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REGULAR ARTICLE

Nitrous oxide emissions from two alpine meadows in the Qinghai–Tibetan Plateau

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Abstract Nitrous oxide (N_2O) emission was measured in a *Kobresia humilis* meadow and a *Potentilla fruticosa* meadow in the Qinghai–Tibet Plateau from June 2003 to July 2006. Five treatments were setup in the two alpine meadows. Two bare soil treatments were setup in the *K. humilis* meadow (BSK) and in the *P. fruticosa* meadow (BSP) by removing the above- and belowground plant biomass. Three plant community treatments were setup with one in the *K. humilis* meadow (herbaceous community in the *K. humilis* meadow-HCK) and two in the *P. fruticosa* meadow (herbaceous community in the *P. fruticosa* meadow-HCP, and shrub community in the *P. fruticosa* meadow-SCP). Nitrous oxide emission from BSP was estimated to be 38.1±3.6 μg m^{-2} h^{-1}, significantly higher than from BSK (30.2±2.8 μg m^{-2} h^{-1}) during the whole experiment period. Rates from the two herbaceous blocks (HCK and HCP) were close to 39.5 μg m^{-2} h^{-1} during the whole experimental period whereas shrub community (SCP) showed significant high emission rates of N_2O. Annual rate of N_2O emission was estimated to be 356.7±8.3 and 295.0±11.6 mg m^{-2} $year^{-1}$ from the alpine *P. fruticosa* meadow and from the alpine *K. humilis* meadow, respectively. These results suggest that alpine meadows in the Qinghai–Tibetan Plateau are an important source of N_2O, contributing an average of 0.3 Tg N_2O $year^{-1}$. We concluded that N_2O emission will decrease, due to a predicted vegetation shift from shrubs to grasses imposed by overgrazing.

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Introduction

Despite its low abundance in the atmosphere, N_2O plays an important role in the radioactive forcing (Finlayson-Pitts et al. 2000; Houghton et al. 1992). Moreover, N_2O catalyzes the destruction of ozone in the stratosphere (Crutzen 1981) due to its long residence time (~120 years) in the atmosphere (Houghton et al. 1995). Since increasing atmospheric N_2O concentrations contribute to changes in the climate of the earth, there has been a growing interest in quantifying its significant sources and sinks in different ecosystems (Flessa et al. 2002).

It has been suggested that soils are a predominant source, contributing about 70% of the total N_2O emitted from the biosphere to the atmosphere (Flückiger et al. 1999). In this regard agricultural lands such as fertilized fields and grasslands make a great contribution to global N_2O emission (Mosier 1994). Because grasslands occupy a large proportion of terrestrial ecosystems in the globe (Adams et al. 1990), numerous studies have been conducted in grassland ecosystems for a better understanding of N_2O emissions. It shows that grasslands are a source of N_2O (Pei et al. 2004; Williams et al. 1999; Xu-Ri et al. 2003) and often exhibit higher emission rates than arable and forest soils (Oenema et al. 1998). Meanwhile, evidence shows that soil moisture (Bouwman 1996; Del Prado et al. 2006; Du 2006; Li et al. 2004), temperature (Bouwman 1996; Du 2006) and grazing (Velthof and Oenema 1997) as well as N fertilization (Del Prado et al. 2006; Stehfest and Bouwman 2006; Velthof and Oenema 1997) have a great impact on N_2O emissions from grasslands. Recent research has identified that some plants have the capacity to emit N_2O to the atmosphere (Goshima et al. 1999; Zhang and Jiang 2006; Zou et al. 2005).

As one of the most important dominant vegetation types, alpine meadows occupy 35% of the Qinghai–Tibet Plateau which extends more than 2.5 million km^2 (Zheng and Zhu 2000). Previous studies showed that alpine meadows such as *Kobresia* and *Potentilla* meadows are a weak sink of atmospheric CO_2 and CH_4 (Cao et al. 2004, 2008; Wang et al. 2004; Zhao et al. 2007). Up to date little is known about N_2O emissions from alpine meadows, although several studies have investigated N_2O emissions from alpine steppes (Pei et al. 2004). This seriously hinders our understanding of N_2O emissions as well as our budget of N_2O fluxes in the Tibet Plateau on a regional scale. Besides, it has been suggested that future changes in N_2O in response to climate change will be more strongly mediated by large-scale changes in vegetation than by direct temperature effects in wet meadows (Verville et al. 1998).

In order to clarify the effects of plant communities on N_2O emissions and thus estimate the contribution to atmospheric N_2O from alpine meadows a three year experiment was conducted in two alpine meadow types in the Qinghai–Tibetan Plateau.

Materials and methods

Site description

The study site was located at Haibei Alpine Meadow Research Station (37°32′ N, 101°15′ E, 3280 m a.s.l.), the Chinese Academy of Sciences. Annual precipitation averaged 560 mm in the past 20 years, of which 85% was concentrated in growing seasons from May to September (Li et al. 2004). Annual precipitation was 546, 536, 450 and 540 mm, while annual air temperature was −0.9, −1.1, −0.5 and −0.7°C for the year of 2003, 2004, 2005 and 2006, respectively.

A *Kobresia humilis* meadow and a *Potentilla fruticosa* meadow were selected for N_2O emission measurements. Both alpine meadows have been fenced and used as winter grazing pasture from late September to the end of April since 1982. The *Kobresia* meadow only contains a herbaceous layer, and is dominated by *K. humilis*, *Saussurea superba, Potentilla saundersiana, Leontopodium nanum*, *Lancea tibetica, Festuca ovina, Festuca rubra*, *Stipa aliena*, *Elymus nutans, Helictotrichon tibetica, Koeleria cristata,* and *Poa crymophila*. Vegetation coverage ranges from 75% to 80%, of which 98% by grasses and 2% by bare soil. The *P. fruticosa* meadow consists of two layers: a shrub layer dominated by *P. fruticosa* and an herbaceous layer dominated by *F. rubra, Stipa alpine, K. humilis* and *E. nutans* with *Polygonum viviparum, Poa pratensis* and *P. saundersiana*. Vegetation coverage ranges from 60% to

75%, of which 50% by shrubs, and 48% by grasses and 2% by bare soil (Zhou and Wu 2006). Alpine grasses are about 25–30 cm high, while alpine shrubs are 50–70 cm high.

The soils developed in alpine meadows and in alpine shrub meadows were Mat-Gryic Cambisols and Mol-Gryic Cambisols (Chinese Soil Taxonomy Research Group 1995). They are rich in organic carbon content and have an Udic soil moisture regime (Bao et al. 1995; Cao et al. 1998). The soil basic properties for both sites are presented in Table 1.

Experimental design

In May 2003, three areas, one in the *K. humilis* meadow (herbaceous community in the *K. humilis* meadow—HCK) and two in the *P. fruticosa* meadow (herbaceous community in the *P. fruticosa* meadow—HCP, and shrub community in the *P. fruticosa* meadow—SCP) were selected for this study. The net primary production (NPP) of the three communities was estimated by harvesting three squares (0.5 m^2) close to the plots which were used for N_2O measurements in 2005. It was 386.3±12.3 g m^{-2} for HCK, 341.4±17.0 g m^{-2} for HCP and 386.6±40.4 g m^{-2} for SCP. In each meadow bare soil plots were prepared by digging three pits, 1 m^2 and 1 m deep. Soils were refilled according to soil layers after roots were removed by sieving. After about 6 weeks they were used for N_2O measurements. The measurement sites are summarized in Table 2.

Samplings and measurements

Nitrous oxide emission was measured by a static chamber method (Cao et al. 2008; Wang et al. 2001). For each vegetation community three chamber bases were installed and one chamber base was placed on each bare plot. In total, 15 chamber bases were used. The stainless steel bases (0.5×0.5×0.1 m^3) were permanently placed into the ground. Sticky clay soil was used between base and soil, in order to avoid gas leakage between soil and air. Twelve plexiglas chambers (0.5×0.5×0.5 m^3) were used to collect N_2O from bare soil and grass communities. Three larger chambers (0.5×0.5×1 m^3) were used for the taller shrub communities. The chambers were equipped with two electric fans to mix the air and a thermo-probe to monitor temperature within the chamber during measurements. In order to prevent an increase of temperature inside the chambers caused by solar radiation, chambers were covered with foam and white waterproof cloth.

For flux measurement chambers were sealed onto the bases for 30 min periods between 9:00 to 10:00 o'clock in the morning. Gas samples were collected from the chambers every 10 min using 100 ml plastic syringes. Flux measurements were made every 4–5 days during growing seasons and twice per month during winter. The sampling time of 9:00 to 10:00 o'clock local time was chosen, because diurnal measurements (every 2 h) showed that these fluxes were close to the diurnal average. Throughout this study the diurnal cycle was monitored once per month, sampling every 2 h during daytime and every 3 h during nighttime. All gas samples were analyzed within 2 days of collection. There was snow cover when flux measurements were made in winter. Snow was removed outside the chamber area, but remained undisturbed inside the chambers.

The samples were analyzed by an improved gas chromatograph (HP4890D, Agilent Co. Produced)

Table 1 Basic soil properties of the two meadows

Meadow type	Soil depth (cm)	pH	Organic C (%)	Field WHC (%)	Bulk density (g cm^{-3})
Alpine *Kobresia humilis* meadow	0–10	7.3±0.4	5.5	53.6	0.75±0.05
	10–20	7.4±0.5	3.3		1.11±0.09
	20–30	–	2.7	35.9	1.13±0.04
	30–40	–	1.9		1.15±0.03
Alpine *Potentilla fruticosa* meadow	0–10	6.4±0.2	5.7	99.6	0.88±0.07
	10–20	6.3±0.3	3.7		0.96±0.04
	20–30	–	3.1	53.1	1.00±0.08
	30–40	–	2.6		1.07±0.09

WHC Water holding capacity, data from Cao et al. (1998)

Table 2 Summary of the vegetation communities used in two alpine meadows

Meadow types	Vegetation communities		
Kobresia humilis meadow	HCK herbaceous community		BSK bare soil[a]
Potentilla fruticosa shrub meadow	HCP herbaceous community	SCP shrub community	BSP bare soil[a]

[a] Removed above- and belowground biomass

system with electron capture detector (ECD). Injection/ detection and column oven (SS-3 m×2 mm× porapak Q) temperature were 55°C and 330°C, respectively. Ultra pure N_2 was used as carrier gas with a flow rate of 30 ml min^{-1} (Wang et al. 2003; Wang and Wang 2003). A certified N_2O standard with a concentration of 355 ppbv (China National Research Center for Certified Reference Materials, Beijing) was used for calibration. Analysis accuracy of samples is ±5 ppbv for N_2O measurements. The analytical range of measured concentrations is between 163 and 9,412 ppbv. Three replicates were measured for each treatment.

Soil temperature at 5 cm depth was measured using JM624 thermometer and volumetric soil moisture at 10 cm soil depth was measured by a moisture meter (Time-domain reflectometer, Campbell Scientific, Inc., North Logan, UT, USA).

Calculation, uncertainties and statistics

Hourly N_2O emissions (μg N_2O m^{-2} h^{-1}) were calculated based on the slope of the linear increase in N_2O concentration over the sampling period, as follows:

$$\mathrm{Flux}_{N_2O} = \rho \times \frac{V}{A} \times \frac{P}{P_0} \times \frac{T_0}{T} \times \frac{\mathrm{d}\,C_t}{\mathrm{d}\,t}$$

where Flux_{N_2O} is the hourly N_2O emission (μg N_2O m^{-2} h^{-1}) gas flux, ρ is gas density inside the chamber, $\mathrm{d}C_t/\mathrm{d}t$ is the slope of linear increase in N_2O concentration during sampling period, V is the volume of the chamber, A is the surface area of the chamber, P_0 is the air pressure at sea level, P is the air pressure at sampling site, T_0 is the temperature (Kelvin) at sea level and T is chamber temperature (Kelvin).

Our estimation of N_2O emissions are suffering from three uncertainties as follows: Firstly, the major uncertainty arises from low resolution of measurements of N_2O. In order to polish this uncertainty, more diurnal measurements of N_2O in these meadows are needed in future studies. Secondly, the removal of above- and below ground plant biomass might affect microbial composition as well as soil environments and thus change the production of N_2O. Thirdly, analytic accuracy of the equipment also has an impact on the estimation of N_2O emission.

The difference among treatments and correlation analysis were tested by multivariate analysis based on independent-samples T-test, whilst the correlation between N_2O emission and environment factors such as temperature and moisture by bivariate process correlations (SPSS11.5).

Results

Nitrous oxide emissions from bare soils

Bare soil patches in the two meadows (BSK and BSP) showed obvious seasonal dynamics of N_2O emissions (Fig. 1a). The maximal emission rates appeared in growing seasons from May to September, while they reached the lowest in dormancy seasons from October to the next April. Nitrous oxide emission from the BSP treatment to the atmosphere averaged 38.1± 3.6 μg m^{-2} h^{-1}, significantly higher than from the BSK treatment with a averaged rate of 30.2±2.8 μg m^{-2} h^{-1} during the entire experimental period (Table 3). Nitrous oxide emissions from BSK and BSP were also significantly different in growing seasons ($p<0.05$, T-test), but there was no significant difference between the two treatments during dormant seasons. No significant difference was found for either BSK or BSP between growing seasons/dormant periods.

Nitrous oxide emissions from different plant communities

Nitrous oxide emissions from each of the three plant communities were significantly larger in growing

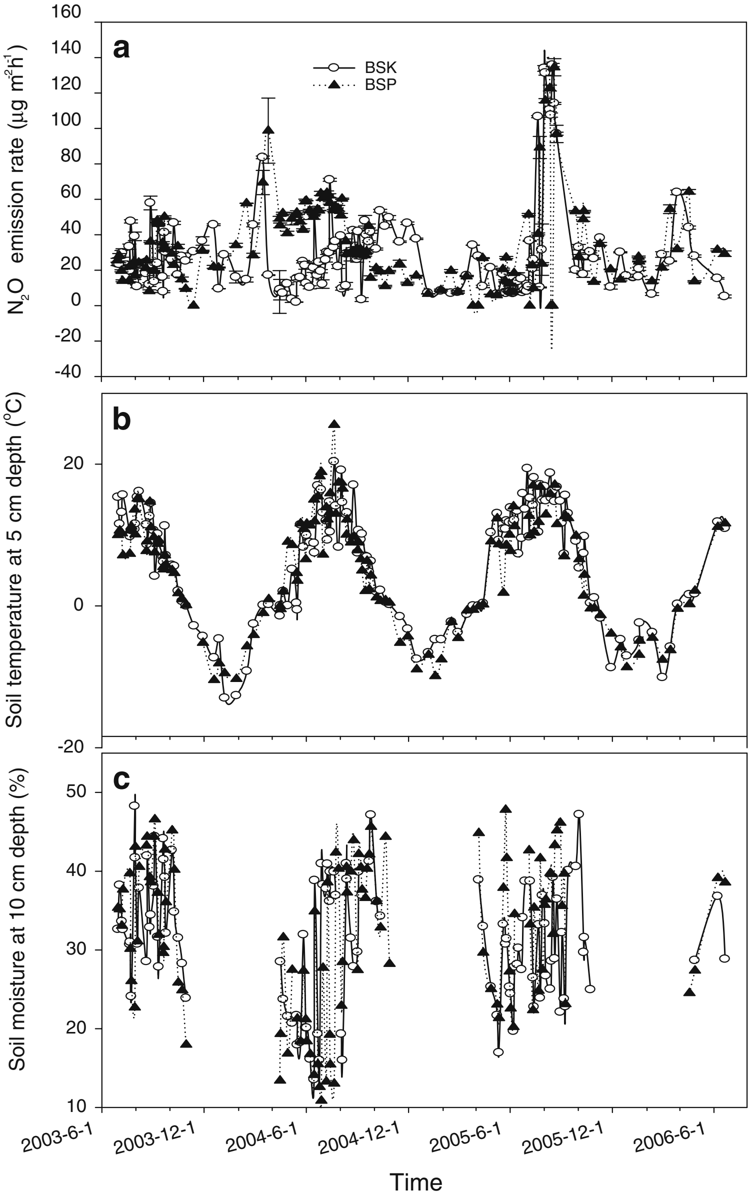

Fig. 1 Seasonal dynamic of N_2O efflux (**a**), soil temperature at 5 cm depth (**b**) and soil moisture at 10 cm depth (**c**) from bare soil plots in the *K. humilis* meadow (*BSK*) and *P. fruticosa* meadow (*BSP*). Means± standard errors (SE) of three replicate measurements were presented. No soil moisture data (**c**) were collected in winter, when soils were frozen

seasons than in dormancy periods ($p<0.01$, Table 3). It is interesting that N_2O emissions from the two herbaceous communities (HCK and HCP) were very similar during the entire experimental period (Table 3, Fig. 2a), in spite of different soil moisture contents ($p<0.01$, 40.3±5.9% for HCK and 35.9±7.6% for HCP). Nitrous oxide emissions from HCK were significantly larger than from BSK, whereas there was no difference in N_2O emission between BSP and HCP (Table 3, Fig. 1a and 2a). For the whole experimental period average N_2O emission from the shrub community (SCP) was estimated at 51.6 μg N_2O m^{-2} h^{-1}. This was significantly larger than from either HCK (39.4±2.8 μg N_2O m^{-2} h^{-1}) or HCP (39.8±2.7 μg N_2O m^{-2} h^{-1}; $p<0.01$, Table 3).

On the whole ecosystem basis *K. humilis* meadows emitted 295.0±11.6 mg N_2O m^{-2} $year^{-1}$ while *P. fruticosa* meadows showed larger N_2O emissions, 356.7±8.3 mg N_2O m^{-2} $year^{-1}$. Nitrous oxide emissions were larger in growing seasons than in dormancy periods in both meadow types. It was 167.0±24.9 vs. 128.0±36.4 mg N_2O m^{-2} in the *K.*

Table 3 N_2O emission rates ($\mu g\ N_2O\ m^{-2}\ h^{-1}$) from different plots. Means±standard errors (SE) were presented

Treatment	Entire experiment period[a]	Growth season[b]	Dormancy period[c]
BSK	30.2±2.8 (*n*=140)	30.8±3.3 (*n*=90)	27.5±2.6 (*n*=50)
BSP	38.1±3.6 (*n*=129)	40.3±2.8 (*n*=81)	34.5±5.0 (*n*=48)
HCK	39.4±2.8 (*n*=128)	47.8±3.9 (*n*=86)	23.2±2.0 (*n*=42)
HCP	39.8±2.7 (*n*=129)	50.6±3.6 (*n*=87)	21.4±1.9 (*n*=42)
SCP	51.6±3.7 (*n*=128)	60.6±5.1 (*n*=79)	34.1±2.6 (*n*=49)

[a] Entire experiment: June 2003 to June 2006

[b] Growth season: June–September in 2003, May–September in2004, 2005, and May–June in 2006

[c] Dormancy period: October to the next April in 2003–2006.

humilis meadow and 227.6±23.2 vs. 129.1±31.5 mg $N_2O\ m^{-2}$ in the *P. fruticosa* meadow.

Discussion

As observed by previous studies (Pei et al. 2004), alpine soils are a source of N_2O (Table 3). Rates of N_2O emission from constructed bare soil plots on both meadow types (BSK, 30 $\mu g\ N_2O\ m^{-2}\ h^{-1}$ and BSP, 38 $\mu g\ N_2O\ m^{-2}\ h^{-1}$) were five to 47 times more than those from bare patches on alpine steppe soils (0.8 $\mu g\ N_2O\ m^{-2}\ h^{-1}$, Pei et al. 2004) and on temperate steppe soils (5.9 $\mu g\ N_2O\ m^{-2}\ h^{-1}$, Du et al. 2001). The great difference in N_2O emission between these grasslands may be caused by different soil moisture contents, e.g. higher moisture in alpine meadow soils than in alpine steppe soils or temperate steppe soils (Du et al. 2001; Pei et al. 2004). The N_2O fluxes in both BSK and BSP were however smaller than in N fertilized agriculture soils of the Northern China Plain (57 $\mu g\ N_2O\ m^{-2}\ h^{-1}$, Zhang et al. 2000), indicating that in the latter high N fertilizer inputs may have enhanced emissions of N_2O from soils (Del Prado et al. 2006; Stehfest and Bouwman 2006; Velthof and Oenema 1997).

On an ecosystem level grasslands are often regarded as a significant source of N_2O (Williams et al. 1999), especially fertilized and grazed grasslands. For these very high rates of N_2O emission are often reported (e.g. 179 to 358 $\mu g\ N_2O\ m^{-2}\ h^{-1}$, Velthof and Oenema 1997). However, few studies have been conducted to compare the difference in N_2O emission between plant communities and bare soils. Our experimental setup allowed us to do this analysis. It showed that plant communities, except HCP in the *P. fruticosa* meadow, significantly enhanced N_2O emission from alpine meadows (Table 3). There are three possible explanations for this. Firstly, root exudates derived from plant photosynthesis may stimulate nitrifying bacteria and denitrifying bacteria responsible for N_2O production, because root exudates are rapidly utilized by rhizosphere microorganisms and regulate rhizomicrobial activity (Anderson and Domsch 1985; Kuzyakov and Cheng 2001). Secondly, a growing number of studies have shown that terrestrial plants can emit N_2O to the atmosphere (Goshima et al. 1999; Zhang and Jiang 2006; Zou et al. 2005), this may also be true for alpine plants. In this study we made a crude calculation of N_2O emissions by plants based on the difference between N_2O emission from plant communities and N_2O emission from bare soils. Grasses in *K. humilis* meadows (9 $\mu g\ N_2O\ m^{-2}\ h^{-1}$) and shrubs in *P. fruticosa* meadows (14 $\mu g\ N_2O\ m^{-2}\ h^{-1}$) showed strong N_2O emissions, while grasses in the *P. fruticosa* meadows emitted only very little N_2O (2 $\mu g\ N_2O\ m^{-2}\ h^{-1}$). These values are significantly lower than those observed from the bare soils. Thirdly, soil moisture differences may contribute to the difference in N_2O emissions between the plant communities. Soil moisture is an important factor controlling N_2O emissions (Du 2006). It was reported for temperate grasslands that nitrification is dominant in N_2O emissions because soil moisture was often kept at low water holding capacity (WHC; Du 2006). Denitrification to N_2 is dominant when soil moisture reached more than 70% of the WHC (Yu et al. 1995). In this study the average soil moisture content in both HCK and SCP was 40.3±5.9% and 35.9±6.0% and ranged from 24.1 to 50.0% and 16.4 to 49.3% in HCK and SCP, respectively. This was equivalent to about 80% of the WHC in HCK and 35% of the

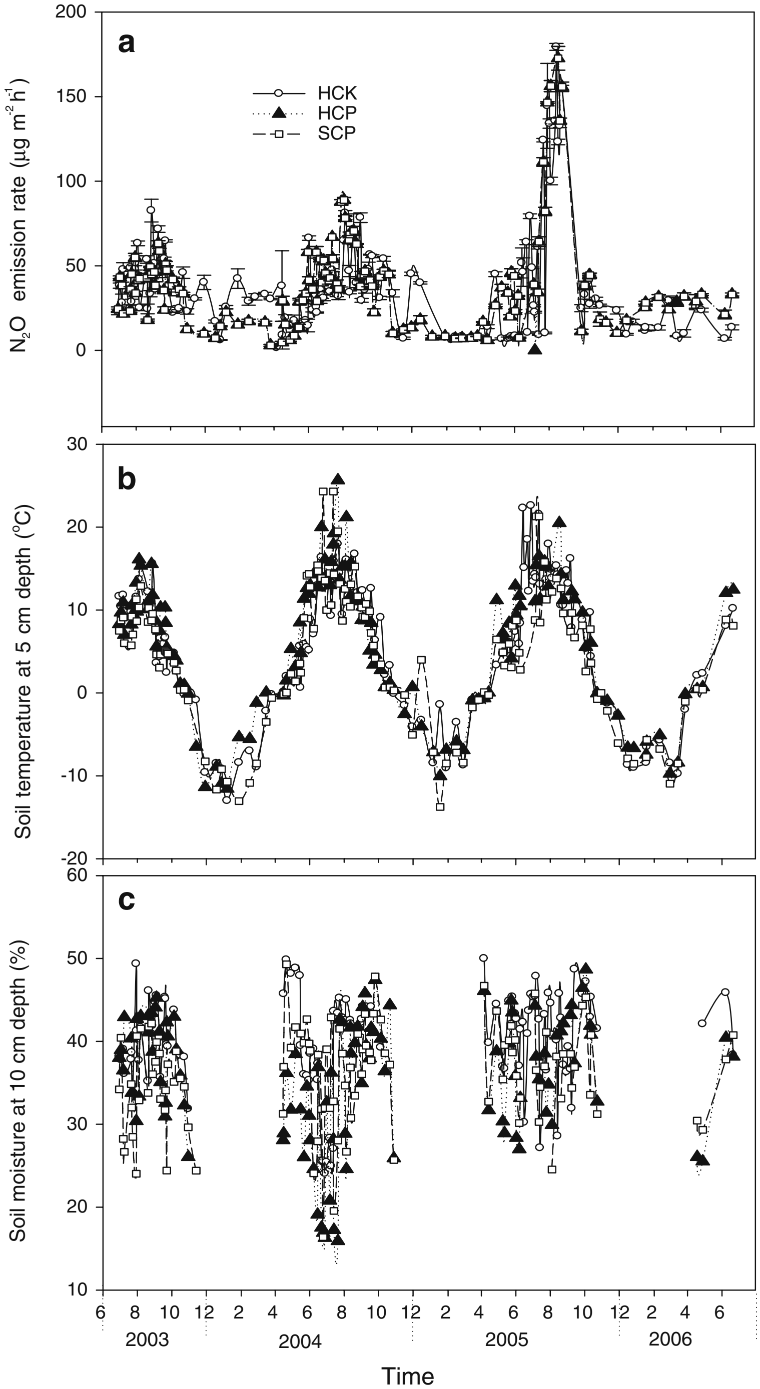

Fig. 2 Seasonal N_2O emission (**a**), soil temperature at 5 cm depth (**b**) and soil moisture at 10 cm depth (**c**) from herbaceous communities in the *K. humilis* (*HCK*) and the *P. fruticosa* (*HCP*) meadows and shrub community in the *P. fruticosa* (*SCP*) meadow. Means± standard errors (SE) of three replicate measurements were presented. No soil moisture data (**c**) were collected in winter, when soils were frozen

WHC in SCP. High soil moisture content (80% of the WHC) and the optimal soil pH (Table 1) in HCK in theory provide good conditions for denitrification to N_2. The significantly lower rate of N_2O emission from HCK compared to SCP (Table 3) may be due to denitrification to N_2. This suggests that different processes control N_2O emissions in both grass and shrub communities. It is possible that nitrification is dominant in SCP while denitrification to N_2 is dominant in HCK. However, HCK and HCP showed similar flux rates despite a significant difference in soil moisture at 10 cm depth ($p<0.01$, *T*-test), implying that N_2O emissions are more complicated and possibly controlled by multifactor in alpine meadows.

Over the entire experimental period all the treatments showed a significant N_2O emission peak in summer 2005 (Fig. 1a, 2a). Low annual precipitation and high annual air temperature may account for a part of variations. However, there was a poor correlation between N_2O emission and soil temperature at 5 cm depth in the two bare soil treatments in spite of a strong correlation between them in the three plant communities (Fig. 3). The discrepancy is possibly ascribed to the variation in the nutrient and

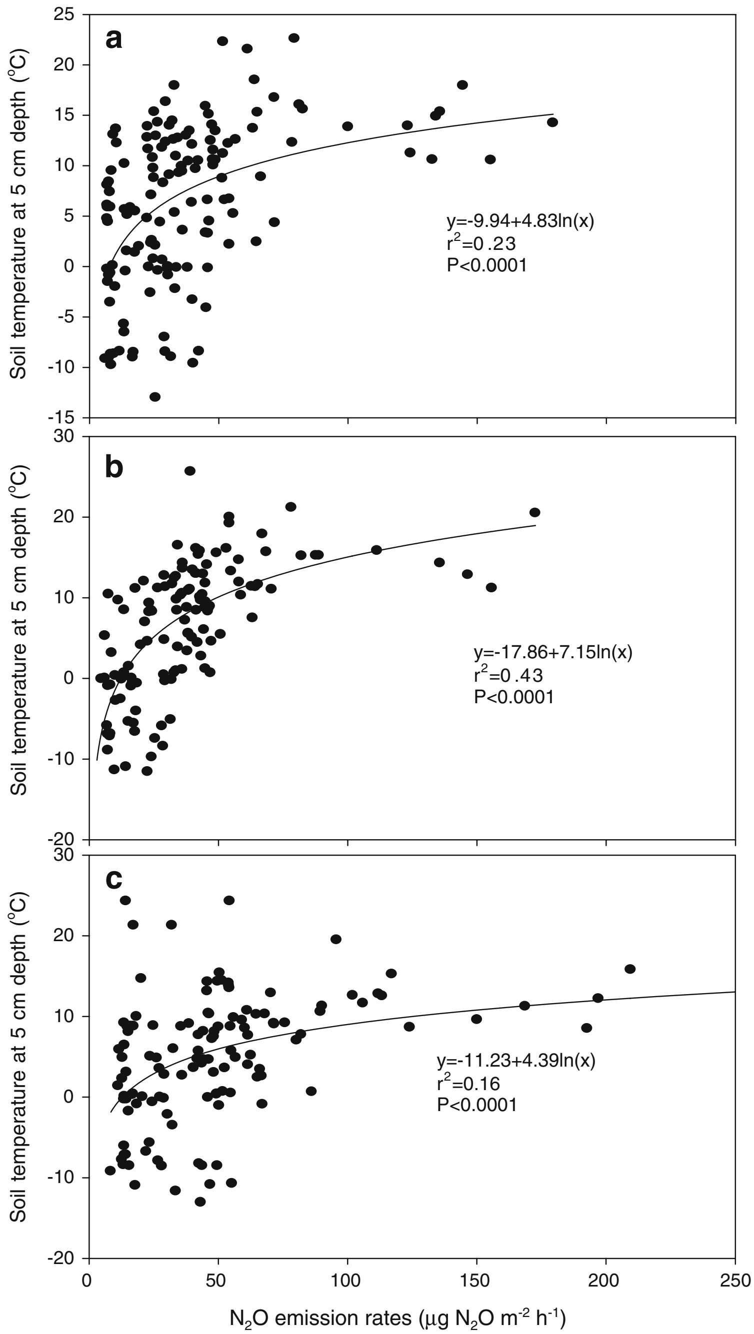

Fig. 3 Correlation between soil temperature at 5 cm depth and N_2O emission rates from herbaceous communities in the *K. humilis* (*HCK*) (**a**) and the *P. fruticosa* (*HCP*) (**b**) meadows and shrub community in the *P. fruticosa* (*SCP*) (**c**) meadow

oxygen concentration profiles of the soils imposed by living roots. Nitrous oxide emission did not show a significant correlation with soil moisture at 10 cm depth as other studies observed (Du 2006), although soil moisture generally plays an important role in N_2O emissions.

Kobresia and Potentilla shrub meadows have been suffering from overgrazing in the Tibetan plateau. This leads to degradation of *Kobresia* meadows to bare areas and of some *Potentilla* shrub meadows to *Kobresia* meadows (Klein et al. 2007). Therefore, N_2O emissions from alpine meadows may be strongly altered by this process. We have used our data to estimate if alpine meadows and a shift in vegetation type due to grazing pressure would have an impact on N_2O emissions at the global scale. For this purpose we assumed that alpine meadows are completely occupied by bare soils or by shrubs. Total N_2O emission from alpine meadows in the Tibetan Plateau was estimated to range from 0.2 to 0.4 Tg N_2O year^{-1}, with an average of 0.3 Tg N_2O year^{-1}. This value is 11% of the estimated global emission from fertilized grasslands (2.8 Tg N_2O year^{-1}, Stehfest and Bouwman 2006). This indicates that alpine meadows are not a negligible source of N_2O in the Tibet Plateau. Vegetation shift caused by heavy grazing gradually reduces the carbon storage potential of grasslands (Allard et al. 2007) and strongly enhances CH_4 and CO_2 emissions (Cao et al. 2004), but as this study has shown can decrease N_2O emissions from alpine meadows.

Although many studies have shown that alpine meadows are a weak sink of atmospheric CO_2 and CH_4 (Cao et al. 2004; Wang et al. 2004; Zhao et al. 2007), the contribution of greenhouse gases from terrestrial ecosystems to climate warming should be assessed based on integrated research. The reason is that there may be a trade-off between mitigation of CH_4 and N_2O emissions and maintenance of carbon sink activity (Soussana et al. 2007). We here made an estimation based on previous studies together with this study. An average amount of 0.2 Tg CH_4 year^{-1} (Cao et al. 2008) and of 46.5 Tg CO_2-C year^{-1} (Kato et al. 2004; Yan et al. 2006; Zhao et al. 2007) have been estimated to be absorbed by alpine meadows in the Tibetan Plateau. Radiative forcing of N_2O and CH_4 is 298 and 25 times more than of CO_2 (IPCC 2007). This means that the whole alpine meadows (more than 8,750 ha) in the Tibet Plateau emit 60.0 Tg CO_2-eq year^{-1} and take up 4.8 Tg CO_2-eq year^{-1}. Consequently, Tibetan alpine meadows contribute 94 Tg CO_2-eq year^{-1} to the atmosphere. This clearly implies that an accurate assessment of the contribution of terrestrial ecosystems to climate warming needs to be based on the simultaneous flux rates of all three greenhouse gases, CO_2, N_2O and CH_4.

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