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Low-level nitrogen deposition significantly inhibits methane uptake from an alpine meadow soil on the Qinghai–Tibetan Plateau

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ABSTRACT

It is crucial to understand the effects of enhanced nitrogen (N) deposition on soil methane (CH_4) uptake to develop a better comprehension of carbon (C) dynamics in terrestrial ecosystems. A two-year field study was conducted to assess the effects of various forms of N (NH_4^+ and NO_3^-) and associated N deposition rates (0, 10, 20 and 40 kg N ha^{-1} yr^{-1}) on alpine meadow soil CH_4 fluxes on the Qinghai–Tibetan Plateau, China. Soil CH_4 fluxes, soil temperature, and soil moisture were monitored weekly using the static chamber technique and gas chromatography. Soil inorganic N pools, soil pH and aboveground biomass were measured monthly to examine the key controlling factors of soil CH_4 flux. Our results showed that N addition significantly promoted plant growth and changed soil water-filled pore space (WFPS), but did not alter soil inorganic N storages over the short term. Low rates of N addition significantly decreased the seasonal amount of CH_4 uptake by 8.6% compared with the control. Soil CH_4 fluxes were mainly determined by soil WFPS, followed by inorganic N availability. N addition increased the contribution of soil WFPS, pH and soil NO_3^- storage. The observed reduction in CH_4 uptake caused by N addition may be largely due to a decrease in physical diffusion, as the biochemical inhibition effects on methanotrophic bacteria are minor. These results suggest that soil inorganic N is a regulatory factor of soil CH_4 uptake, and its promotion or inhibition to soil CH_4 uptake depends on the N status in terrestrial ecosystems.

1. Introduction

Methane (CH_4) is a powerful greenhouse gas and contributes to approximately 17% of global warming, with a relative global warming potential 23 times that of CO_2 on a molar basis (Parry, 2007). Over the past 200 years, human activities such as fossil fuel exploration, rice production, large-scale animal husbandry of ruminants, biomass burning and landfill gas emission have resulted in an increase of atmospheric CH_4 concentration by 148%, which is currently increasing by about 0.9% yr^{-1} (Parry, 2007). Meanwhile, atmospheric CH_4 reacts with hydroxyl radicals (OH) in the troposphere and transfers to the stratosphere, accounting for 84% and 7% of the global CH_4 sink, respectively (Dutaur and Verchot, 2007). Also, uptake of CH_4 by aerobic soils removes a significant amount from the atmosphere (10–44 Tg yr^{-1}), and accounts for up to 10% of the global CH_4 sink (Lowe, 2006). However, there is evidence that increases of atmospheric nitrogen (N) deposition can significantly decrease CH_4 uptake by soils (Liu and Greaver, 2009), which may also contribute to increasing atmospheric CH_4 concentrations.

N addition may increase (Saari et al., 2004; Veldkamp et al., 2001), decrease (Domingues et al., 2007; Liebig et al., 2008; Mosier et al., 1998) or have no effects on (Phillips and Podrebarac, 2009; Sawamoto et al., 2010; Van den Pol-van Dasselaar et al., 1999) CH_4 uptake from grassland ecosystems, appearing to depend on the form and the rate of N addition, as well as on soil properties (Rigler and Zechmeister-Boltenstern, 1999). Serious debates have focused on the role of NH_4^+ and NO_3^- on soil CH_4 consumption. Many studies have demonstrated that elevated soil NH_4^+ may significantly reduce CH_4 oxidation rates (Bodelier and Laanbroek, 2004). However, several studies reported that NO_3^-, rather than NH_4^+, had the greatest inhibitory effect on CH_4 oxidation in forest soils (Reay and Nedwell, 2004; Wang and Ineson, 2003; Xu and Inubushi, 2004; Xu and Inubushi, 2007). Unfortunately, most studies on the response of soil CH_4 uptake to the forms and rates of N addition have been conducted using soil core incubation in a laboratory, which differs from N addition experiments done in the field. Also, all of these studies were focused on temperate forest ecosystems (Reay and Nedwell, 2004; Wang and Ineson, 2003; Xu and Inubushi, 2004; Xu and Inubushi, 2007), with no data available

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from alpine meadow ecosystems. Overall, the patterns and intrinsic mechanisms of how NO_3^- and NH_4^+ affect CH_4 uptake in grassland ecosystems remain unclear.

As the largest grassland unit on the Eurasian continent, the Qinghai–Tibetan Plateau is averagely situated at 4000 m above sea level, and covers an area of approximately 2.5 million km^2 (Yang et al., 2008). Soil carbon (C) storage for 1 m in depth is estimated to be 4.68 Pg C, accounting for about 1/10 of total soil C storage in China (Yang et al., 2008). Due to an increase in regional economic development as well as long-range transport of atmospheric reactive N, atmospheric N deposition is very obvious in the eastern Qinghai–Tibetan Plateau, ranging from 4 to 13.8 kg N ha^{-1} yr^{-1} (Liu et al., 2013; Lü and Tian, 2007). Chronic N deposition can significantly change the soil CH_4 uptake over the short term (C. Jiang et al., 2010), and can further offset C sequestration in the entire alpine meadow ecosystem (Fang et al., 2012). To clarify CH_4 uptake in the alpine meadow system within the context of increased N deposition, it is necessary to explore the responses of soil CH_4 uptake by the different forms and the rates of N addition.

We hypothesized that NO_3^- and NH_4^+ played different roles to soil CH_4 uptake. This hypothesis was tested by conducting a two-year N addition experiment in an alpine meadow on the Qinghai–Tibetan Plateau. The main purposes of this paper are: (1) to examine the effects of the forms and rates of N addition on soil variables (soil temperature, water-filled pore space (WFPS), inorganic N pools and pH) and aboveground biomass; (2) to quantify the effects of the forms and rates of N addition on CH_4 uptake in the alpine meadow soil; and (3) to investigate which factors are responsible for changes in CH_4 uptake from the alpine meadow soil induced by N addition.

2. Materials and methods

2.1. Study site

The experiment was conducted at the Haibei alpine meadow ecosystem research station, Chinese Academy of Sciences (37°37′ N, 101°19′ E), located in the eastern of Qinghai–Tibetan Plateau. The site is subjected to a plateau monsoon climate. Weather data collected between 2008 and 2009 at the meteorological station showed a mean annual air temperature of −0.4 °C, with an overall minimum and maximum of −23.2 °C (January) and 14.5 °C (July), respectively. The annual average precipitation was approximately 383.3 mm, of which 85.6% occurred in May and September (Fig. 1). The vegetation type is a typical *Kobresia humilis* meadow. Dominant species are *Kobresia humilis*, *Saussurea superba*, *Potentilla saundersiana*, *Leontopodium nanum*, *Lancea tibetica*, *Festuca ovina*, *Festuca rubra*, *Stipa aliena*, *Elymus nutans*, *Helictotrichon tibetica*, *Koeleria cristata* and *Poa crymophila* (Cao et al., 2008). The soils developed in the Kobresia meadow are Mat-Gryic Cambisol (Cao et al., 2008).

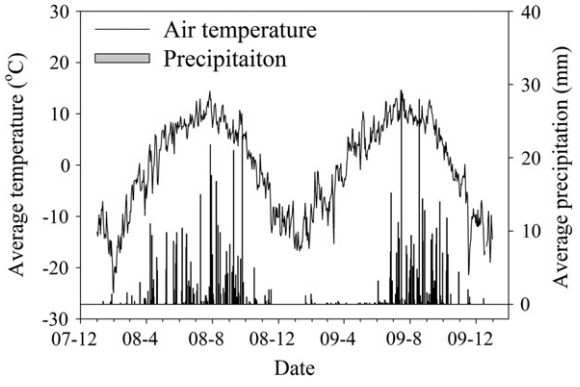

Fig. 1. The annual patterns of the daily average temperature and precipitation of the study site in 2008 and 2009.

2.2. Experimental design

The N addition experiment is a split plot design with N levels defining the main plots and N forms as subplots. Three N fertilizers (NH_4Cl, $(NH_4)_2SO_4$ and KNO_3) were applied as three levels (10, 20 and 40) of kg N ha^{-1} yr^{-1}. A control (0 kg N ha^{-1} yr^{-1}) was set at each plot and each N treatment had three replicates. Each plot had an area of 9 m^2 (3 m × 3 m) and a 2 m isolation band was set between plots. The N addition experiment started on May 1, 2007. N fertilizer solutions were sprayed on the plots once a month, totally 12 equal applications over the year. Control plots received equivalent applications of water only. All plots are in the winter pastures, not grazed in the growing season, and grazed in non-growing season.

2.3. CH_4 flux measurement

Over the two growing seasons (from May to September) of 2008 and 2009, the soil CH_4 fluxes were determined using the static chamber and gas chromatography method (Wang and Wang, 2003). At each plot, a stainless square box (length × width × height = 50 cm × 50 cm × 50 cm), made up of one collar and one chamber, was installed. Gas samples were collected weekly between 9:00 AM and 11:00 AM (China Standard Time, CST) by fitting the chambers to the collars and removing headspace samples at ten-minute intervals over a 30-min period. Within 24 h following gas collection, the CH_4 concentrations were analyzed on a gas chromatograph (HP Series 4890D, Hewlett Packard, USA), equipped with a flame ionization detector (FID). The CH_4 fluxes were calculated, using chamber air temperature, barometric air pressure and the slope of the temporal change in CH_4 concentration within the chamber headspace (Wang and Wang, 2003). The seasonal amount of CH_4 uptake can be calculated using the following equation (J. Jiang et al., 2010):

$$E_{CH4} = \frac{\sum_{i=1}^{n} 0.5 \times (F_i + F_{i+1}) \times (t_{i+1} - t_i) \times 24}{1000}$$

where, E_{CH4} is the seasonal amount of CH_4 uptake (g CH_4 m^{-2}), F_i and F_{i+1} are the CH_4 fluxes of the i-th and $i+1$-th measurement (mg CH_4 m^{-2} h^{-1}), the term of $(t_{i+1} - t_i)$ denotes the days between two adjacent days of the measurements, n is the total times of the measurements, and 24 is the number of hours per day.

Parallel to the flux measurements, soil temperature was recorded at the soil surface, 5 cm, and 10 cm belowground. Soil moisture was recorded at the 10 cm depth. Due to the proximity of the four subplots (<10 m apart) and the simultaneous collection of air samples, soil temperature in the four subplots is considered to be the same. Volumetric soil moisture was transformed to water-filled pore space (WFPS): WFPS = volumetric soil moisture / (1 − bulk density / 2.65) (C. Jiang et al., 2010).

2.4. Field sampling and measurements

On the 15th day of each month during the two growing seasons, cores of mineral soil nearby the gas chambers were taken at 10 cm intervals to a depth of 50 cm using an auger (2.5 cm in diameter). Four core sets were collected at each plot and like depths were homogenized to obtain a sample. Soils were immediately passed through a 2 mm sieve to remove roots, gravel and stones. Subsamples of each depth interval were extracted to determine NH_4^+–N and NO_3^-–N concentrations using a continuous-flow autoanalyzer

(Bran Luebbe, Germany). Soil inorganic N storages (SIN, g m^{-2}) at each plot were calculated using the following equation:

$$SIN = \sum_{i=1}^{5} C_i \times BD_i \times 0.1$$

where, *SIN* is the storage of inorganic N at a plot (mg m^{-2}), C_i is the concentration of inorganic N in the *i*-th horizon (mg kg^{-1}), BD_i is soil bulk density of the *i*-th horizon (g cm^{-3}), and 0.1 is the conversion factor.

Soil pH was determined in a 1:2 soil:water suspension using a standard pH meter (Mettler Toledo, Switzerland). In addition, aboveground biomass at each plot was measured by clipping vegetation at the ground level, drying plants at 60 °C to a constant mass, and weighing.

2.5. Statistical analysis

Repeated measurement analysis of variance was used to test the differences of soil temperature, WFPS, pH, inorganic N storages, aboveground biomass and CH_4 fluxes among the different forms and rates of N addition. Comparisons of the means were conducted using the Tukey's HSD test. Simple and multiple stepwise regression analyses were used to examine the relationships between soil CH_4 fluxes and related environmental variables. All statistical analyses were conducted using the SPSS software package (version 16.0). Statistical significant differences were set with p values < 0.05 unless stated otherwise.

3. Results

3.1. Soil CH_4 uptake

The alpine meadow ecosystem behaved as a net sink of atmospheric CH_4 during the growing seasons in 2008 and 2009. Soil CH_4 fluxes varied as a single-peak pattern, and the maximum occurred in early August 2008 (Fig. 2a–c). However, in 2009, the seasonality of soil CH_4 fluxes weakened (Fig. 2a–c). In the control plots, the CH_4 uptake fluxes from the alpine meadow ecosystem averaged 31.1 ± 3.5 μg CH_4 m^{-2} h^{-1}, which was converted into the seasonal amount of 104.69 ± 5.60 g CH_4 m^{-2} (Table 1). N addition tended to inhibit soil CH_4 uptake, especially in medium N treatments (Table 1). N addition decreased the seasonal amount of CH_4 uptake by −1.9% to 18.5% without considering N addition types, with a mean of 8.6% (Table 1).

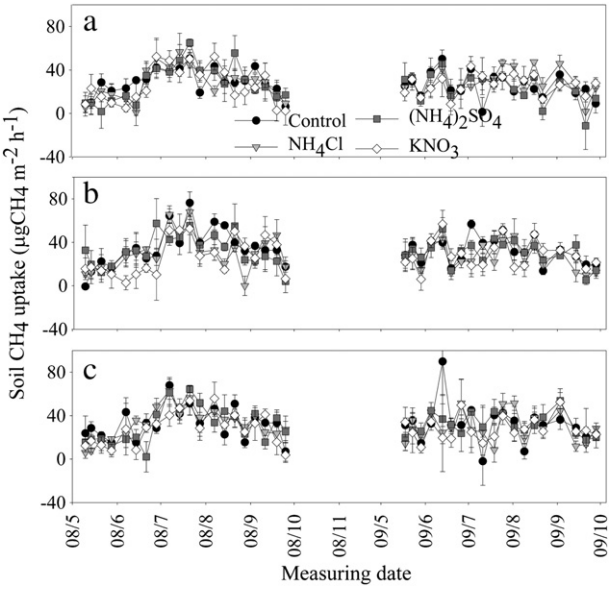

Fig. 2. Seasonal variations of soil CH_4 fluxes in low (a), medium (b), and high (c) N treatments.

3.2. Soil temperature and WFPS

During the entire growing season, the soil surface temperature fluctuated greatly (Fig. 3a–c). Soil temperature at the 5 cm and 10 cm depths exhibited a mono-peak change, ranging from 3.2 to 15.9 °C (Fig. 3a–c). The maximum soil temperature occurred at the end of July (Fig. 3a–c). There was no significant difference in soil temperature from the surface, 5 cm or 10 cm depths among the different N addition rates (Table 1).

In contrast to soil temperature, soil WFPS exhibited an overall single-pit pattern in 2008. The high WFPS values were recorded in early May and at the end of September, and fluctuated violently in the other months (Fig. 4a–c). Among the different types of nitrogenous fertilizers, soil WFPS showed a similar trend, with low and high rates of N addition trending to decrease soil WFPS, while medium N significantly increased soil WFPS (Table 1). In addition, the effect of NO_3^-–N fertilizer on soil WFPS seemed to be stronger than those of NH_4^+–N fertilizers (Table 1).

3.3. Soil NH_4^+–N and NO_3^-–N pools

The pool of soil NH_4^+–N peaked in June, and either August or September, and obviously dropped in July (Fig. 5a–c). In the control plots, soil NH_4^+–N storage in the alpine meadow ranged from 1.83 to 7.86 g m^{-2}, with an average of 4.01 ± 0.30 g m^{-2} (Fig. 5a–c). N addition was seen to both deplete and accumulate soil NH_4^+–N pool, despite the fertilizer form, but the difference between N addition plots and control plots was not significant after three-year N addition (Table 1).

The monthly variation of soil NO_3^-–N pools was not consistent with that of soil NH_4^+–N pools. The peaks of soil NO_3^-–N pools occurred in June or July, and minimum values occurred in August or September (Fig. 6a–c). In the control plots, soil NO_3^-–N pools in the alpine meadow soils ranged from 0.59 to 3.14 g m^{-2}, with an average of 1.47 ± 0.12 g m^{-2}, which was significantly lower than that of soil NH_4^+–N pool (Table 1). In 2008 and 2009, soil NO_3^-–N pool accumulated in a positive trend with N addition; moreover, the cumulative effect of NO_3^-–N fertilizer was slightly higher than those of NH_4^+–N fertilizers (Table 1). However, the difference between N addition treatments and control was not significant (Table 1).

3.4. Aboveground biomass

Aboveground biomass was lowest in May, then gradually increased and reached its maximum in August, after which it began to decrease (Fig. 7a–c). In the control plots, aboveground biomass in the alpine meadow ranged from 147.6 to 581.3 g m^{-2}, with an average of 356.4 ± 9.9 g m^{-2} (Fig. 7a–c). Three levels of N addition consistently increased aboveground biomass during the growing seasons of 2008 and 2009; moreover, the positive effect of N addition on plant growth significantly increased with the N addition rate (Table 1).

3.5. Soil pH

Throughout the growing season, soil pH did not vary dramatically (Fig. 8a–c). In 2008, N addition tended to decrease soil pH, especially in the high N plots (Fig. 8a–c). In 2009, N addition significantly decreased soil pH values in the forms and levels of nitrogenous fertilizer addition (Fig. 8a–c). The decline of soil pH caused by N addition ranged from 0.07 to 0.21 units without considering N addition forms (Table 1). Moreover, the decrease of soil pH values caused by NO_3^-–N fertilizer was higher than that caused by NH_4^+–N fertilizers (Table 1).

Table 1
The seasonal amount of soil CH_4 uptake and relevant soil properties in different N treatments over the two growing seasons of 2008 and 2009.

N level	N form	Seasonal CH_4 uptake ($g\ CH_4\ m^{-2}$)[a]	Soil temperature (°C)[a]			Soil WFPS ($m^3\ m^{-3}$)[a]	Soil NH_4^+–N pool ($g\ m^{-2}$)[a]	Soil NO_3^-–N pool ($g\ m^{-2}$)[a]	Aboveground biomass ($g\ m^{-2}$)[a]	Soil pH[a]
			Surface	5 cm	10 cm					
Control	Control	104.69 ± 5.60 a	13.7 ± 0.7 a	9.2 ± 0.6 a	9.3 ± 0.7 a	0.37 ± 0.02 b	4.01 ± 0.30 ab	1.47 ± 0.12 a	356.4 ± 9.9 b	7.37 ± 0.02 a
Low N	NH_4Cl	106.68 ± 1.56 a	13.0 ± 0.8 a	9.2 ± 0.6 a	9.2 ± 0.6 a	0.35 ± 0.03 b	3.81 ± 0.56 b	1.53 ± 0.16 a	376.0 ± 7.2 ab	7.29 ± 0.09 ab
Low N	$(NH_4)_2SO_4$	103.83 ± 6.99 a				0.35 ± 0.03 c	4.30 ± 0.61 ab	1.58 ± 0.17 a	397.1 ± 7.6 a	7.30 ± 0.07 ab
Low N	KNO_3	104.52 ± 3.19 a				0.34 ± 0.03 c	3.81 ± 0.56 b	1.78 ± 0.18 a	390.6 ± 7.3 ab	7.24 ± 0.17 ab
Medium N	NH_4Cl	85.31 ± 9.76 b	13.5 ± 0.5 a	9.4 ± 0.6 a	9.3 ± 0.7 a	0.39 ± 0.02 ab	4.23 ± 0.60 ab	1.44 ± 0.18 a	378.3 ± 6.7 ab	7.30 ± 0.08 ab
Medium N	$(NH_4)_2SO_4$	93.78 ± 6.91 ab				0.39 ± 0.03 ab	4.28 ± 0.62 ab	1.65 ± 0.19 a	398.8 ± 6.9a	7.32 ± 0.08 ab
Medium N	KNO_3	87.37 ± 0.87 b				0.40 ± 0.02 a	4.20 ± 0.64 ab	1.68 ± 0.20 a	404.8 ± 8.1 a	7.15 ± 0.13 b
High N	NH_4Cl	94.59 ± 8.22 ab	13.8 ± 0.9 a	9.6 ± 0.5 a	9.5 ± 0.7 a	0.36 ± 0.02 bc	4.54 ± 0.61 a	1.62 ± 0.18 a	390.7 ± 7.0 ab	7.28 ± 0.03 ab
High N	$(NH_4)_2SO_4$	94.17 ± 1.18 ab				0.35 ± 0.03 c	4.15 ± 0.58 ab	1.58 ± 0.17 a	400.8 ± 7.7a	7.27 ± 0.05 ab
High N	KNO_3	91.05 ± 4.22 ab				0.34 ± 0.02 c	3.85 ± 0.56 b	1.66 ± 0.16 a	409.8 ± 7.1a	7.19 ± 0.10 b

[a] Data are shown as means with standard errors; different lower case letters in a column indicate significant differences between treatments at $p < 0.05$.

3.6. Relationships between soil CH_4 fluxes and environmental variables

Soil CH_4 fluxes were positively correlated with soil temperature at the 5 cm depth, while negatively correlated with soil WFPS at the 10 cm depth (Fig. 9a–b). The relationships between soil CH_4 fluxes and soil WFPS could be well fitted with an exponential decay equation (Fig. 9b). Although soil CH_4 uptakes were positively correlated with soil NO_3^-–N and NH_4^+–N pools, only the relationships between CH_4 fluxes and soil NO_3^-–N pools were significant (Fig. 9c–d and Table 2). These results showed that soil drought and NO_3^-–N accumulation contributed to soil CH_4 consumption. Also, the relationships between soil CH_4 fluxes and aboveground biomass values were fitted by a quadratic equation (Fig. 9e–f), suggesting that vegetation has positive and negative effects on soil CH_4 uptake. Except for control plots, soil CH_4 fluxes at the N addition plots were positively correlated with soil pH, suggesting that soil acidification caused by N addition could inhibit soil CH_4 uptake. In the control plots, soil WFPS, temperature, aboveground biomass and NO_3^-–N pool could explain 38.5%, 23.4%, 12.7% and 3.7% of the variation of soil CH_4 uptakes, respectively (Table 2). N addition tended to increase the contributions of soil WFPS, pH and NO_3^- pool to CH_4 uptake, which could be reflected by regression coefficient (R^2) values (Table 2). Multiple stepwise regression analysis indicated that soil CH_4 fluxes were mainly controlled by soil WFPS, followed by soil NH_4^+–N and NO_3^-–N pools at the control plots (Table 2). However, only soil WFPS and NO_3^-–N pool dominated soil CH_4 uptakes at the N addition treatment plots (Table 2). Therefore, our results suggest that the decreasing physical diffusion by soil WFPS rather than biochemical inhibition by other variables was responsible for the decrease in soil CH_4 uptake.

4. Discussion

4.1. Comparisons with other studies

Under natural conditions, the alpine meadow ecosystem is a sink of atmospheric CH_4. The average CH_4 uptake flux during the study period (31.1 ± 3.5 μg $CH_4\ m^{-2}\ h^{-1}$) is close to the values (26–30 μg $CH_4\ m^{-2}\ h^{-1}$) reported by other studies at the same site (Cao et al., 2008; Lin et al., 2009). However, the fluxes of CH_4 uptake are lower than fluxes reported in alpine steppe grasslands in the middle Tibetan Plateau, China (63.4–70.2 μg $CH_4\ m^{-2}\ h^{-1}$, Wei et al., 2012), the alpine grassland of the Tianshan Mountains, China (54.2 ± 6.9 μg $CH_4\ m^{-2}\ h^{-1}$, Li et al., 2012) and the alpine dry meadow in the Eastern Alps (41.7–87.5 μg $CH_4\ m^{-2}\ h^{-1}$, Koch et al., 2007). CH_4 fluxes are significantly correlated with soil moisture (Fig. 9), and the difference in moisture availability is likely to be the most important driver of soil CH_4 fluxes in these alpine grasslands (Sjögersten et al., 2012). The soil moisture in the Haibei alpine meadow (37%) was higher than those in the above study sites (less than 30%), which is the main reason for the lower soil CH_4 uptake.

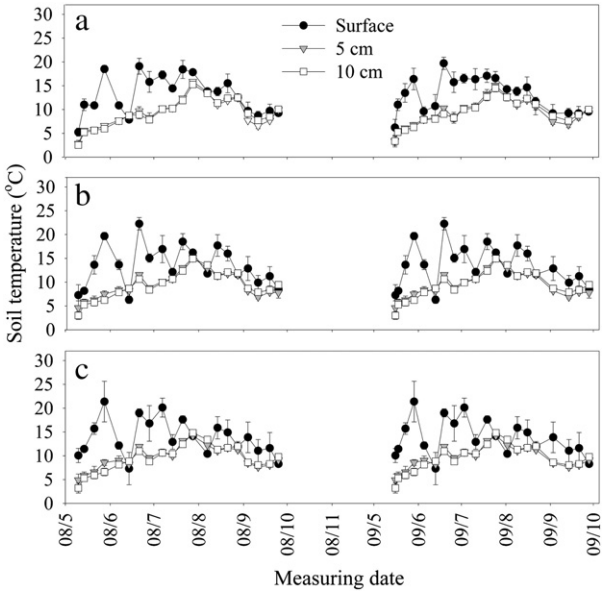

Fig. 3. Monthly variation of soil temperature in low (a), medium (b), and high (c) N treatments.

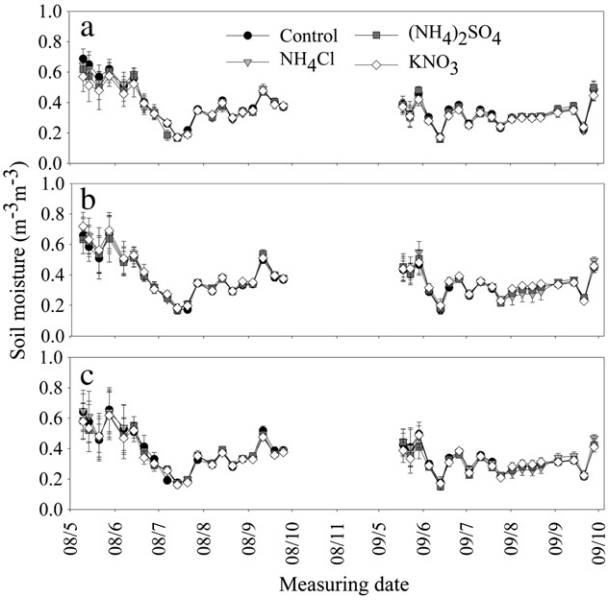

Fig. 4. Monthly variations of soil WFPS in low (a), medium (b), and high (c) N treatments.

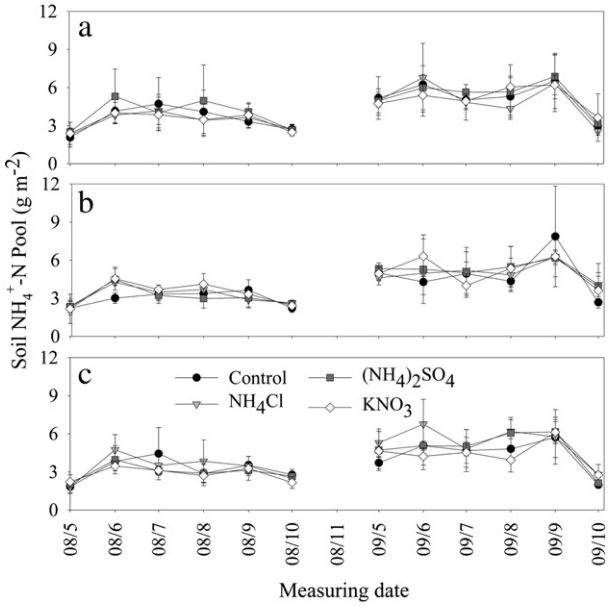

Fig. 5. Monthly variations of soil NH_4^+–N pool in low (a), medium (b), and high (c) N treatments.

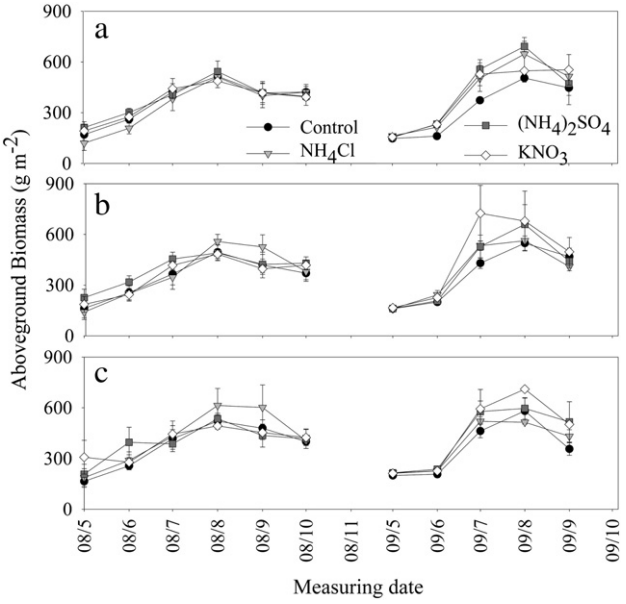

Fig. 7. Monthly variations of aboveground biomass in low (a), medium (b), and high N (c) treatments.

Similar to many N addition experiments in grassland ecosystems (Domingues et al., 2007; Liebig et al., 2008; Mosier et al., 1998), CH_4 uptake in the alpine meadow system is significantly inhibited by N addition over the short-term. This differs from some studies saying that N addition does not significantly affect or promote soil CH_4 uptake (Phillips and Podrebarac, 2009; Sawamoto et al., 2010; Van den Pol-van Dasselaar et al., 1999). Moreover, the rates of N addition in our study were lower than those in the above studies, suggesting that the alpine meadow ecosystem is very sensitive to increased N deposition. The fact that N addition is inhibiting the CH_4 uptake implies that the Tibetan Plateau may remove less CH_4 under future increased nitrogen deposition conditions.

4.2. Effects of soil WFPS on CH_4 uptake

Theoretically, the variation of soil moisture content depends on the dynamic balance between the input by precipitation and the loss by ecosystem evapotranspiration in semiarid alpine meadow ecosystems. In the study, precipitation was the same among the plots, and thus the differences in soil moisture content among the different N addition plots could be attributed to differences in ecosystem evapotranspiration among the plots. Ecosystem evapotranspiration is positively correlated with soil moisture (St Clair et al., 2009). N fertilizer application generally not only increases plant primary production and decreases species diversity, but also increases evapotranspiration (Sonnleitner et al., 2001). Our study showed that low and high N addition tended to decrease soil moisture, which could be related to the increase of ecosystem evapotranspiration. However, the responses of soil moisture

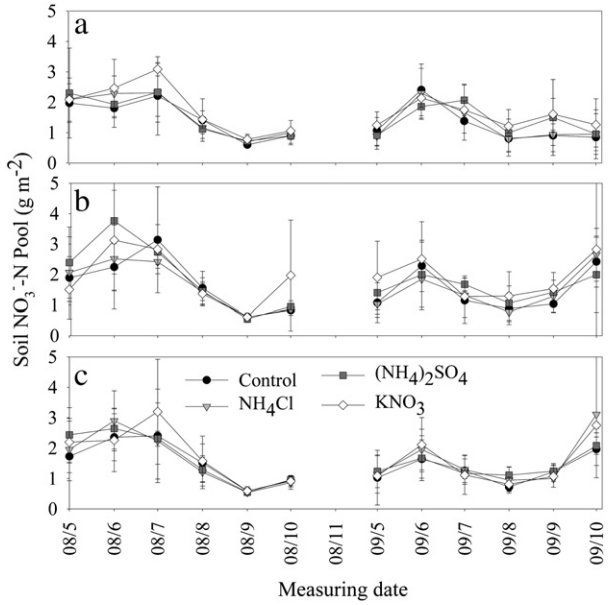

Fig. 6. Monthly variations of soil NO_3^-–N pool in low (a), medium (b), and high (c) N treatments.

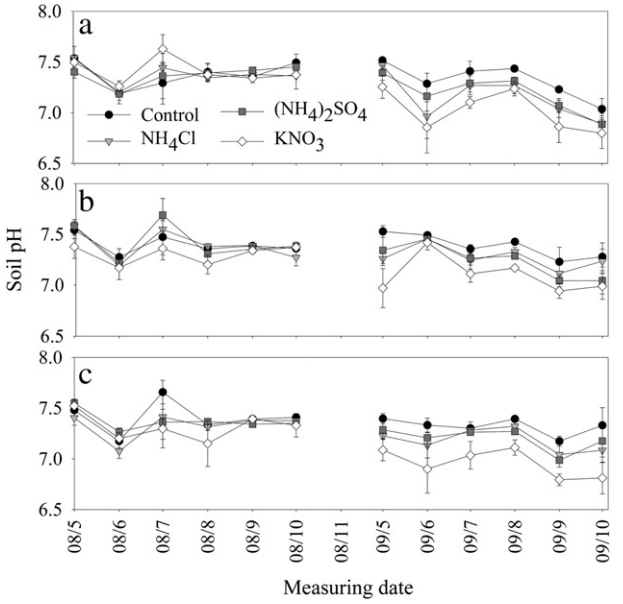

Fig. 8. Monthly variations of soil pH in low (a), medium (b), and high (c) N treatments.

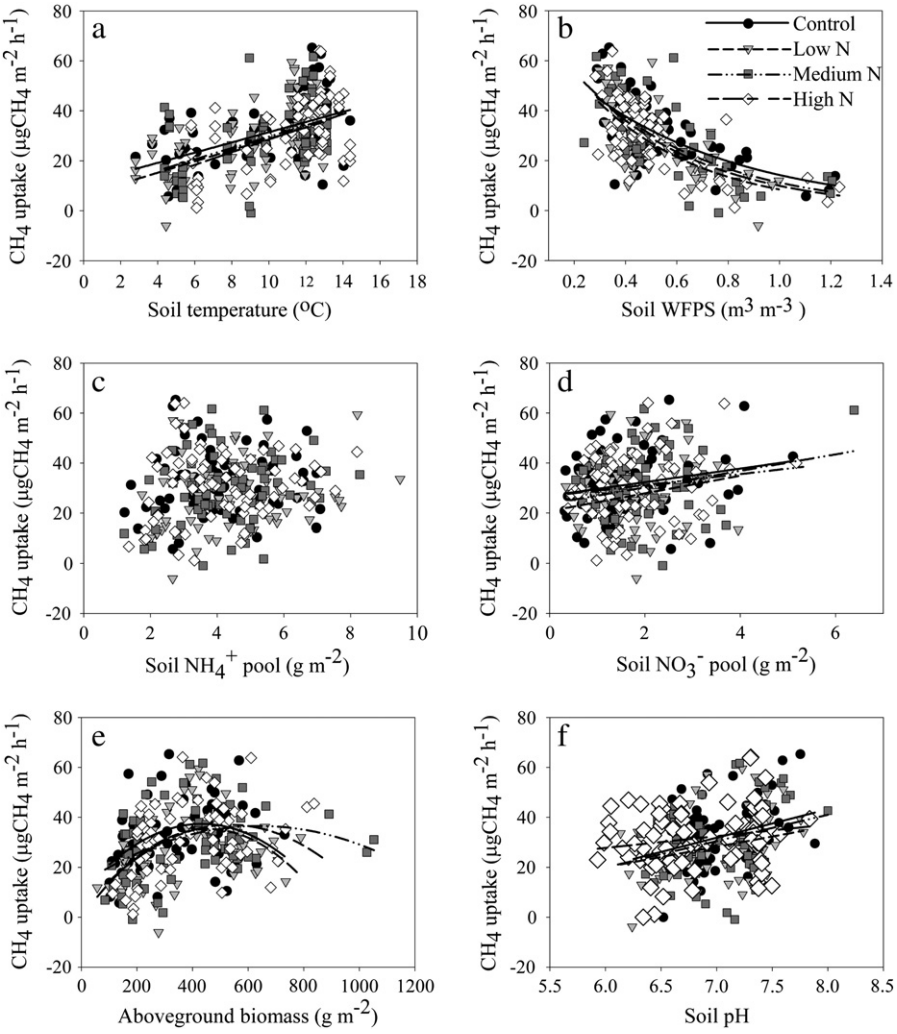

Fig. 9. Relationships between soil CH_4 fluxes and soil temperature, WFPS, inorganic N pools, pH and aboveground biomass.

to N addition are ambiguous—including positive (Fang et al., 2012), negative (Inouye, 2006), and neutral (Xia et al., 2009) results. Therefore, the driving mechanism behind this pattern needs to be examined further.

Because diffusion of CH_4 in water is 104 times slower than in air (Marrero and Mason, 1972), soil moisture controls the mass flow of air and diffusion of atmospheric CH_4 into the soil by altering the WFPS of soils (Domingues et al., 2007; Lin et al., 2009). The temporal variation in CH_4 uptake from each plot was consistent with that of soil WFPS (Figs. 2 and 4). Moreover, the fluxes of CH_4 uptake from N addition plots and control plots were significantly related to soil WFPS (Fig. 8b and Table 2). N addition usually stimulates vegetation growth in terrestrial ecosystems, and the subsequent changes in evapotranspiration enhance or lower soil WFPS, leading to higher or lower diffusion of CH_4 and O_2 into the soil (Veldkamp et al., 2001). In our study, medium N addition significantly increases soil WFPS, which corresponds to the significant decrease in soil CH_4 uptake (Table 1). Compared with other variables, soil WFPS plays a more important role in CH_4 uptake based on multiple regression results. This implies that physical diffusion dominates the direction and magnitude of the CH_4 uptake variation caused by N addition. Moreover, the determination coefficient (R^2) between CH_4 uptake fluxes and soil WFPS values increases from 38.5% at control plots to 43.4–47.2% at N addition plots (Table 2), suggesting an increasing contribution of soil WFPS to the variation of CH_4 uptake induced by N addition.

4.3. Effects of soil NH_4^+–N variation on CH_4 uptake

Previous studies have shown that CH_4 oxidation in grassland soils can be inhibited by the addition of NH_4^+–N fertilizers (Chan and Parkin, 2001; Dittert et al., 2005; Jacinthe and Lal, 2006), probably because (1) NH_4^+ competes with CH_4 for the same active site on the CH_4 monooxygenase of methanotrophs (Carlsen et al., 1991). (2) NH_4^+ oxidizes to the intermediate hydroxylamine (NH_2OH) by CH_4 monooxygenase, or to its further oxidation by other enzyme systems of the methanotrophs to the end product nitrite (NO_2^-). Hydroxylamine and nitrite in turn might lead to intoxication of CH_4 oxidizers (Schnell and King, 1994). (3) Indirect effects of N-treatments, such as high osmotic pressure, could have killed methanotrophs (Bodelier and Laanbroek, 2004). Generally, the oxidation of methanotrophic bacteria is optimally active at low osmotic stress (Saari et al., 2004). (4) N addition probably increases soil CH_4 emission to offset CH_4 uptake. Higher litter input under N enrichment alleviates C limitation to microbes (Bodelier and Laanbroek, 2004). As a result, the activities of methanogenic archaea are enhanced and more CH_4 is produced (Bodelier and Laanbroek, 2004).

However, in this study, it seems that decreased CH_4 uptake is likely to be unrelated to any competitive inhibition of monooxygenase by NH_4^+ and toxic inhibition by hydroxylamine or nitrite. The relatively insignificant or positive effect of NH_4^+ on CH_4 uptake observed here may be attributed to the following aspects. First, the alpine meadow

Table 2
Regression model between soil CH_4 fluxes and environmental variables.

N addition rates[a]	a	b	c	d	p	R^2
(a) $F_{CH4} = a * T_s + b$						
Control	2.04	11.03			<0.0001	0.234
Low N	2.27	6.20			<0.0001	0.266
Medium N	2.26	7.04			<0.0001	0.210
High N	2.54	3.12			<0.0001	0.253
(b) $F_{CH4} = a * exp(-b * WFPS)$						
Control	72.27	1.62			<0.0001	0.385
Low N	86.51	2.33			<0.0001	0.434
Medium N	82.74	2.00			<0.0001	0.472
High N	85.36	2.15			<0.0001	0.449
(c) $F_{CH4} = a * NH_4^+ + b$						
Control					0.4341	0.0006
Low N					0.1508	0.0154
Medium N					0.1436	0.0165
High N					0.3034	0.0011
(d) $F_{CH4} = a * NO_3^- + b$						
Control	2.71	26.92			0.039	0.037
Low N	3.54	20.77			0.029	0.042
Medium N	3.76	22.63			0.010	0.062
High N	2.20	26.77			0.014	0.057
(e) $F_{CH4} = a * AB^2 + b * AB + c$						
Control	−0.0001	0.128	9.71		0.003	0.127
Low N	−0.0001	0.104	7.22		0.008	0.085
Medium N	−0.0001	0.073	13.31		0.005	0.118
High N	−0.0001	0.128	2.851		0.009	0.161
(f) $F_{CH4} = a * pH + b$						
Control	4.67	−0.258			0.109	0.020
Low N	8.19	−29.08			0.011	0.066
Medium N	10.54	−43.32			0.004	0.087
High N	11.38	−47.83			0.002	0.103
(g) $F_{CH4} = a * WFPS + b * NH_4^+ + c * NO_3^- + d$						
Control	−44.39	−1.72	2.13	58.48	<0.001	0.433
Low N	−53.22		3.97	47.45	<0.001	0.458
Medium N	−44.61		2.03	49.44	<0.001	0.430
High N	−46.05		2.62	49.43	<0.001	0.428

[a] T_s is soil temperature at 5 cm depth, WFPS is soil water-filled pore space at 10 cm depth, NH_4^+ and NO_3^- are soil NH_4^+–N and NO_3^-–N storages at 50 cm depth, and AB is aboveground biomass.

soil in our study site is N-limited and has a strong capacity to immobilize exogenous NH_4^+ (Song et al., 2007). The NH_4^+ immobilization by soil organic and mineral materials rapidly removes applied NH_4^+, which would protect methanotrophs from exposure to NH_4^+ and accordingly mitigate the inhibition of methanotrophs. Second, the increasing nitrification by N addition would to some degree alleviate the inhibition of inorganic N to CH_4 oxidation (Chan et al., 2005). Although NH_4^+-oxidizing bacteria are capable of oxidizing CH_4 at rates lower than methanotrophs, CH_4 oxidation is dominated by nitrifiers (Steudler et al., 1996). Thus, N addition enhances the availability of NH_4^+ to nitrifiers, which would accordingly decrease the extent to which CH_4 consumers are exposed to NH_4^+ (Chan et al., 2005). Finally, the ratio of NH_3:NH_4^+ in soils is decreased by N addition. Gulledge et al. (1997) suggested that NH_3, rather than NH_4^+, was the key determinant of this inhibition, because the decreased soil pH induced by N addition would decrease the ratio of NH_3:NH_4^+ of soils. This is likely to decrease the degree of inhibition linked to N addition; however, no such clear regulation of NH_4^+ inhibition through pH has so far been identified (Gulledge et al., 1997; Hütsch, 1996).

4.4. Effects of soil NO_3^-–N variations on CH_4 uptake

Similar with NH_4^+, NO_3^- also showed a very strong inhibitory effect in some forest ecosystems (Rigler and Zechmeister-Boltenstern, 1999). Moreover, some studies suggest that NO_3^- may have a greater importance in the inhibition of CH_4 oxidation in forest soils than that attributed to NH_4^+ (Wang and Ineson, 2003; Xu and Inubushi, 2004; Xu and Inubushi, 2007). Generally, NO_3^- has been found inhibitory only in very high concentrations, which likely give rise to osmotic effects (Bodelier and Laanbroek, 2004). The other reason is that added NO_3^- and NO_2^- produced via NO_3^- reduction in anaerobic 'microsites' are probably toxic to CH_4-oxidizing bacteria (Schnell and King, 1994; Xu and Inubushi, 2004; Xu and Inubushi, 2007).

However, our study showed that NO_3^- accumulation could significantly promote CH_4 uptake in soil (Fig. 9 and Table 2). Bodelier and Laanbroek (2004) proposed a schematic explanation about the stimulation of CH_4 oxidation by NH_4^+ or NO_3^- addition to soils. For one thing, atmospheric methanotrophic bacteria are limited by N because they have a relatively high N requirement during C assimilation (Megmw and Knowles, 1987). N addition enhances soil mineralization rates and C and N availability for soil microbes (Rigler and Zechmeister-Boltenstern, 1999). Besides utilizing CH_4 in the atmosphere and in soil pores, it has been demonstrated that atmospheric CH_4 consumers can profit from and even depend on some non-methane substrates such as methanol, formate, and acetate (Bodelier and Laanbroek, 2004; Jensen et al., 1998). The improved availability of these C sources would promote CH_4 consumption by aerobic soils. Also, during the rainy season, the alpine meadow soils may become partially anoxic following high precipitation events and begin producing CH_4. The methanotrophic bacteria can profit from this enhanced CH_4 flux and grow when sufficient N is present (Bodelier and Laanbroek, 2004). However, in our study, N addition decreased overall soil CH_4 uptake. The promotion produced by NO_3^- accumulation is almost masked by the inhibition associated with decreasing WFPS.

4.5. Effects of other associated ions on CH_4 uptake

Besides NH_4^+ or NO_3^-, the associated ions of nitrogenous salts can also partly explain the different inhibition patterns. Some studies suggest that salt-effect may be a more reasonable explanation for reduced CH_4 oxidation than the specific NH_4^+ or NO_3^- effect (Borken and Brumme, 2009; King and Schnell, 1998; Whalen, 2000). A laboratory study showed that high concentration of Cl^- has a strong inhibitory effect on CH_4 oxidation by comparing the difference in ability to do so between N-salts (NH_4Cl and $NaNO_3$) and non-N-salt (NaCl) (Whalen, 2000). In the field, however, various N treatments ($(NH_4)_2SO_4$, NH_4-acetate, urea, NH_4Cl, $NaNO_3$, NH_4NO_3 and KNO_3) added at a same rate of 30 kg N ha^{-1} had little or no effect on CH_4 uptake within one year (Borken and Brumme, 2009). The rates of N addition (10–40 kg N ha^{-1} yr^{-1}) in our study are comparable to that of Borken and Brumme (2009), so added K^+, SO_4^{2-} and Cl^- could have little contribution to the decrease in CH_4 uptake. Also, the K^+ can exchange NH_4^+ from the exchange sites in the soil and thus released NH_4^+ could then inhibit CH_4 oxidation. If K^+ was the responsible component of the added salt in the current study, ion exchange should result in a higher NH_4^+ concentration. However, the soil NH_4^+ pool did not accumulate significantly, and even declined in the low and high KNO_3 addition plots (Table 1). Thus, the salt effects could not be a main reason for the CH_4 uptake in our study.

4.6. Effects of vegetation on CH_4 uptake

Plant communities affect soil CH_4 uptake through the following three ways: (1) increased N input to grasslands can increase soil moisture among the fine root biomass (Magill et al., 1997), which may decrease air-filled porosity and limit rates of diffusion and atmospheric CH_4 oxidation. Our data on soil WFPS and aboveground biomass partly supports this deduction (Figs. 4 and 7). (2) Plant-derived CH_4 emission can indirectly offset the CH_4 uptake of the entire ecosystem (Cao et al., 2008; Ferretti et al., 2007; Keppler et al., 2006; Keppler et al., 2008). However, serious debates and questions on CH_4 emission by living plants under aerobic conditions are raised. Dueck et al. (2007) reported

that there was no evidence for substantial aerobic CH_4 emission by plants. Moreover, aerobic CH_4 emission by plants is highly uncertain, and depends on species (Cao et al., 2008; Kirschbaum and Walcroft, 2008; Wang et al., 2007). Based on regression analysis results, CH_4 emission by alpine vegetation could have a small effect on ecosystem net CH_4 flux, although a significant relationship between CH_4 uptake and aboveground biomass is observed (Table 2 and Fig. 9e).

4.7. Soil acidification and CH_4 uptake

N addition can, to some degree, result in soil acidification in the alpine meadow, and the NO_3^-–N fertilizer seemed to have a stronger effect than the NH_4^+–N fertilizer. Generally, soil H^+ mainly originates from acid deposition, microbial decomposition of organic matter, and soil nitrification (Arnold et al., 1994; Sun et al., 2006). The oxidation of soil NH_4^+ to NO_3^- ($NH_4^+ + 2O_2 \rightarrow 2H^+ + NO_3^- + H_2O$) can produce H^+, so ammonium fertilizer application will directly result in soil acidification. Soil acidification caused by NO_3^-–N fertilizer addition is attributed to the exchange between the accompanied cations, such as K^+ and H^+, on soil particle exchange sites (Fang et al., 2012; Gao et al., 2013). Compared with NH_4Cl and $(NH_4)_2SO_4$, the effects of KNO_3 fertilizer on soil acidification were stronger, indicating the different effects of NH_4^+ and NO_3^- on soil acidification. The added NH_4^+ is partly absorbed by plants, immobilized by soil microbes, fixed by clay minerals and lost through ammonia volatilization. Only the NH_4^+ involved in the N mineralization and nitrification can produce H^+. On the contrary, most of the added NO_3^- can be replaced by an H^+ due to negligible leaching and denitrification.

In some forest soils, negative effects of soil acidification on soil physical parameters and bioturbation have the potential to reduce CH_4 uptake (Borken and Brumme, 2009). However, stepwise regression analysis showed that pH was not a key factor in the control of CH_4 uptake, suggesting that: (1) soil pH plays a minor role in determining CH_4 oxidation compared with other variables, and (2) methanotrophs in the alpine meadow soils can tolerate low pH (Saari et al., 2004).

5. Conclusions

This study emphasizes the appropriateness of using realistic levels rather than saturating levels of N-inputs in attempts to simulate increased N deposition. Our study suggested that low rates of N addition had significantly reduced the CH_4 sink of alpine meadow on the Qinghai–Tibetan Plateau over the short term. This indicates that the alpine meadow has low potential to consume more CH_4 under future elevated N deposition conditions on the Tibetan Plateau. Soil CH_4 uptake was primarily driven by soil moisture. The observed reduction in CH_4 uptake induced by N addition may mainly result from the decrease in physical diffusion, which is different from those in N-rich ecosystems or in high-dose N addition experiments. Overall, N is a regulatory factor of CH_4 uptake in the alpine meadow ecosystems. To elucidate the complex mechanisms by which inorganic N affects soil CH_4 uptake, further investigation should be carried out to determine the biochemical inhibition effects of NH_4^+ and NO_3^- accumulation on soil methanotrophic bacteria.

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