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Variations of N_2O fluxes in response to warming and cooling in an alpine meadow on the Tibetan Plateau

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Abstract Little is known about the impacts of climate change especially for cooling on N_2O emissions from alpine meadows on the Tibetan Plateau. Along a slope of Qilian mountains, China, we transferred intact soil cores covering different vegetation types (graminoid, shrub, forb, and sparse vegetation) downhill (warming) and uphill (cooling) across a 600-m elevation gradient to examine the responses of soil-atmosphere N_2O exchange rates to climate warming and cooling. N_2O fluxes were measured during two growing seasons from May to October in 2008 and 2009. The Tibetan alpine meadow acted as a net N_2O source at an average rate of

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5.2 μg m^{-2} h^{-1} (ranging from 2.0 to 11.5 μg m^{-2} h^{-1}). In situ N_2O emission generally decreased with elevation increase except for sparse vegetation, but significant differences were only found between graminoid and other three vegetations in 2008 and between graminoid and shrub vegetation in 2009. Warming averagely increased mean N_2O fluxes by 219% (ranging from 126 to 287%) while cooling decreased it by 75% (ranging from 57 to 95%) across four vegetation types over the variation of soil temperature from 1.3 to 5.5 °C. However, opposite effects were also observed in some cases due to modification of variations in soil moisture. Soil temperature and moisture had a positive effect on N_2O fluxes and explained 48 and 26% of the variation in mean N_2O fluxes across the four vegetation types, respectively. No relationship was found between mean N_2O fluxes and aboveground biomass. Our results suggest that more N_2O-N would be released from soil in a warmer future and that less N_2O emission during cool and dry years is expected in the Tibetan alpine meadow.

1 Introduction

Nitrous oxide (N_2O) is both a powerful greenhouse gas and a contributor to the depletion of ozone (IPCC 2007; Ravishankara et al. 2009). Variations in historical atmospheric N_2O concentration are closely paralleled with patterns of climate fluctuation (Pfeiffer et al. 2013; Schilt et al. 2010) with important feedbacks to the global climate (Wuebbles 2009; Xu et al. 2012). Recent manipulative field experiments have also shown that soil-atmosphere N_2O exchange is sensitive to climate change (Cantarel et al. 2011; Dijkstra et al. 2013; Flechard et al. 2007; Hu et al. 2010; Teh et al. 2014).

N_2O is produced in soils during the processes of nitrification and denitrification and is regulated by soil C and N availability and abiotic factors such as temperature and moisture (Davidson et al. 2000; Chapuis-Lardy et al. 2007; Dijkstra et al. 2013; Teh et al. 2014). For instance, plant biomass and C availability vary with altitude on the mountainous Tibetan Plateau (Hu et al. 2016a, b; Wang et al. 2008). Although the plateau is undergoing obvious climate warming (Hansen et al. 2006; Thompson et al. 2000), higher and lower temperature spells with variable rainfall are common on the plateau (Du et al. 2004). However, there are many uncertainties in the evaluation and prediction of N_2O budgets from Tibetan alpine meadows due to scarce available data, especially with regard to N_2O fluxes under climate change (Hu et al. 2010; Shi et al. 2012).

Many previous studies have found that warming can increase C and N availability through enhancement of plant biomass and N mineralization (Hu et al. 2016b; Rui et al. 2011; Rustad et al. 2001) that may enhance N_2O emission (Davidson et al. 2000; Dijkstra et al. 2013). However, increased plant N uptake due to stimulated plant growth under warming (Rustad et al. 2001; Wang et al. 2012) may also limit mineral N supply to nitrification and denitrification that may reduce N_2O production. Experimental warming had no effects on annual N_2O emission from a Tibetan alpine meadow over 3 years (Hu et al. 2010), which was ascribed to drier soil conditions caused by warming (Hu et al. 2010; Shi et al. 2012). In contrast, reduced temperature (cooling) may have opposite effects on N_2O emission that may be modified by variations in soil moisture but that remain unclear and largely unexplored.

The use of an elevation gradient is a particularly powerful tool to understand responses of ecosystems to global changes (Malhi et al. 2011). Here, we conducted a reciprocal translocation experiment to imitate climate warming (uphill translocation) and cooling (downhill translocation) by using an elevation gradient along a slope of the Qilian mountains in the northeastern Tibetan Plateau. N_2O fluxes were measured over two growing seasons from May to October in 2008 and 2009. Our research objectives were to investigate variations of N_2O fluxes along the elevation gradient and examine warming and cooling effects on N_2O fluxes in the Tibetan alpine meadow. We hypothesized that (1) N_2O exchange rates would decrease with elevation increase, and (2) there would be a positive feedback of warming (i.e., soil brought down to lower elevation) on N_2O emission while cooling (i.e., soil brought up to higher elevation) would have the opposite effect.

2 Materials and methods

2.1 Study site and experimental design

The study was conducted at the Heibei Alpine Meadow Ecosystem Research Station (37° 37′ N, 101° 12′ E) of the Chinese Academy of Sciences. The mean annual air temperature and precipitation from 1981 to 2000 were −1.7 °C and 561 mm, respectively. The soil is classified as Gelic Cambisols according to FAO classification system. Our study consisted of four sites (aspect <3°) within 9 km in distance from each other. These sites covered a 600-m elevation gradient and contained four different vegetation types. At 3200 m, the vegetation is dominated by graminoids including *Kobresia humilis*, *Festuca ovina*, *Elymus nutans*, *Poa* spp., *Carex* spp., *Scirpus distigmaticus*, *Gentiana straminea*, *Gentiana farreri*, *Leontopo diumnanum*, and *Potentilla nivea*. At 3400 m, the vegetation is dominated by alpine shrubs including *Potentilla fruticosa*, *Kobresia capillifolia*, *Kobresia humilis*, and *Saussurea superba*. At 3600 m, the vegetation is dominated by *K. humilis*, *Saussurea katochaete* Maxim, *P. nivea*, *Thalictrum alpinum*, *Carex* spp., *Poa* spp., and *P. fruticosa*. At 3800 m, the vegetation is sparse and include *K. humilis*, *L. odiumnanum* and *Poa* spp. We refer to these four vegetation types as graminoid, shrub, forb, and sparse vegetation, respectively (Zhang et al. 2011). Plant biomass and physico-chemical properties differed from each other (Table 1). Soil depth decreased with increasing elevation with a mean thickness of 0.65, 0.7, 0.5, and 0.3 m for graminoid, shrub, forb, and sparse vegetations, respectively.

A detailed description about the experimental design can be found elsewhere (Wang et al. 2014; Zhang et al. 2011). Briefly, in early May 2007, 12 1-m long * 1-m wide * 0.3–0.4-m deep (with 30 cm depth for sparse vegetation due to a shallower soil layer) intact soil blocks with attached vegetation from each site were manually cut off for translocation. Three of these soil blocks were reinstated in situ as control blocks (home monoliths) while the other nine soil blocks were transferred to the other three elevation sites (translocated monoliths). All intact soil blocks were fully randomly translocated and arranged, and surrounded by plastic film to prevent exchange and invasion of roots with/from the ambient soil environment. Thus, there was only uphill translocation (cooling) for graminoid vegetation, both uphill and downhill translocation (warming) for shrub and forb vegetation, and only downhill translocation for sparse vegetation. There were a total of 48 intact soil blocks (4 elevations * 4 vegetations * 3 replicates) in our study.

2.2 Soil temperature and soil moisture

A HOBO weather station (Onset Computer Corporation, Cape Cod, MA, USA) was installed with temperature sensors of Model S-TMB-M002 and soil moisture smart sensors of model S-

Table 1 Characteristics of selected sites along the slope of the Qilian mountains in the northeastern Tibetan Plateau

Site name	Elevation (m a.s.l.)	Landforms	Latitude (N)	Longitude (E)	Bulk Density A horizon (g cm^{-3})	AGB[a] (g m^{-2})	BGB[a] (kg m^{-2})	Soil C A horizon (%)	Soil N A horizon (g kg^{-1})	Soil C/N A horizon
Graminoid	3200	Slope, flat	37° 36′ 42.3″	101° 18′ 47.9″	0.6	277.7	3.4	6.2	4.6	13.5
Shrub	3400	Slope, flat	37° 39′ 55.1″	101° 19′ 52.7″	0.8	164.4	2.8	5.7	4.1	13.7
Forb	3600	Slope, flat	37° 41′ 46.0″	101° 21′ 33.4″	0.7	85.7	2.5	5.4	4.6	11.8
Sparse	3800	Flat, basin	37° 42′ 17.7″	101° 22′ 09.2″	0.8	52.1	1.9	5.0	4.6	10.9

[a] AGB and BGB mean aboveground biomass and belowground biomass within 20 cm soil depth in 2009

SMC-M005 ECH2O (Onset Computer, Bourne, MA, USA) at the center of the fenced experimental area outside of the blocks at each site. The sensors were connected to a CR1000 datalogger, data of soil temperature and soil moisture at 20 cm depth were measured every 1 min, and then 30-min averages were stored.

2.3 N_2O fluxes

During the growing seasons from May to September in 2008 and 2009, N_2O fluxes were measured by using static chambers and gas chromatography techniques. Details about the chambers and methods of the gas sampling can be found in the study by Lin et al. (2009). Briefly, the static chamber consisted of a bottom anchor (0.4 m length * 0.4 m width * 0.1 m height) that was permanently inserted into the soil about 10 cm below the soil surface and a removable cover box (0.4 m length * 0.4 m width * 0.4 m height) with a fan (0.1 m in diameter) attached to the inside wall and a white cover on the outside wall to reduce warming inside the chamber. The cover box was placed on the bottom anchor during sampling and sealed by adding water into the groove of the bottom anchor. Samples were taken between 9:00 and 11:00 a.m. local time every 7–10 days depending on weather conditions (measurements of N_2O fluxes were delayed due to heavy rain events and continued when the rain stopped). Four gas samples (about 100 ml for each sample) were manually taken from the closed chamber every 10 min by using 100-ml plastic syringes. The N_2O concentration was analyzed by using gas chromatography (HP Series 4890D, Hewlett Packard, USA) within 24 h after sampling. The N_2O fluxes were calculated as the slope of linear regressions from the measured gas concentrations with time (Dijkstra et al. 2013).

Here, we made an assumption that variations in N_2O fluxes of translocation monoliths were caused by changes in temperature and moisture; influences from other factors like wind and solar radiation were ignored. Variations of aboveground biomass in response to warming and cooling were reported in details by Hu et al. (2016a).

2.4 Statistical analysis

Normality distribution of N_2O fluxes was tested in one-sample Kolmogorov-Smirnov with SPSS version 16.0. Linear mixed models with repeated measurements were used for analysis of variance (ANOVA); type III SS was adopted because of missing data at 3600 m elevation in 2009. To examine variation among the home monoliths (in situ vegetation) at the different elevations, vegetation was taken as the between-subject factor. To examine warming and cooling effects, vegetation type and elevation were between-subject factors. For all ANOVAs, date and year were within-subject factors. Pearson simple correlation, stepwise linear regressions, and a quadratic term were used to test the possible dependency of N_2O fluxes on soil temperature, soil moisture, and aboveground biomass. Differences were considered to be significant at $P < 0.05$.

3 Results

3.1 N_2O fluxes in situ

In general, soil temperature increased with a decrease in elevation (Fig. 1). Average soil temperatures during the sampling period were 9.5, 7.3, 5.9, and 4.5 °C in 2008 and 10.1, 7.8, 6.5, and 5.3 °C in 2009 at 3200, 3400, 3600, and 3800 m, respectively. Average soil moistures were 33.2, 26.9, 36.2, and 12.7% in 2008 and 35.3, 28.5, 43.0, and 16.3% in 2009 at 3200, 3400, 3600, and 3800 m, respectively.

For the home monoliths with in situ vegetation, N_2O fluxes were significantly affected by date, elevation and their interaction (Table 2). N_2O fluxes did not show a clear variation pattern across the 2-year period. The N_2O fluxes were small except for several small "bursts" in the early spring that depended on vegetation, and sometimes were negative which suggested soil uptake of N_2O. Mean N_2O fluxes decreased with elevation increase except at the highest elevation with values of 11.5, 4.1, 2.2, and 3.0 μg m^{-2} h^{-1} at 3200, 3400, 3600, and 3800 m in 2008 and 8.5, 2.0, and 4.8 μg m^{-2} h^{-1} at 3200, 3400, and 3800 m in 2009, respectively. However, there was no significant difference among the 3400, 3600, and 3800 m elevations over 2 years (Fig. 1).

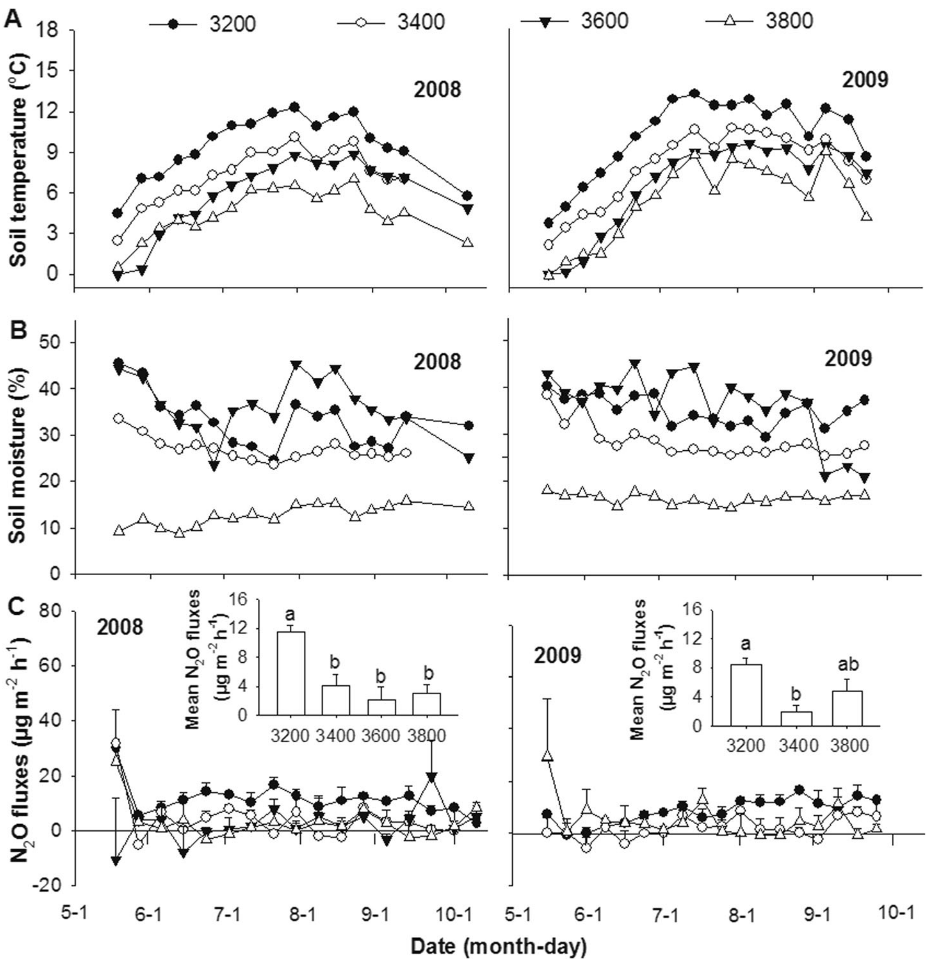

Fig. 1 Soil temperature (**a**), soil moisture (**b**), and N_2O fluxes (**c**) for graminoid (*3200*), shrub (*3400*), forb (*3600*), and sparse vegetation (*3800*) in situ during the growing seasons in *2008* and *2009*. *Panels* inside the figures show mean N_2O fluxes under no-transferring. *Error bars* indicate standard error. *Different letters* indicate significant differences at $P < 0.05$ level. In 2009, N_2O fluxes at 3600 m (forb vegetation) were not recorded due to damage to monoliths from pikas (*Ochotona curzoniae*)

3.2 N_2O fluxes of translocation

After being translocated, date, elevation, vegetation type, and the interactions of elevation and/or vegetation type with date and year significantly affected N_2O fluxes (Table 1). Variations in N_2O fluxes were similar to that of home monoliths with in situ vegetation, with no clear variation patterns and several small bursts in the early spring that depended on vegetation type and elevation (Fig. S1). The effects of warming and cooling varied with vegetation type and elevation based on mean N_2O fluxes (ranging from −4.2 (N_2O uptake) to 17.4 μg m^{-2} h^{-1}) (Fig. 2). Compared with home monoliths, warming increased mean N_2O emission in most combinations of vegetation type and elevation across the 2-year period, with increases ranging between 126 (sparse vegetation when moved down from 3800 to 3600 m) and 287% (sparse vegetation when moved down from 3800 to 3200 m), but slightly decreased it at other two occasions by 69 (forb vegetation when moved from 3600 to 3400 m) and 58% (sparse vegetation when moved down from 3600 to 3400 m). In contrast, cooling decreased N_2O emission in most cases, with decreases ranging between 75 (graminoid vegetation when moved from 3200 to 3600 m) and 95% (shrub vegetation when moved from 3400 to 3800 m), but increased it by 73% for shrub vegetation when moved from 3400 to 3600 m (Fig. S2).

3.3 Relationships of N_2O fluxes with environmental factors

Although the correlations between N_2O fluxes and soil temperature and moisture were significant, the *r* values were small except for shrub, forb, and sparse vegetation with warming. In these cases, soil temperature and moisture explained 14–23% of the variation in N_2O fluxes. On the other hand, soil temperature and moisture only explained 2–12% of the variation in N_2O fluxes for the different vegetation types with cooling and pooled vegetation types (Table 1S). Based on mean N_2O fluxes over the growing season, a quadratic relationship

Table 2 Summary of linear mixed models of variance (ANOVA) on N_2O fluxes for home monoliths (in situ) and pooled home and translocated monoliths (translocation) over two growing seasons in 2008 and 2009

Gradient	Source	Df	*F*	Sig.
In situ	Year (Y)	1	0.792	0.374
	Date (D)	17	2.330	*0.003*
	Vegetation (V)	3	15.799	*<0.001*
	Y * D	16	1.643	0.059
	Y * V	2	2.181	0.115
	D * V	50	1.891	*0.001*
	Y * D * V	31	1.027	0.433
Translocation	Year (Y)	1	0.280	0.597
	Date (D)	17	2.959	*<0.001*
	Elevation (E)	3	3.530	*0.015*
	Vegetation (V)	3	92.449	*<0.001*
	Y * D	16	2.218	*0.004*
	Y * E	3	1.943	0.121
	Y * V	2	9.051	*<0.001*
	D * E	51	1.788	*0.001*
	D * V	50	2.325	*<0.001*
	E * V	9	4.081	*<0.001*
	Y * D * E	48	1.967	*<0.001*
	Y * D * V	31	2.107	*<0.001*
	Y * E * V	6	2.770	*0.011*
	D * E * V	150	1.324	*0.009*
	Y * D * E * V	93	1.445	*0.005*

Values of significance at $P < 0.05$ are shown in italic.

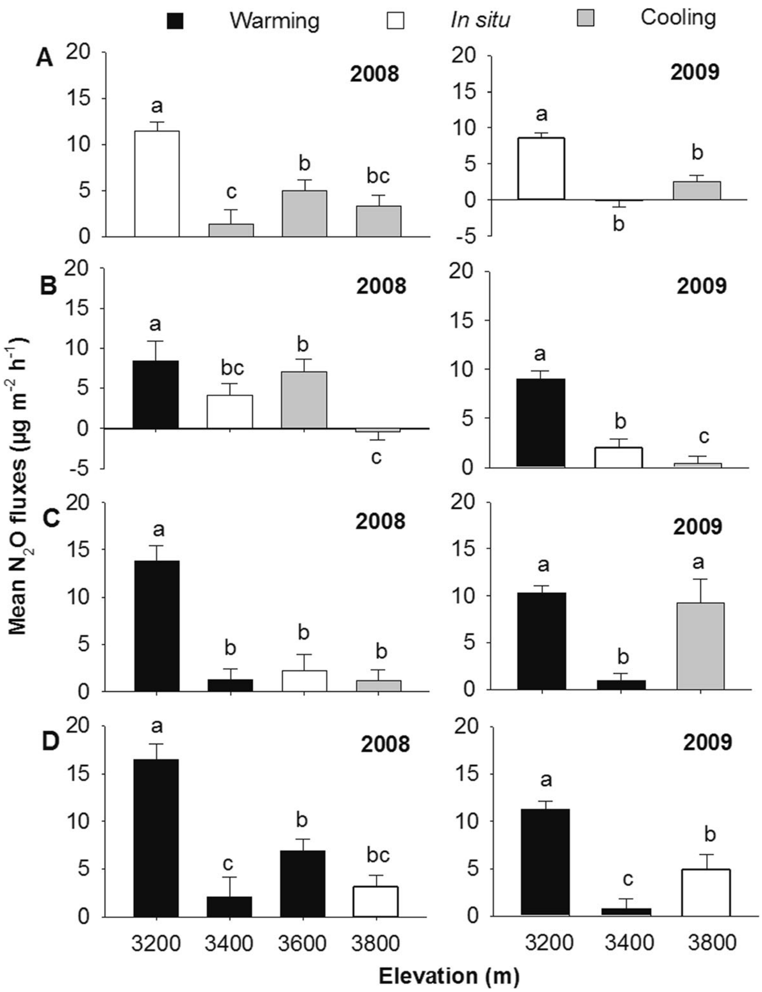

Fig. 2 Effects of warming and cooling on N_2O fluxes for graminoid (**a**), shrub (**b**), forb (**c**), and sparse vegetation (**d**) during the growing seasons in 2008 and 2009. *Error bars* indicate standard error. *Different letters* indicate significant differences at $P < 0.05$ level under different treatments. In 2009, N_2O fluxes at 3600 m for all vegetations were not recorded due to damage to monoliths from pikas (*Ochotona curzoniae*)

was found between N_2O fluxes and soil temperature and moisture, which explained 48 and 26% of the variation in N_2O fluxes for the pooled vegetation types, respectively. There was no relationship between N_2O fluxes and aboveground biomass (Fig. 3).

4 Discussion

4.1 Temporal and spatial variations of N_2O fluxes

Similar to the results of previous studies (Hu et al. 2010; Jiang et al. 2010), variations in N_2O fluxes showed no clear pattern across all vegetation types over a 2-year period. Both emission (positive value) and uptake of N_2O (negative value) were observed across all vegetations and

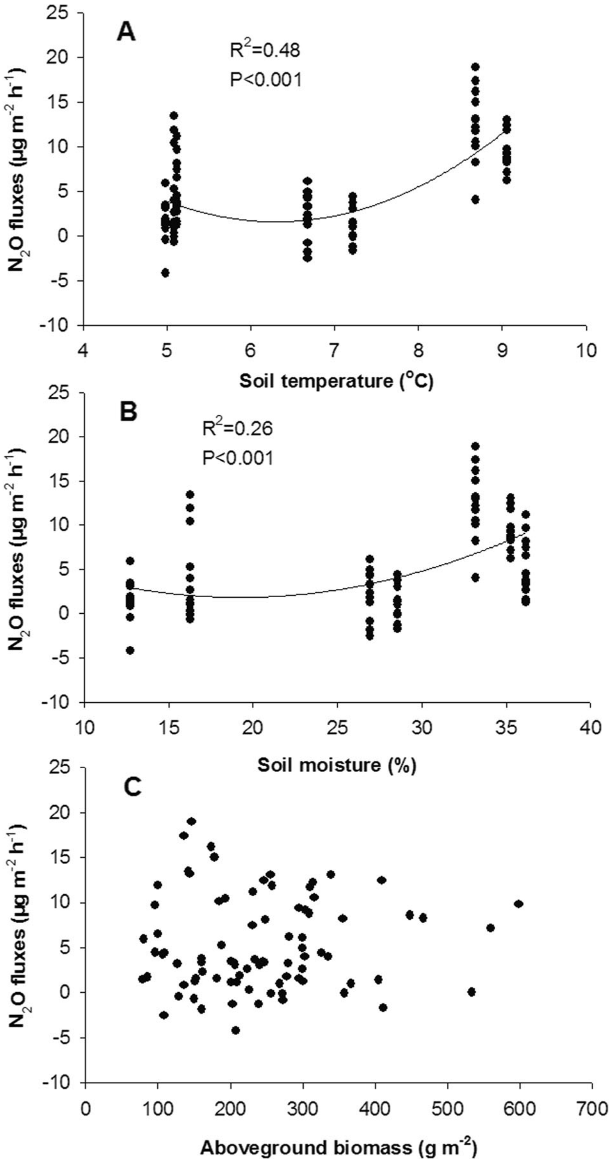

Fig. 3 N_2O fluxes as a function of soil temperature, soil moisture, and aboveground biomass. Each data point is the mean N_2O flux, average soil temperature, and soil moisture or aboveground biomass. *Regression lines* are only shown when significant ($P < 0.05$)

elevations, which was also reported by other studies (Cantarel et al. 2011; Dijkstra et al. 2013; Jiang et al. 2010; Pei et al. 2003; Teh et al. 2014). The uptake of N_2O might result from denitrification (Chapuis-Lardy et al. 2007), where denitrifying bacteria might use atmospheric N_2O as an alternative electron acceptor when nitrate is in short supply (Rosenkranz et al. 2006). N_2O fluxes also showed large temporal and spatial variability (Flechard et al. 2007; Jiang et al. 2010), with an average variation coefficient (CV) of 202% across all monoliths. Several small bursts of N_2O emission in the early growing season were likely caused by freeze-thaw processes (Burton and Beauchamp 1994; Elberling et al. 2010; van Bochove et al. 2000) and originated from (1) release of N_2O accumulated beneath frozen soil layers (Burton and Beauchamp 1994; van Bochove et al. 2001) and (2) freezing-induced release of available C and N that stimulates N_2O emission (DeLuca et al. 1992; van Bochove et al. 2000). However, these small bursts of N_2O may have depended on vegetation type and elevation, and it is likely that we missed some of these events with our sampling frequency.

In support of our first hypothesis, mean N_2O fluxes decreased with elevation increase except for the in situ sparse vegetation (home monoliths) at the highest elevation, which was also found in other studies (Neto et al. 2011; Teh et al. 2014). Many studies found that C and N availability, particularly nitrate, might play a vital role in limiting N_2O emission (Dijkstra et al. 2012; Jiang et al. 2010; Teh et al. 2014). The decline in N_2O emission in our study also coincided with reduced C and ammonium availability with increasing elevation (Hu et al. 2016b, c). Decreased labile C might have caused C constraints on denitrification thereby causing a decrease in N_2O emission (Dijkstra et al. 2012), while reduced ammonium likely limited nitrification. Higher N_2O emission for sparse vegetation than forb or shrub vegetation may be linked to both bursts of N_2O emission resulted from freeze-thaw processes due to its cold weather condition and higher soil nitrate concentrations (Hu et al. 2016c), providing denitrification with more N substrates (Davidson et al. 2000). It is further possible that high moisture contents and low ammonium concentrations favored N_2O uptake at the elevation with forb vegetation (Chapuis-Lardy et al. 2007).

4.2 Warming and cooling effects

Previous studies found that warming increased (Cantarel et al. 2011; Larsen et al. 2011; Shi et al. 2012) or had no effect (Hart 2006; Hu et al. 2010) on N_2O emission. In our study, mean N_2O emission was positively related to soil temperature (Fig. 3), and as expected, warming increased mean N_2O emission while cooling reduced it in most cases (Fig. 2S), supporting our second hypothesis. N_2O fluxes seemed to be minimized at about 6 °C and the implied mechanism was unknown, but it is the best fit for the relationship between mean N_2O fluxes and soil temperature over the growing season. This was also in accordance with the decreased trend in the mean N_2O fluxes with elevation of the in situ vegetation types (home monoliths), suggesting that N_2O fluxes of this alpine meadow had a rapid response to climate warming and cooling. This finding was paralleled with similar responses of aboveground biomass and labile C (Hu et al. 2016a, c). As discussed above, the warming-induced increase in labile C (Hu et al. 2016b; Rui et al. 2011) reduced C constraints on denitrification leading to an increased N_2O emission (Dijkstra et al. 2012). It is also possible that higher levels of mineral N in the soil due to warming-induced increases in N mineralization, nitrification, and denitrification may have increased N_2O emission (Hart, 2006; Larsen et al. 2011; Rustad et al. 2001).

There are very few field studies focused on the response of N_2O fluxes to climate cooling. According to a soil transfer study from Hart (2006), cooling (mean annual 2.5 °C) had no significant effects on N_2O fluxes. Our results showed that cooling commonly, but not consistently, decreased N_2O fluxes. Probably, the reduced soil labile C in response to cooling (Hu et al. 2016c) increased C constraints on denitrification (Dijkstra et al. 2012). Alternatively, cooling may have reduced nitrification by limiting aerobic ammonia oxidation due to the decreased abundance of ammonia-oxidizing archaea and bacteria (Zheng et al. 2014). Hart (2006) has found that warming significantly increased but cooling had no significant effects on mean N_2O emission when soil moisture condition was almost the same between in situ and translocation, suggesting that N_2O fluxes seems to be more sensitive to warming than cooling. In our study, soil moisture highly varied among different elevations and we were unable to distinguish soil moisture and temperature effects. As a result, our work failed to compare the temperature sensitivity of N_2O fluxes to warming and cooling. Given the importance of N_2O fluxes to climate feedback (Wuebbles 2009; Xu et al. 2012) and its higher variations in response to soil temperature and moisture conditions, direct manipulations of soil water content would be need in the future soil transfer studies.

Mean N_2O fluxes were positively related to soil moisture, indicating that increased soil moisture had a positive effect (Dijkstra et al. 2013; Hart 2006), while drought can lead to a reduction in N_2O emission (Goldberg and Gebauer 2009; Larsen et al. 2011; Shi et al. 2012). Soil moisture affected N_2O fluxes by changing oxygen conditions in the soil (Goldberg and Gebauer 2009; Hartmann and Niklaus, 2012). Higher soil moisture could create anaerobic conditions that are beneficial to denitrification (Maag and Vinther 1999) and lower soil moisture lead to a reduction of N_2O emission by denitrifiers (Goldberg and Gebauer, 2009; Hartmann and Niklaus, 2012). Therefore, the decrease in N_2O emission of forb vegetation when moved to 3400 m and the increase N_2O emission of shrub vegetation when moved to 3600 m could be explained by drier and wetter soil conditions, respectively, indicating that soil moisture could modify warming and cooling effects on N_2O fluxes. These results affirmed that the direct stimulatory effect of warming on the N_2O flux could be offset by the indirect inhibitory effect of reduced soil moisture (Bijoor et al. 2008; Shi et al. 2012).

4.3 Loss of N as N_2O emission

Most reported loss of N as N_2O emission was below 6.5 μg N m^{-2} h^{-1} or smaller than 0.6 kg N ha^{-1} $year^{-1}$ (Chen et al. 2000; Epstein et al. 1998; Hu et al. 2010; Mosier et al. 1996, 2002; Mummey et al. 2000) except for (sub)tropical forests and pastures where N_2O emissions can be higher (ranging from 1.5 to 5.7 kg N ha^{-1} $year^{-1}$) (Hadi et al., 2000; Keller and Reiners, 1994; Melillo et al. 2001; Mosier and Delgado 1997). In our study, the average loss of N as N_2O emission from alpine meadow was 0.34 ± 0.09 kg N ha^{-1} $year^{-1}$ across the four vegetation types. Taking the area of alpine meadow (35% of the plateau area) into consideration, the Tibetan alpine meadow acted as a net source of N_2O emission with a mean total annual flux of 0.30 ± 0.07 Tg N, which is lower than estimated for temperate and tropical grasslands (0.59~1.52 Tg N $year^{-1}$) based on an empirical model study (Xu et al. 2008), and accounted for 1.6–3.6% of the annual global N_2O emission (8.2–18.4 Tg N $year^{-1}$) according to estimates from model studies (Xu et al. 2008; Xu et al. 2012). By considering positive effects of temperature on N_2O emission, more N_2O-N is expected to be released from the Tibetan alpine meadow soil under warmer and wetter climate conditions. However, less N_2O emission in cool and dry years should also be considered to evaluate N_2O budget from the Tibetan Plateau.

5 Conclusion

Although N_2O fluxes showed large spatial and temporal variation, the Tibetan alpine meadow showed net N_2O emission with an average annual emission rate of 0.30 ± 0.07 Tg N. Our results showed that mean N_2O emission generally decreased with elevation increase except for sparse vegetation, but significant differences were only found between graminoid and other three vegetations in 2008 and between graminoid and shrub vegetation in 2009. Warming commonly, but not consistently, increased mean N_2O emission while cooling had a similar opposite effect depending on vegetation type and elevation. N_2O fluxes were positively related to soil temperature and moisture but not correlated to aboveground biomass. More N_2O-N is predicted to be released in the warmer future, while less N_2O emission is expected to occur during cool and dry years in the Tibetan alpine meadow. Our study has important implications for the contribution of N_2O emissions from the Tibetan Plateau and to the global N_2O budget with warmer future conditions.

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