conditions, and then were shifted to weak sources (< 13 μg C m⁻² h⁻¹) at WUG89 after simulated rainfall. During the freeze-thaw period, although the CH4 fluxes also switched to “low-high-low” pattern (Fig. 2), the flux levels were comparable with other periods.

Under all simulated conditions, soil CH4 concentrations decreased with the increase in soil depth in the investigated plots except for WUG89 after intense rainfall (Fig. 5), which was consistent with the shift of the soil CH4 sink and source. Soil CH4 concentrations in the steppes and sand dune had clear gradual gradients in different depths during the dry period, and quickly decreased after simulated rainfall, especially in deep soil (< 1 ppmv). Compared with the steppes and sand dune, the ranges of decreasing gradient were much smaller in the wetland rangelands, and soil CH4 concentrations were close to ambient concentrations after simulated intense rainfall. During the freeze-thaw period, the small differences of CH4 concentrations in soil depths occurred with simulated freeze conditions, while the large ranges occurred with the thaw simulation.

The CH4 uptake in the Leymus steppe did not greatly vary (42–46 μg C m⁻² h⁻¹) among moistures of 5%, 12.5% and 20%, but
they gradually decreased in Stipa steppes with increasing moisture (Fig. 7b). Opposite of the steppes, the CH4 uptake in the sand dune showed the positive trend with the increase in moisture. In addition, the average CH4 fluxes in wetland plots fluctuated around zero in three moisture conditions with no significant differences. With the change of air temperature from −10 °C to 10 °C, the CH4 uptake increased from 27 to 38 μg C m$^{-2}$ h$^{-1}$ in the Leymus steppe, from −11 to 30 μg C m$^{-2}$ h$^{-1}$ in the Stipa steppe, and from 4 to 20 μg C m$^{-2}$ h$^{-1}$ in the sand dune, showing the substantial effect by temperature. In contrast to the CO2 fluxes, we determined that only long-term grazing significantly reduced CH4 uptake by 37% in the Leymus steppe. Among all rangelands, soil CH4 uptake was highest in the Leymus and Stipa steppes (> 30 μg C m$^{-2}$ h$^{-1}$), followed by the sand dune (−13 μg C m$^{-2}$ h$^{-1}$) and lowest in the wetlands (Fig. 8b).

### 3.4. Nitrous oxide fluxes and concentrations

The range of N2O fluxes from steppes, sand dunes and wetlands were 0–132, 0–49 and 0–343 μg N m$^{-2}$ h$^{-1}$ (Fig. 3). Under extreme dry conditions, wetlands were weak N2O sources with an average flux of 14.5 μg N m$^{-2}$ h$^{-1}$, while the N2O fluxes were nearly 0 in other types. The first simulated rainfall aroused N2O emissions at all rangelands with the peak occurring in the first or second day and gradually decreasing in the following days. Similarly, the second simulated rainfall (i.e., intense rainfall) substantially promoted N2O emissions with higher fluxes at all rangelands except the sand dunes (Fig. 3). The Leymus steppes and sand dunes had only a quick N2O peak on the first day, but the N2O peaks in the Stipa steppes and wetlands occurred on the third and fifth days with higher N2O emissions. During freeze-thaw cycles, N2O fluxes were nearly 0 under freeze conditions and slightly increased (< 15 μg N m$^{-2}$ h$^{-1}$) with the thaw practices in the steppes and sand dunes. Although the wetlands had similar variation patterns of “low-high-low” with the simulated freeze and thaw practices, the N2O emissions (11–96 μg N m$^{-2}$ h$^{-1}$) were significantly higher than other types (Fig. 6).

Soil N2O concentrations in the steppe and sand dune rangelands were close to ambient N2O concentrations (∼330 ppbv) at the extreme dry condition and quickly increased to 500–1036 ppbv following the first rainfall in the dry-wet cycle (Fig. 6), indicating the production of N2O. The second rainfall also increased the soil N2O concentrations in the steppe rangelands, and had the maximum (2623 ppbv). Soil N2O concentrations in the wetlands gradually increased with the first and second rainfall events and reached the maximum of 20,401 ppbv. Simulated soil freeze and thaw cycles presented the pattern “low-high-low”, with significant promotion in the steppe rangelands. Compared to the steppe and sand dune, the wetland kept a continuously high soil N2O concentration, showing a stronger N2O production.

In the steppe and wetland rangelands, soil N2O emissions gradually increased with the moisture increase, from 5% to 20%, while N2O emissions remained at continuously low levels at the sand dune rangeland under all moisture conditions (Fig. 7c). The increased ranges of soil N2O fluxes were substantial at the Stipa steppe (2–83 μg N m$^{-2}$ h$^{-1}$) and the wetland (10–220 μg N m$^{-2}$ h$^{-1}$) rangelands. Compared with the frozen temperature (−10 °C), the N2O emissions had increasing trends at all rangelands, but we only determined significant differences of N2O emissions at the Stipa steppes. Furthermore, the increasing ranges of soil N2O emissions were significantly less under the two temperature conditions than that which
occurred in the different moisture conditions.

3.5. Total soil GHG emissions

The average emissions of soil GHG (i.e., CO$_2$, CH$_4$, and N$_2$O) were 83.1, 97.2, 95.5, and 14.4 tons CO$_2$ eq. ha$^{-1}$ in the investigated Leymus steppes, S$\delta$pa steppes, sand dune, and wetland rangelands, respectively (Table 2). Of the total GWPs of soil GHG emissions, CO$_2$ emission, CH$_4$ uptake/emission and N$_2$O emission had average contributions of 97.7%, −1.6% and 3.9% in the Leymus steppes and 84.7%, −1.1% and 16.4% in the S$\delta$pa steppes. Sand dune rangelands had similar contributions (CO$_2$: 97.2%; CH$_4$: −0.5%; N$_2$O: 3.3%) to the Leymus steppes. Significantly different from other types, the wetland rangelands had higher N$_2$O shares (28.4%) in total GHG emissions, where CO$_2$ emissions accounted for 71.5% and the CH$_4$ contribution could be ignored. These results indicate that the total soil GHG emissions were dominated by CO$_2$ emissions in the Leymus steppe and sand dune rangelands, and that the grazing effect on the soil GHG emissions was dependent on CO$_2$ changes. Nevertheless, the net CO$_2$ exchanges should also consider CO$_2$ uptake by plant photosynthesis, thus the roles of N$_2$O and CH$_4$ contribution could be ignored. Compared to the ungrazed Leymus steppes (i.e., LUG79), the S$\delta$pa steppes (i.e., SUG79) and sand dune (i.e., SDUG02), both continuously grazed sites, were significantly reduced by 22%, 38% and 48% in total GHG emissions, respectively (Table 2). Furthermore, these results also indicate that the potential of steppe soil as a CH$_4$ sink function can be offset by the N$_2$O emission, especially in over-grazed plots, due to the significant reduction of the soil CH$_4$ sink and enhancement of the potential of soil N$_2$O sources. In contrast, N$_2$O emissions should be considered in the wetland rangelands, as grazing has reduced GHG emissions by 47%.

4. Discussion

4.1. Carbon dioxide

Soil CO$_2$ emission rates (0–110 mg C m$^{-2}$ h$^{-1}$) under different conditions at the investigated rangelands were comparable with the reported fluxes (1–198 mg C m$^{-2}$ h$^{-1}$) in the Eurasia steppes (e.g., Cui et al., 2000; Jia et al., 2007; Wang et al., 2007; Chen et al., 2013; Gong et al., 2014) and North America prairies (e.g., Bremer et al., 1998; Zhou et al., 2006; Casasovas et al., 2012). A large number of studies have shown that soil respiration rates are closely linked to surface soil temperature and moisture (Howard and Howard, 1993). Generally, high temperature and appropriate water conditions can greatly promote soil respiration, and conversely, soil respiration can be inhibited in low temperature and low water supply conditions. In addition, the high water supply causes soil surface water saturation, which can also weaken the soil respiration rate. In our study, under simulated drought conditions, soil respiration rates from all types of grasslands were weak, mainly due to a severe lack of water to reduce the microbial activity, thereby reducing the microbial regulation of isotonic respiration (Nakano et al., 2008). There was some soil respiration in the wetland under the dry condition, which was mainly caused by CO$_2$ generation from the underlying soil by the wetting and CO$_2$ diffusion of the surface soil. Rainfall can affect soil respiration by influencing the biological activity of the soil and the amount of water required for root growth (Reference). In arid ecosystems or dry-wet transition seasons, rainfall events can strongly arouse soil respiration (Jia et al., 2006; Hao et al.,
Similarly, this phenomenon also appears in our study, with the appearance of a quick CO₂ emission pulse after each rainfall event. In arid or semiarid ecosystems, soil respiration has a positive correlation with water content that is below the saturated water content of the soil. Our study shows that, except for sand dunes, the surface soil moisture content after the second rainfall at the other three types of grassland were higher than the first after the rainfall, and the soil respiration after second rainfall is higher than the first time. Under frozen conditions, soil respiration rates were very weak, since very low temperature greatly inhibited the activity of soil microbes. When the soil was thawed, the surface soil temperature was recovered and therefore promoted the recovery of microbial activity. However, the soil respiration intensity was still weak compared to that under the 20 °C condition because the soil temperature and microbial activity had a significant positive correlation.

Overgrazing will reduce soil respiration in semiarid grassland soils, mainly because excessive grazing greatly reduces the substrate organic carbon of soil heterotrophic respiration and attenuates the autotrophic respiration of the underground part of a plant (Wang and Fang, 2010). For management of low grazing intensity, it is generally believed that the growth of plant roots under- ground will be promoted to increase soil respiration (Chen et al., 2011). Thus, in the grazing tests with low grazing intensities, there was no significant difference or significant increase in soil respiration compared with the ungrazed site. In this study, all four selected types of grassland including a long-forbidden grazing plot, a long-term continuous grazing rangeland and long-term grazing have significantly changed the grassland vegetation and soil characteristics. Our incubation experiments showed that grazing had little effect on the soil respiration rate under the conditions of drought and freeze-thaw in all grass types because the activity of soil microbes in the ungrazed and grazing areas was strongly inhibited. However, long-term continuous grazing significantly reduced the soil respiration rate under appropriate temperature and rainfall conditions, which indicates that soil carbon, nitrogen and microbial activity reduction caused by grazing were only manifested under appropriate hydrothermal conditions.

4.2. Methane

Negative CH₄ fluxes from soil core incubation indicate the uptake is by steppes, which are consistent with field measurements in this region (Wang et al., 2005; Liu et al., 2007; Chen et al., 2011). The CH₄ uptake rates (3–59 µg C m⁻² h⁻¹) in the investigated steppes fall into a range of different ecosystems in arid and semiarid regions (2–105 µg C m⁻² h⁻¹), including deserts, prairies, croplands and steppes (e.g., Mosier et al., 1996; Galbally et al., 2008; Chen et al., 2011). The results of our experiments showed that typical steppes and sand dune grasslands still obviously absorbed the CH₄ in the atmosphere under the very dry condition of the surface soil. Before the start of incubation experiments, we added 15 mm of water to activate the soil microbes, which would be more likely to penetrate deeper into the soil in the arid soil cores. Thus, after more than a month of evaporation, although the surface soil moisture content has been very low (< 5% v/v) and the activity of CH₄ oxidizing bacteria was very low at the
surface, the atmospheric CH$_4$ can also be diffused to the more humid soil and then oxidized. In the first day after the simulated rainfall, soil surface gas diffusion reduced CH$_4$ diffusion from atmosphere to the soil due to a large amount of water input, so there appeared to be short and weak CH$_4$ absorption, and CH$_4$ absorption gradually increased followed by the surface soil water evaporation. These change characteristics were more obvious in typical steppes than other types. Because the soil texture is loose and the water permeability is better, the input of water was transferred to the deep soil over time, and the surface soil did not accumulate a large amount of water to affect the soil diffusion. Thus the response of the CH$_4$ absorption to the rainfall in the sand dune rangeland may not be sensitive. For soil cores collected from wetlands, these soils have been in place for nearly a year and the surface soil had been very dry when we started measurements. However, the soils in the lower part (20–40 cm) remain moist. At this time, the wetland soil can be considered a natural grassland soil after the river water retreated. The CH$_4$ flux was almost zero, meaning there was a balance between soil CH$_4$ emission and absorption. Our simulated 20 mm rainfall looks as though it is not enough to change this situation. The alteration of CH$_4$ uptake in typical steppes and sand dune rangeland was also obvious under freezing and thawing conditions due to the large alteration of temperature (−10 °C and 10 °C). This mainly accounted for the change of microbial activity in the surface soil, which influenced CH$_4$ absorption (Chen et al., 2011). Generally, when the soil temperature is lower than −5 °C, the activity of soil CH$_4$ oxidizing bacterial will be greatly reduced (Smith et al., 2000).

The order of CH$_4$ uptake rates in the different types of grassland was Leymus chinensis steppe ≥ Stipa Grandis steppe > Sand dune > Wetland. For the typical steppe, the results showed that the grazing significantly inhibited the CH$_4$ uptake by the Leymus chinensis steppe, which was consistent with the field observation (Chen et al., 2011; Liu et al., 2007). Severe grazing significantly reduced the annual CH$_4$ uptake, mainly due to the remarkable decrease in surface soil gas permeability. Although we did not detect the gas permeability of the soil cores during the incubation periods, the soil bulk density (0.99 g cm$^{-3}$) of the long-term grazing in the Leymus chinensis steppe was higher than that of the forbidden grazing area (0.87 g cm$^{-3}$), which may also suggest that the gas permeability of the grazing rangeland was low. However, the soil bulk density (1.24 g cm$^{-3}$) was also significantly higher than that of the forbidden grazing plot (1.06 g cm$^{-3}$), but we did not detect the significant effect of grazing on the Stipa grandis steppe. This suggests that in addition to the gas permeability reduction, the reducing soil microbial activity by vegetation changes and induced environmental factors (e.g., soil temperature and moisture) was also important for the grazing reduction effect on CH$_4$ uptake by the Stipa grandis steppe.

The soil CH$_4$ sink function of the two types of typical steppes was significantly higher than that in the sand dune and wetland rangelands (p < 0.05). Most of sand dune areas used for grazing are formed by overgrazing or reclamation in a typical grassland. The grass coverage on the sand dune rangeland is very sparse, and the microbial activity in the soil was significantly lower than that of the typical steppes. The
sand dune rangelands can be regarded as typical steppes under extreme overgrazing conditions; therefore, CH$_4$ uptake capacity of sand dune rangelands were significantly lower than that of the typical steppes (Chen et al., 2013). For the seven years of forbidden sand dune rangelands, although vegetation has been restored, our incubation experiment indicates that the soil CH$_4$ sink capacity has not been improved. This result may be different from field observations in view of the effects of vegetation alone on the activity of soil microorganisms or the changing environmental factors (e.g., soil temperature and moisture). However, for degraded grasslands or sand dunes under excessive grazing practices, there is still large uncertainty as to whether the CH$_4$ sink capacity could be restored to natural grassland or how long it will take to recover. Mosier and Delgado (1997) found that the soil CH$_4$ oxidation rate was only one-third that of the natural grassland when the arable land was converted into grassland for 50 years. Smith et al. (2000) considered the CH$_4$ oxidation rate when the original grass was reclaimed or fertilized and found that the recovery was slow and takes more than 100 years to recover to the CH$_4$ absorption rate before interference.

In addition, our incubation experiment suggests that the seasonal river floodplain wetland did not function as a CH$_4$ sink after river water retreat, and grazing had no significant effect on the weak absorption or discharge of CH$_4$. This means that with the depletion or reduction of grassland water resources, the wetland soil was the only weak source or sink and can be ignored in the regional CH$_4$ budget. For the flood plain, when the river flows over the surface of the wetlands, the wetlands are a strong source of atmospheric CH$_4$. In addition, Hirota et al. (2005) have reported that grazing can reduce CH$_4$ emissions from alpine wetlands in the short term by affecting the ventilation of aquatic plants. Although some CH$_4$ emission observations were carried out in the Inner Mongolia floodplain wetlands, most of them were on grazing wetlands. For grazed and ungrazed comparisons, there was little research to understand the impact of grazing on CH$_4$ emissions from floodplains, which would also help to estimate regional CH$_4$ budget.

4.3. Nitrous oxide

The N$_2$O emission rates from the soil core incubation of steppes (0–132 μg N m$^{-2}$ h$^{-1}$) and sand dunes (0–49 μg N m$^{-2}$ h$^{-1}$) fall in the range of field measurements (Mosier et al., 1996; Wang et al., 2005; Wolf et al., 2010). Many studies have shown that soil N$_2$O emissions are positively correlated with soil moisture (Mosier et al., 1996; Steffens et al., 2008). In our study, the N$_2$O emissions of the three types of grassland under drought conditions were weak. Insufficient water supply would reduce the activity of microorganisms during nitrification and denitrification, resulting in a decrease in soil N$_2$O production. In general, heavy rainfall during the wet and dry transition process will stimulate the N$_2$O pulses, which are reflected in many field observations and indoor experiments (e.g., Teepe et al., 2004; Holst et al., 2008; Yao et al., 2010). We found that, in addition to the Leymus chinensis steppe, there was a N$_2$O emission pulse in the other three types of grassland in the short term after rainfall, especially after continuous rainfall. The surface soil moisture content will be greatly increased, which greatly improved the nitrification and denitrification process by
Fig. 7. Soil CO₂, CH₄ and N₂O fluxes from investigated grasslands (Leymus steppe, Stipa steppe, Sand dune and Wetland) in different air temperature and soil moisture conditions. Two temperatures represent conditions of freeze period and thaw period, respectively. Three values of soil moisture (5%, 12.5% and 20%) averaged from dry period, dry-wet simulation period, and intense rainfall and freeze-thaw periods, respectively. These values of soil moistures were rounded to nearest value. Temporal-spatial standard deviations of four soil core replicates were calculated for each data. The lowercases above or below the bars indicate the significant differences between two air temperatures and among three soil moistures.

Fig. 8. The average of soil CO₂, CH₄ and N₂O fluxes from investigated grasslands (Leymus steppe, Stipa steppe, Sand dune and Wetland) during whole incubation periods. Spatial standard deviations of four soil core replicates were calculated for each data. The lowercases above or below the bars indicate the significant differences between ungrazed and grazed plots.
providing hydrothermal conditions to increase the amount of soil N2O production. The N2O emissions were greatly reduced during the freeze-thaw conditions compared to the field snowmelt period. This may due to the large consumption of soil substrate in N2O production during two rainfall simulations and to relatively low temperatures that inhibit microbial activity. Because the texture of the surface soil was relatively loose at the typical steps and sand dunes, the rainfall water was easy to penetrate the deep soil; therefore, the surface soil moisture was easily evaporated to reduce the water conditions of soil N2O production. The surface soil density of the *Stipa grandis* steppe was 0.2 g cm⁻³ higher than that of the *Leymus chinensis* steppe. Therefore, the soil moisture in the topsoil was easy to accumulate after rainfall and formed a high humidity condition, which was beneficial to the production of soil N2O. The wetland soils in the flood plains were wetter at the deeper depth. After wetting, the wetland soil had a strong water retention capacity and provided a high humidity condition. Moreover, wetland soil can provide more organic substrate, so the wetland soil N2O emissions should be much higher than the other three types.

The order of soil N2O emission rate of different types of grassland was Wetland > *Stipa Grandis* steppe > Sand dune > *Leymus chinensis* steppe. In general, long-term grazing affects the bulk density and porosity of the surface soil, which could easily form an anaerobic zone to increase the N2O emission potentials under rainfall conditions (Steffens et al., 2008). In addition, sheep feces in heavily grazed plots were obviously greater than in other soil cores. Thus, through leaching with rainfall, animal feces nutrients may provide more reaction substrates for soil denitrification bacteria. However, in the four types of grasslands surveyed, we did not find that grazing had a significant effect on the soil N2O emissions. Soil N2O emission has high spatial heterogeneity, and the variation coefficient of emissions between different soil cores were as high as 80%–290% (Fig. 3), especially in the wetland. In the undisturbed soil we collected, the surface area of the soil column was only 0.02 m², and the height of gas collection in soil cores was 10 cm. This may result in large differences in hydrothermal conditions or soil organic carbon and nitrogen content in the microenvironment and thus affect the soil N2O production. Therefore, it is important to improve the spatial distribution of N2O emission in different grassland types and to increase the number of spatial samples, which plays an important role in the accurate detection of the impact of grazing management on the N2O emission in grasslands.

5. Conclusions

All steppe and sand dune rangelands were CH4 sinks (−3 to −59 μg C m⁻² h⁻¹), while wetland rangelands were shifted between weak sinks or sources (−13 to 13 μg C m⁻² h⁻¹) under various conditions. The order of CH4 uptake rate of different types of grassland is *Leymus chinensis* Steppe > *Stipa grandis* steppe > Sand dune > Wetland. Wetland showed significantly higher N2O emission potential (range: 0–343 μg N m⁻² h⁻¹) than the steppes (range: 0–132 μg N m⁻² h⁻¹) and sand dune (range: 0–49 N m⁻² h⁻¹). The order of soil CO2 emission in the four types of forbidden grazing sites was Wetland > Sand dune > steppes, but there was no statistically significant difference considering both grazed and ungrazed sites. Grazing significantly reduced the soil respiration rate of different types of soils and only significantly inhibited the absorption of CH4 in *Leymus chinensis* steppe; we did not find a significant effect on soil N2O emissions. Compared to the ungrazed *Leymus* steppes, *Stipa* steppes, sand dune and wetland, continuously grazed sites were significantly reduced by 22%, 38%, 48% and 47% in total GHG emissions, respectively. Our study found the potential of the steppe soil CH4 sink function can be offset by N2O emission, especially during overgrazing practices, which indicates a net GHG budget might mainly depend on the net CO2 exchange. In addition, N2O emissions in wetland rangelands during dry periods should be considered in the regional N2O budget due to the higher emission potential. However, it is important to comprehensively consider results from both field observation and incubation experiments to evaluate the grazing effect on ecosystem GHG emissions because soil properties and environmental factors could be changed by vegetation growth in the field.

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