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Effects of mowing on N_2O emission from a temperate grassland in Inner Mongolia, Northern China

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Abstract

Grazing and mowing are two common practices for grassland management. Mowing is now recommended as an alternative to traditional grazing for grassland conservation in Inner Mongolia, northern China. Many studies have revealed that both mowing and grazing may alter ecosystem properties in various ways. However, little attention has been paid to the effect of mowing on trace gas emissions, especially on N_2O flux. In this study, we conducted an experiment to investigate the effects of mowing on N_2O fluxes from a semiarid grassland in Inner Mongolia. The mowing experiment, which started in 2003, comprised four mowing intensity treatments, i.e. mowing heights at 2, 5, 10 and 15 cm above the soil surface, respectively, and a control of non-mowing, with five replicates. Gas fluxes were measured through a closed static chamber technique during the growing seasons (usually from May to September, depending on local climate at the time) of 2008 and 2009, respectively. Our results showed that mowing decreased N_2O emissions, above-ground biomass and total litter production. N_2O emissions were greater in May and June than in other sampling periods, regardless of treatments. A co-relationship analysis suggested that variations in seasonal N_2O fluxes were mainly driven by variations in soil moisture and microbial biomass nitrogen, except in July and August. In July and August, above-ground plant biomass and soil total nitrogen became the major drivers of N_2O fluxes under the soil temperatures between 16 °C and 18 °C. Overall, our study indicated that the introduction of mowing as a management practice might decrease N_2O emissions in grasslands, and both mowing height and soil properties affected the magnitude of the reduction. Our findings imply that grasslands, along with proper management practices, can be a N_2O sink mitigating the rise of N_2O in the atmosphere.

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1 Introduction

The temperate steppe in northern China is a typical vegetation type on the Eurasian continent and is sensitive to anthropogenic disturbances and climate changes (Christensen et al., 2004; Niu et al., 2009). Both mowing and grazing are prevailing management practices in these areas (Tix, 2005). Recently, mowing was highly recommended for sustainable grassland management in a national project called Grain for Green, which aims to restore the degraded ecosystems in western China (Liu et al., 2009). Mowing, the removal of a part of plant shoot tissue, has negative effects on overall plant growth and carbon allocation (Ferraro, 2002), which can influence the root carbon exudation and the rhizosphere organisms that rely on the nitrogen released from the plant roots (Hamilton et al., 2008). The removal of some plants by mowing inevitably leads to the adjustment of the size of the root system and thus causes the death and decay of the roots and nodules, followed by decomposition, mineralization of nitrogen, nitrification and denitrification. Mowing also reduces the input of above-ground litter into the soil (Valko et al., 2012), and consequently decreases the amount of coarse organic matter in the soil (Mikola et al., 2009) and related gas emissions from the soil, including nitrous oxide (N_2O).

N_2O is a vital greenhouse gas, and it contributes approximately 6 % to the anticipated global warming (IPCC, 2007). The global atmospheric N_2O concentration increased from a preindustrial value of 270 to 322 ppb in 2008 (IPCC, 2007). N_2O emitted from soils is considered as one of the major contributors to this rise (Wrage et al., 2001). Denitrification is a key ecological process that determines N_2O production in an ecosystem. Related studies suggest that N_2O emissions would be determined by soil properties and processes including soil temperature, soil moisture, substrate availability (Wrage et al., 2001), soil diffusive characteristics, air-fillled porosity (Neftel et al., 2000), the activity of nitrifying/denitrifying microbial communities (Steenwerth, 2008) and concurrent N_2O consumption processes in the soil (Cavigelli, 2001). The complexity of these factors, which regulates N_2O production, consumption and emission, results in considerable uncertainties in estimating actual N_2O exchange rates for given management scenarios.

Both grazing and mowing alter soil properties in grasslands, subsequently affecting the grassland N cycle, including soil N_2O emission. Wolf et al. (2010) found that grazing decreased grassland N_2O release via changing soil and environmental conditions. Sørensen et al. (2008) reported that mowing altered N cycling by decreasing soil N mineralization. Other aspects of grazing, such as random urine and faeces deposit of livestock, increased N_2O emissions (Yanulki et al., 1998). Therefore, it is necessary to quantify the changes in N_2O emission caused by mowing to fully understand the regional budget of trace gases.

However, there is no information available on how mowing affects N_2O emission (Calanca et al., 2001), and findings from grazing management cannot be extrapolated to those from mowing, as defoliation by grazing is more frequent and not comparable to mowing. To quantify N_2O fluxes in response to different mowing intensities, we conducted an experiment setup in 2003 with different mowing heights in a steppe ecosystem in Inner Mongolia of northern China. Here, we present results of N_2O fluxes over the two growing seasons (from May to September) of 2008 and 2009, analysing the relation between N_2O emission and abiotic and biotic factors to identify the controls of the emission. We hypothesize that (1) mowing will decrease N_2O emission due to the removal of a part of plants above the soil surface, which can result in continuous decreases in the availability of substrate and nutrient for N_2O production (Berliner, 1999) and the related soil microbes; (2) both soil biotic and abiotic factors play important roles in underlying mowing effects on N_2O flux.

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2 Material and methods

2.1 Study site

This study was carried out at the Duolun Restoration Ecology Research Station, Institute of Botany, Chinese Academy of Sciences (IBCAS), which is located in Duolun County (116°17′ E, 42°02′ N) in Inner Mongolia, China. The area is situated in a semi-arid, middle temperate zone and characterized by a continental monsoon climate. The mean annual air temperature is around 2.1 °C, with monthly mean temperatures ranging from −17.5 °C in January to 18.9 °C in July. The mean annual precipitation is approximately 385 mm, with 80 % of precipitation occurring from mid-June to late September. The topography is featured by low foothills at elevations of 1150–1800 m. The soil at the study site is classified as chestnut soil in the Chinese soil classification, containing 62.75 ± 0.04 % sand, 20.30 ± 0.01 % silt and 16.95 ± 0.01 % clay, with mean soil bulk density of 1.31 $g\,cm^{-3}$ and a pH value of 7.12. The dominant plant species in the temperate grassland are *Stipa krylovii* Roshev., *Cleistogenes squarrosa* (Trin.) Keng., *Artemisia frigida* Willda, *Potentilla acaulis* L., *Allium bidentatum* Fisch. Ex Prokh. and *Agropyron cristatum* (L.) Gaertn.

2.2 Experimental design

Mowing experiment was set up in 2003 and consists of one control and four mowing height treatments: non-mowing control (M_{ck}), mowing heights at 2 cm (M_2), 5 cm (M_5), 10 cm (M_{10}) and 15 cm (M_{15}) above the soil surface, respectively, in a complete randomized block design, with five replicates. The five treatments were randomly assigned to the five plots of 10 m × 20 m, being part of a block design (i.e. five in total), where adjacent blocks were separated by 4 m. Any adjacent blocks and plots within a block were 4 m apart from each other. Mowing with complete removal of the plant cuttings was carried out in late August each year starting in 2003. The ambient precipitation data from 2008 to 2009 were provided by a meteorological station in an open field,

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which is approximately 2 km away from the experimental site and run by the Duolun Restoration Ecology Research Station, IBCAS. Prior to the setup of the experiment, the site had been kept free from disturbance and large animal grazing by fencing since 2001.

2.3 N_2O flux measurements

N_2O fluxes were measured by a static chamber technique following Zhang et al. (2007). Briefly, the chamber consists of a stainless steel permanent base (50 cm × 50 cm × 12 cm) and a stainless steel top (50 cm × 50 cm × 50 cm). The base, with a 3 cm-deep groove on the upper side for water sealing, was driven into soil down to 12 cm each year approximately a month before the measurement started in each plot (Song et al., 2009). The top is covered by heat-isolating and light-impenetrable materials outside and equipped with one rubber septa for gas sampling and two electric fans inside for mixing the air in the chamber headspace continuously and thoroughly (Wang and Wang, 2003). During the measurements, the top was installed over the base, with downsides into the groove. The grooves were filled with water to seal the chamber. Gas samples were collected at 10 min intervals for 30 min (i.e. 0, 10, 20 and 30 min) through the septa using 60 l syringes with airtight stopcocks. All gas samples were brought to a laboratory at the research station for N_2O analyses within 12 h after sampling. N_2O concentration was analysed using a gas chromatograph (HP 5860, Agilent Technologies). N_2O flux was calculated from the linear slope of the mixing ratio changes in the four samples taken at 0, 10, 20 and 30 min after the chamber was closed. The N_2O flux was measured weekly from June to September in 2008 and biweekly from May to September in 2009. Concurrent with the N_2O flux sampling, air temperature in the chamber, soil temperature and soil moisture next to the chambers were measured using a portable digital thermometer. Air temperature was measured at 40 cm height above the soil surface, and soil temperature was measured at 5 cm depth.

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2.4 Measurements of vegetation and soil

Prior to experiments in 2008 and 2009, vegetation variables were measured once at peak biomass (i.e. August). A 1 m × 1 m frame with 100 equally distributed grids of 10 cm × 10 cm was put above the canopy adjacent to the flux chambers in each 10 m × 20 m plot. The coverage of each species was visually estimated following Yang et al. (2011) in all the grids, and then summed as the total coverage for the quadrat. After the measurement of the coverage, all plants were clipped at ground level within the quadrat of 1 m^2 and separated into living vegetation as total biomass (i.e. above-ground biomass, ANPP; see also Zhang et al., 2012) and dead plant materials as standing litter. The total litter was the sum of the standing litter and litter collected on the surface within the quadrat. All plant materials sampled were oven dried at 70 °C for 48 h and weighed.

Soil samples (0–10 cm layer) were collected monthly during the 2009 growing season using a soil corer (5 cm diameter) at the time of the fourth gas sampling. At each soil sampling, three soil cores were taken randomly at each plot and mixed evenly. These samples were separated into two set of sub-samples: one set was stored at 4 °C for microbial analysis, and the other was air-dried for soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) analyses as well as soil temperature (ST), soil moisture (SM), soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) for identifying the controls of N_2O fluxes (for details see Zhang et al., 2012).

2.5 Statistical analysis

A repeated measure analysis of variance (ANOVA) was performed to examine interannual variability in SOC, TN and TP with the pooled data of all treatments during the growing season. Between-subject effects were evaluated as mowing effects and within-subject effects were the time-of-season. Regression analyses were made between N_2O fluxes and the measured variables (e.g. ST, SM, SOC, TN, TP, MBC, MBN and ANPP, total litter, total coverage). Because some parameters were measured at different times, we used the means of the whole growing season. Therefore, every variable had five replicates and five treatments. Differences in seasonal cumulative N_2O flux, total litter and ANPP among treatments were determined by analysis of simple one-way ANOVA. To examine which variable had the most important effect on N_2O fluxes, a stepwise multiple regression analysis was applied between the whole growing season mean N_2O fluxes (as an independent variable) and the measured variables (as dependent variables). All statistical analyses were conducted with the SAS 8.0 software package (SAS Institute Inc., Cary, NC, USA).

3 Results

3.1 Climate

The study area received 370 mm and 185 mm of rain for 2008 and 2009, respectively, and showed great variations in temporal distribution (Fig. 1). Most of the rain fell over the summer months (from June to August), which accounts for 90 % of the annual total precipitation in the two years. Soil temperature and moisture varied seasonally at this site (see Zhang et al., 2012). Briefly, soil temperature at 5 cm depth ranged from 13.1 to 31.1 °C with an average of 22.3 °C in 2008, and 8.5 to 27.9 °C with an average of 18.1 °C in 2009. The temperature also generally correlated negatively with mowing height. Soil moisture peaked in July and had similar temporal fluctuation patterns over the two growing seasons, although the rainfall that occurred in this area was substantially different during the same period. However, no consistent relationship was observed between soil moisture and mowing height.

3.2 Effect of mowing on total coverage, above-ground biomass and litter

Total coverage, above-ground biomass and litter measure in 2009 (prior to the N_2O experiment) are presented in Table 1. The mowing treatments did not significantly affect plant coverage, regardless of mowing heights ($P > 0.05$). The above-ground biomass and total litter decreased progressively as cutting height decreased from 15 cm to 2 cm, except for the above-ground biomass of M_5 in 2008, and significantly lower litter mass was found for the M_2 and M_5 treatments ($P < 0.01$). This was also observed for ANPP, indicating that a cutting height > 10 cm has little effect on net primary productivity. Above-ground biomass and total litter were markedly lower in 2008 compared with 2009, except for the M_2 treatment in ANPP. These results indicated that the effects of higher cutting heights (M_{15} and M_{10}) on net primary production were limited in this grassland ecosystem. We also observed that the above-ground biomass and total litter were significant differences in the two years, except for the above-ground biomass of treatment M_2, suggesting that a significant year effect existed in the grassland (Table 1). In addition, the biomass of *Artemisia frigida*, a species with low height, contributed most of the total biomass of M_2 and M_5 plots relative to that of the control, M_{15} and M_{10} plots (data not shown).

3.3 Temporal dynamics in N_2O fluxes

Mean N_2O emission rates from the different mowing treatments varied in a range of −31.7 to 67.2 $\mu g\, N_2O\, m^{-2}\, h^{-1}$, with means of 12.7, −4.2, 4.8, −5.2 and 4.1 $\mu g\, N_2O\, m^{-2}\, h^{-1}$ for treatments of M_{ck}, M_{15}, M_{10}, M_5, and M_2, respectively, over the growing season of 2008, and means of 13.6, −9.0, 3.7, −2.9 and 5.5 $\mu g\, N_2O\, m^{-2}\, h^{-1}$ for M_{ck}, M_{15}, M_{10}, M_5, and M_2, respectively, in 2009 (Fig. 2). The variation of N_2O fluxes was relatively narrow in the dry year (2009) compared with the wet year (2008) (Fig. 2).

The higher variation in N_2O emission rate resulted in high variation in the monthly cumulative N_2O flux, with a range of 0.48 to −0.35 $kg\, N_2O\, ha^{-1}$ over the two growing seasons (Fig. 3). Figure 3 also indicates that the grassland could possibly function as a N_2O source (positive value), but that it has also frequently acted as a N_2O sink (negative flux values). Regardless of the mowing heights, surprisingly, the monthly cumulative N_2O flux was negative in July for most of the treatments, except for the controls both in 2008 and 2009 and the M_{10} and M_2 in 2008 (Fig. 3).

3.4 Effects of mowing on N_2O fluxes

Table 1 presents the seasonal cumulative N_2O emissions based on a linear interpolation, spatially averaged, of daily or monthly mean fluxes. Over the two growing seasons, an estimated amount of $0.22\,kg\,N_2O\,ha^{-1}$ per season was emitted in the control treatment, of which more than 88 % occurred in May and June. Occasionally, negative values were observed in the control and other mowing treatments (Fig. 2). The estimated seasonal cumulative emissions in the different treatments ranged from $-0.08\,kg\,N_2O\,ha^{-1}$ to $0.1\,kg\,N_2O\,ha^{-1}$ in 2008, whereas they fluctuated from $-0.27\,kg\,N_2O\,ha^{-1}$ to $0.33\,kg\,N_2O\,ha^{-1}$ in 2009 (Table 1). M_{ck} and most of the mowing treatments acted as net sources of N_2O, except for the M_5 treatment, which promoted the grassland to uptake N_2O from atmosphere, with an estimated cumulative flux of $-0.08\,kg\,N_2O\,ha^{-1}$ (Table 1) in both 2008 and 2009. For the total fluxes over the two growing seasons, the value for M_5 was the only mowing treatment significantly different from that of the control ($p < 0.05$). Compared with the control, the M_{15}, M_{10}, M_5 and M_2 mowing treatments decreased N_2O emission by 96, 40, 180 and 0 %, respectively, in 2008 (Table 1), and by 182, 82, 124 and 118 %, respectively, in 2009 (Table 1). Over the two-year period, the M_{15}, M_{10}, M_5 and M_2 mowing treatments decreased the total N_2O emission by 159, 73, 36 and 77 %, respectively, relative to the control (Table 1).

3.5 Controls of N_2O fluxes

The seasonal N_2O flux increased with increasing soil moisture content, indicating a strong influence of soil moisture on seasonal N_2O flux (Fig. 4a). The results of regression analyses showed that the closest relationship existed between the N_2O fluxes and soil moisture ($r^2 = 0.8$, $P < 0.0001$), followed by above-ground plant biomass ($r^2 = 0.30$, $P = 0.02$), and microbial biomass nitrogen ($r^2 = 0.16$, $P = 0.14$) in this experiment (Fig. 4a, b, and d). A significant linear relationship between N_2O fluxes and soil total nitrogen was only observed within soil temperatures ranging from 16 to 18 °C

(Fig. 4f). Our stepwise regression analyses showed that a combination of soil moisture (partial $R^2 = 0.42$, $P = 0.0005$), soil temperature (partial $R^2 = 0.13$, $P = 0.02$) and total phosphorus (partial $R^2 = 0.08$, $P = 0.047$) explained 62.5 % of the variation in the N_2O fluxes ($P < 0.005$) in May. Microbial biomass nitrogen explained 21.2 % of the variation in the N_2O fluxes ($P = 0.02$) in June, and soil moisture explained 21.4 % of the variation ($P = 0.02$) in July. Other factors did not contribute significantly to the explanation of the variation in N_2O fluxes in these summer months. In addition, we did not find a significant correlation between N_2O fluxes and any other variables measured at $P < 0.05$ in August and September.

Using the pooled data of the whole growing season in the different treatments, stepwise regression analyses show that microbial biomass nitrogen was a major controlling factor in N_2O fluxes in the control and the M_2 treatment, explaining 25 % and 27 % of the variation in the N_2O fluxes, respectively ($P = 0.01, P = 0.008$). Microbial biomass carbon was a major controlling factor in the M_{10} treatment, explaining 23 % of the variation in the N_2O fluxes ($P = 0.014$), and soil moisture was the most important controlling factor in the M_5 treatment, explaining 21 % of the variation in the N_2O fluxes ($P = 0.02$).

4 Discussion

4.1 Controls of changes in N_2O fluxes

Our observations, showing a decrease in N_2O with mowing height, generally supported the hypothesis that mowing would decrease the grassland N_2O emissions into the atmosphere. This was in line with others, though the mowing effects were not statistically significant in most cases. In this experiment, these observations are in line with the results of another similar investigation also conducted in a grazed grassland in Inner Mongolia (Wolf et al., 2010), but opposite to the findings in a heavily grazed alpine grassland by Gao et al. (2008). Mowing not only led to lower N_2O emission rates, but also led to lower above-ground plant and litter biomass as well as total plant coverage (Table 1), and most likely a removal of nitrogen from the system. Nitrification is commonly repressed by nitrogen limitation, which explains the decline in N_2O with mowing height. Indeed, we observed a linear relationship between N_2O fluxes and total soil nitrogen (Fig. 4f). However, this relationship was only found with soil temperatures ranging from 16 to 18 °C. This was in line with findings that N mineralization and nitrification were repressed during the growing season, but increased after that period (Both et al., 1992).

In July of 2008 and 2009, a number of weak N_2O uptake peaks occurred in some of the mowing treatments (Fig. 3a and b), leading to significant uptake of N_2O on a monthly basis (Fig. 3b). Though the temperature was favourable in July, microbial activity may decrease due to the low precipitation (Fig. 1a). Additionally, plants strongly compete for the mineralized N, leaving less N for nitrifying and denitrifying bacteria (Verhagen et al., 1994; Mikola et al., 2009). This competition may be the reason for the N_2O uptake observed in grasslands during July in our study. This result confirms that grassland soils may act as net sinks of atmospheric N_2O under certain conditions due to high N_2O reduction activity by denitrifying microorganisms (Wrage et al., 2004; Flechard et al., 2005). N_2O reduction by denitrifying microorganisms is bound to reduced levels of oxygen, which is usually related to increased moisture content (Schlesinger, 2013). Despite the different patterns of N_2O fluxes in July 2008 and 2009, soil moisture content was not very different between these months (Zhang et al., 2012). Hence, unknown soil factors might have been responsible for the observed differences in the fluxes in July.

In August, however, there was a net N_2O emission (Fig. 3b). At this time of the year, the temperature is still high enough for soil microbial activity (data not shown). Therefore soil microbes will decompose plant material and likely result in mineralization of N. However, most of the plants get senescent with more substrate released into the soil, and require fewer nutrients from the soil for growth at that time; subsequently the competition between plants and microorganisms for mineralized N will be reduced. The

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higher substrate and N availabilities likely promote microbial nitrification, leading to high N_2O production.

Using the pooled data of the whole growing season and all treatments, stepwise regression analyses show that soil moisture was the most important controlling factor in N_2O fluxes, which explains 80 % of the observed variations in seasonal average N_2O fluxes ($P < 0.0001$) at our study site (Fig. 4a). Similar results were reported for grasslands in Ireland (Leahy et al., 2004) and New Zealand (Müller et al., 2004). Therefore, soil moisture could be considered as a major control of seasonal N_2O fluxes, and determines microbial N_2O emissions (Merino et al., 2001). In some agricultural regions, soil moisture was also found to be the controlling factor in N_2O fluxes (Izaurrade et al., 2004). Because soil moisture is the key determinant of the microbial processes that consume or produce N_2O, soil moisture shifts in arid and semiarid regions will likely affect N_2O fluxes.

4.2 Effect of mowing on N_2O fluxes

The relationship between N availability and N_2O flux is commonly examined for predicting N_2O fluxes on large scales, and Millar et al. (2010) had even reported that N availability is the only factor affecting N_2O fluxes at metre scales. However, in our study, we did not find any significant correlation between total nitrogen and N_2O fluxes; combing with another result, the mowing treatments did not alter the concentrations of soil TN (including NH_4^+ and NO_3^-) (Table 2), and we may explain why there was no significant effect of mowing on the cumulative N_2O fluxes in 2008 in this study (Table 1).

Our other hypothesis is that both soil biotic and abiotic factors play important roles underlying mowing effects of decreasing plant biomass on N_2O fluxes. Since the cumulative seasonal N_2O fluxes were only slightly different among different mowing treatments, and no consistent changes were found among any of the mowing treatments (Table 1), we tested the effects of mowing on N_2O fluxes by comparing the pooled data of all the mowing treatments, including those of the control. The result suggests that mowing might decrease N_2O emissions by reducing plant litter and above-ground

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biomass (Table 1), since the decreased plant litter and biomass might result in decreases in the substrates supplied to microbes, which are in charge of nitrification and denitrification processes.

The above finding agrees with that of some previous studies. Zou et al. (2005) established a positive linear relationship between above-ground plant biomass and N_2O emissions. Kammann et al. (1998) found that increasing numbers of cuts reduced N_2O emissions. However, in other cases, for instance, Beck and Christensen (Beck, 1987) found that N_2O emissions increased when all above-ground grass was removed, and Klumpp et al. (2011) only observed that some small peaks of N_2O emission occurred in response to cutting events. Further analysis indicates that there was a significant effect of the differences in soil moisture on the N_2O fluxes after mowing (Fig. 5), which explains 76 % of the variation in the N_2O emissions induced by mowing ($P < 0.001$). Similar results were found in a study performed in grazed grasslands by Wolf et al. (2010).

Overall, our results showed that the N_2O emissions from the grassland mowed at plant heights of 5 cm were smaller than those from the grasslands not mowed during the growing season in Inner Mongolia. We may extrapolate from this finding that by changing grassland management, such as introducing a proper mowing intensity, the greenhouse effects of N_2O emission might be mitigated in the grassland. Thus, emission estimates from grasslands may need to take into account more specific management practices, for instance, mowing intensity. The most significant finding from this study is that soil moisture played a key role in the seasonal cumulative N_2O fluxes.

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Author contributions

Conceived and designed the experiments: L. L. Performed the experiments: L. Z., Q. W., C. W., D. G. Analysed the data: L. Z., Q. W., H. J. L., L. L. Contributed reagents/materials/analysis tools: L. Z., L. L., C. W. Wrote the paper: L. Z., Q. W., H. J. L., L. L.

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Table 1. Means of total plant litter ($g\,m^{-2}$), above-ground plant biomass ($g\,m^{-2}$), total plant coverage (%), and cumulative N_2O emission/uptake ($kg\,ha^{-1}$) under different mowing treatments in a steppe ecosystem in Inner Mongolia, northern China.

Treatment	Total litter		Above-ground biomass*		Total coverage		Soil moisture*		Cumulated N_2O ($kg\,ha^{-1}$)	
	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
M_{ck}	53.93*a*	124.93*a*	249.14*ab*	317.03*a*	71*a*	80*a*	12.98*a*	12.9*a*	0.10*a*	0.33*a*
M_{15}	53.16*a*	109.34*a*	277.52*a*	293.26*a*	76*a*	77*a*	12.11*a*	11.3*a*	0.004*a*	−0.27*b*
M_{10}	41.51*a*	102.43*a*	232.99*abc*	267.82*ab*	75*a*	74*a*	13.41*a*	13*a*	0.06*a*	0.067*ab*
M_5	15.22*b*	100.57*a*	170.17*c*	249.36*ab*	66*a*	76*a*	13.42*a*	12.2*a*	−0.08*a*	−0.08*ab*
M_2	4.66*b*	56.81*a*	181.04*bc*	178.09*b*	68*a*	71*a*	13.24*a*	12.8*a*	0.10*a*	−0.06*ab*

* Zhang et al. (2012).
Values represent the mean of five replicates. Different letters in a column indicate a significant difference between treatments at $P < 0.05$. M_{ck} represent the no-mowing control. M_{15}, M_{10}, M_5 and M_2 represent the treatments of plants mowed at heights of 15 cm, 10 cm, 5 cm and 2 cm above the soil surface, respectively.

Table 2. P values of repeated measures ANOVAs on the effects of mowing (M), sampling date (D) and their interactions on C/N ratio, soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) under different mowing treatments. Data with * indicate a significant difference at the $P < 0.05$ level.

Treatment		C/N	SOC	TN	TP
M_{15}	D	0.2284	0.1455	0.1636	0.1178
	M	0.2138	0.512	0.7797	0.9884
	D×M	0.0909	0.1562	0.7075	0.9653
M_{10}	D	0.1571	0.0063*	0.0368*	0.0614
	M	0.1509	0.1818	0.8528	0.6434
	D×M	0.2127	0.8222	0.845	0.9732
M_5	D	0.0168*	0.0242*	0.347	0.2438
	M	0.0722	0.0961	0.9945	0.751
	D×M	0.2579	0.6451	0.5151	0.5519
M_2	D	0.1605	0.0044*	0.0021*	0.0024*
	M	0.0607	0.1257	0.5455	0.3897
	D×M	0.5507	0.0387*	0.0682	0.345

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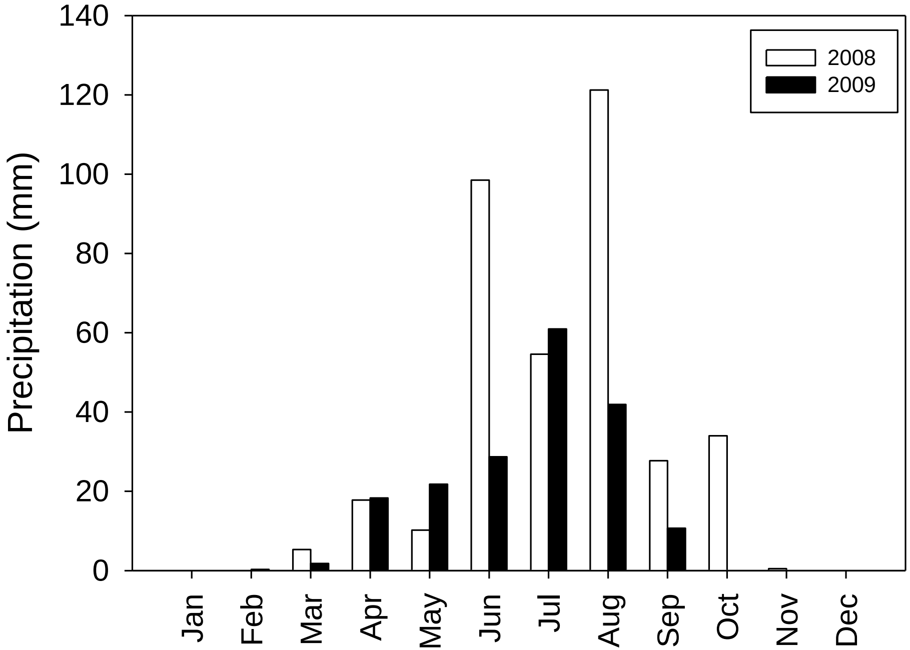

Fig. 1. Monthly precipitation in 2008 and 2009 in the study area.

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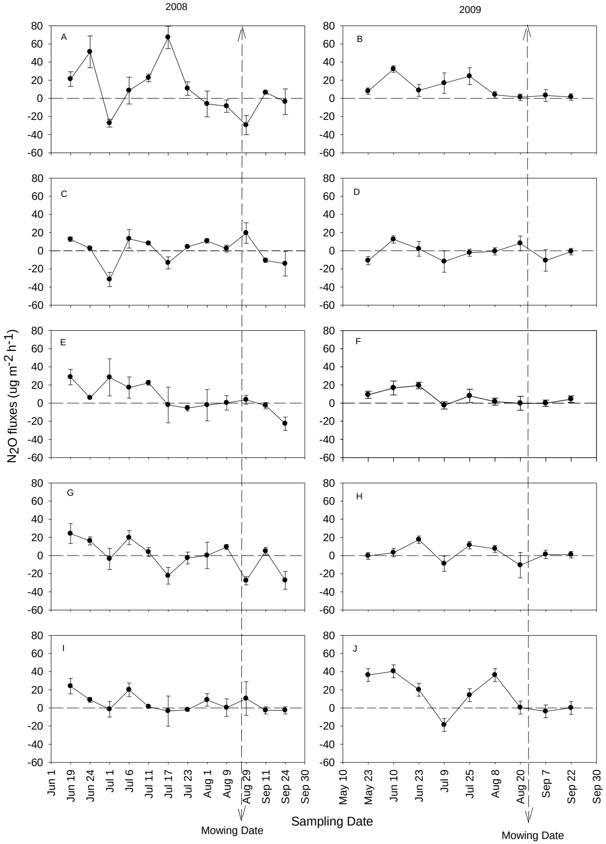

Fig. 2. Temporal variations in N_2O fluxes under different mowing treatments in 2008 (left) and 2009 (right). **(A)** and **(B)** represent the no-mowing control (M_{ck}). **(C)** and **(D)**, **(E)** and **(F)**, **(G)** and **(H)**, and **(I)** and **(J)** represent the treatments of plants mowed at heights of 15 cm (M_{15}), 10 cm (M_{10}), 5 cm (M_5) and 2 cm (M_2) above the soil surface, respectively. Data are mean ± SE ($n = 5$).

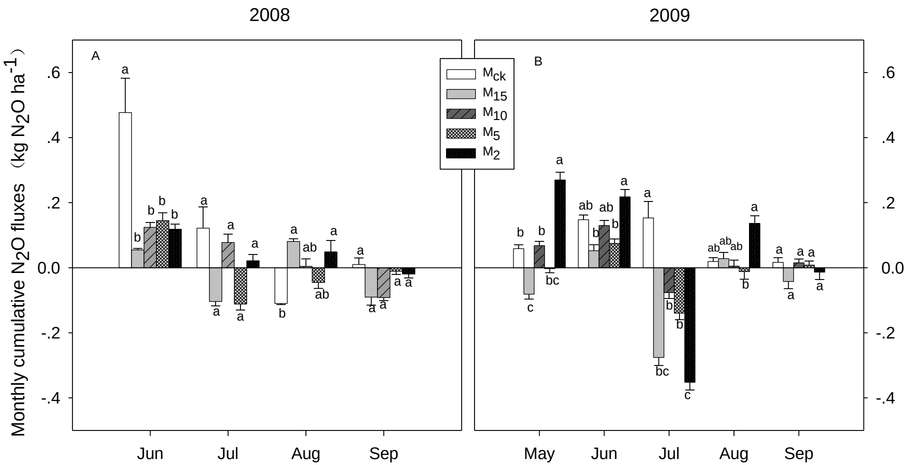

Fig. 3. Monthly cumulative N_2O fluxes in 2008 **(A)** and 2009 **(B)** under different mowing heights. Values are mean ± SE ($n = 5$). Different letters represent statistically significant differences between treatments in the same month at $P < 0.05$.

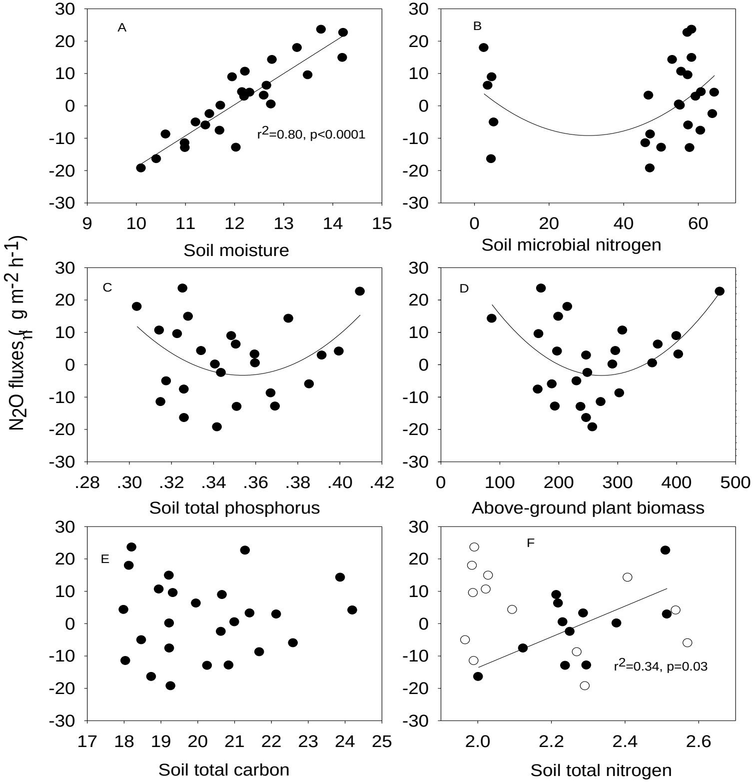

Fig. 4. Relationships between N_2O fluxes and soil moisture (%, **A**), microbial biomass nitrogen ($mg\,kg^{-1}$, **B**), total soil phosphorus ($g\,kg^{-1}$, **C**), above-ground plant biomass ($g\,m^{-2}$, **D**), total soil carbon ($g\,kg^{-1}$, **E**), total soil nitrogen ($g\,kg^{-1}$, **F**). Solid circles in **(F)** only plotted from the data obtained at soil temperatures between 16 and 18°, while the open circles represent those values measured outside of the temperature range.

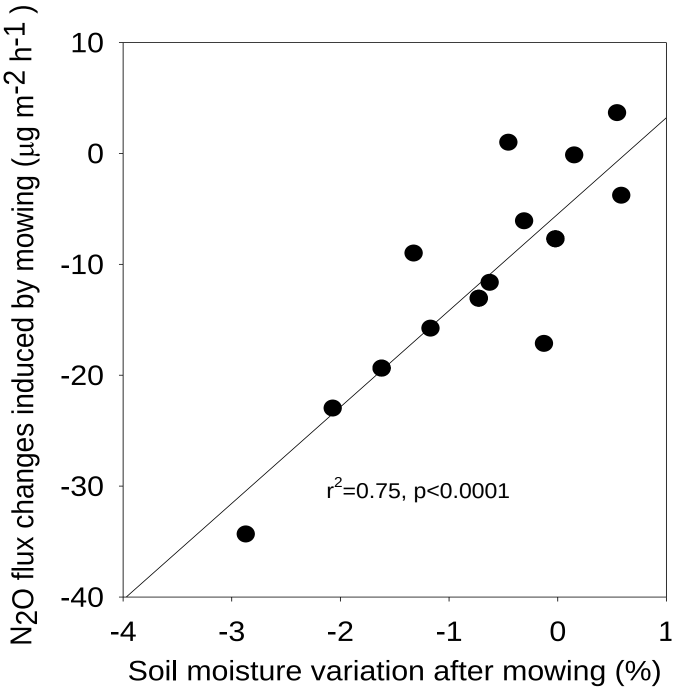

Fig. 5. The relationship between soil moisture and N_2O fluxes at sites after mowing.