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ORIGINAL PAPER

Impacts of altitude and position on the rates of soil nitrogen mineralization and nitrification in alpine meadows on the eastern Qinghai–Tibetan Plateau, China

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Abstract Alpine and tundra grasslands constitute 7% world terrestrial land but 13% of the total global soil carbon (C) and 10% of the global soil nitrogen (N). Under the current climate change scenario of global warming, these grasslands will contribute significantly to the changing global C and N cycles. It is important to understand the controlling factors on soil N cycling in these ecosystems. To evaluate climate effects on N cycling, soil N mineralization and nitrification rates (0–15 cm) were measured using an in situ closed-top tube incubation across altitudes and positions from 2006 to 2008 in alpine meadows. The data indicated that soil N mineralization and nitrification rates decreased with increasing altitude, but only significantly ($P<0.05$) between the lowest and the two higher altitudes. Soil N mineralization and nitrification rates of south-facing slopes were higher than north-facing slopes at each altitude. This suggests that soil temperature and soil water content (WC) were the controlling factors for soil N mineralization and nitrification rates across altitude with soil WC being the most important factors over positions. Soil nitrification rate depended on soil N mineralization rate, and both rates may increase in response to regional warming of the alpine meadow.

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Introduction

Grasslands occupy a large proportion of the global terrestrial ecosystem (Adams et al. 1990), and understanding of grassland N dynamics is essential for clarifying the contribution of grassland ecosystems to the global C and N budget (Frank et al. 2002). For example, increasing mean annual temperature may increase soil net N mineralization (Smith et al. 2002), causing an increase in soil nitrification and N_2O flux to the atmosphere (Hutchinson 1995). Therefore, there may be a greenhouse gas contribution from grassland ecosystems.

Soil N mineralization is a key process of the soil N cycle and is the controlling process of soil inorganic N that is essential for plant growth. The rates of soil N mineralization, used as indices of N availability, often correlate well with site productivity and plant growth (Keeney 1980). However, N mineralization often differs with vegetation type, altitude, and topographic position, which are often due to variations in soil organic matter, temperature, and soil water availability (Powers 1990; Garten et al. 1994; Von Lutzow and Kogel-KNabner 2009). Soil N mineralization and nitrification rates are controlled by several factors, including total N (TN), soil organic C (SOC), and soil water content (Swift et al. 1979; Sprent 1987), soil C/N ratio (Frankenberger and Abdelmagid 1985), soil microbial respiration (Alef et al. 1988), and soil microbial C and N content (Dalal and Meyer 1987; Fisk and Schmidt 1995). Microbial controls on N mineralization and nitrification depends on microbial activity and composition of microbial

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communities (Dalal and Meyer 1987; Fisk and Schmidt 1995). Early studies showed that the N mineralization or nitrification rates were reduced by increasing altitude in forest soils, and this indicated that temperature was the controlling factor (Marrs et al. 1988; Kitanyanma et al. 1998; Hart and Perry Dnge 1999). The decrease in the rate of soil N mineralization by increasing altitude generally depends on the decrease of temperature (Floate 1970; Ross et al. 1979; Swift et al. 1979; Barry 1981; Marion and Black 1987) and also as a result of water logging caused by increased precipitation (Barry 1981). Morecroft et al. (1992) suggested that the field N mineralization rates were influenced by the concentration of readily decomposed N compounds and that at high altitudes these were not broken down during winter as much as at low altitudes, because of the incidence of freezing temperature. However, contradictory results have been also reported since N mineralization rate was not directly related to altitude (Strader et al. 1989; Powers 1990; Smith et al. 2002) or was simply greatest at the highest elevation site possibly influenced by organic matter quality and vegetation type (Nadelhoffer et al. 1991; Casals et al. 1995; Knoepp and Swank 1998). Ross et al. (1979) carried out laboratory incubations at uniform temperature of soils collected over 355 m range on a sub-antarctic island and found no trend in potential N mineralization rate with altitude that may be due to the use of well mixed soils and constant and warmer laboratory conditions. Powers (1990) found the highest rates of soil net N transformations at intermediate elevations across altitudinal gradients in northern California. His results suggested that soil water availability limited soil net N transformations at the low-elevation sites, while low soil temperatures limited these processes at the higher elevations.

The Qinghai–Tibetan Plateau, which extends over 2.5 million km^2, is the youngest and highest plateau in the world (Shi et al. 2010). The plateau ecosystem is very fragile and sensitive to changes in climate, and may act as an "indicator region" for early climate change in China and East Asia (Tang et al. 1986). An alpine meadow, covering about 42% of the plateau area, is a representative vegetation type and the major grazing (alpine yak and sheep) land of this region (Zhang et al. 2007). The alpine ecosystem may be a major C and N sink because of its high productivity and the low rate of decomposition resulting from low temperature (annual mean temperature below 2.4°C from 1958 to 2008). There are several studies on the soil properties, soil respiration, and soil C and N cycling in the alpine meadow ecosystem on eastern Qinghai–Tibetan Plateau (Kitanyanma et al. 1998; Wang et al. 2002, 2007; Cao et al. 2004; Kato et al. 2006; Tian et al. 2008; Baumann et al. 2009). To our knowledge, no one has done a comparable investigation on soil N mineralization and nitrification rates before, especially under field conditions in alpine meadow. The objective of this study was to measure soil N mineralization and nitrification rates at three altitudes and two positions using an in situ incubation technique to determine the factors influencing soil N mineralization and nitrification rates in alpine meadow on eastern Qinghai–Tibetan Plateau. The altitude and position gradients were used as a space-for-time substitution argument about the potential impact of warming and/or precipitation changes brought about through climate change upon soil N cycling. We addressed the following questions: (1) Which were the patterns of soil N mineralization and nitrification rates with altitudes within two positions? (2) How did soil N mineralization and nitrification rates differ between south-facing (SF) and north-facing (NF) slope at each altitude, being the former warmer and drier than the latter? A good understanding of these soil processes will allow us to identify the changes of N cycling that may occur in the future due to climate change in alpine meadow soils.

Materials and methods

Site description

This study was conducted in alpine meadows on eastern Qinghai–Tibetan Plateau, Gansu, China. Three altitudes (3,000, 3,500, and 4,000 m) were selected from southwest to northeast (101°52′–103°9′ E, 33°57′–35° N) on the plateau, and measurements were made from 2006 to 2008. The maximum distance was 65 km between any two sites at each altitude. Due to differences in micrometeorological conditions between SF slope (warmer/drier) and NF slope (cooler/wetter) at each altitude, both SF and NF slopes were selected. Meteorological data of each altitude got from nearest local station showed that the mean annual temperature varied from 2.4°C to −3.8°C when altitude varied from 3,000 to 4,000 m (mean over the last 40 years). Annual precipitation ranged from 350 to 650 mm (mean of 3-year data from 2006 to 2008) and was mainly distributed during the short, cool summer and autumn. Average soil temperature at 15 cm depth increased from 14°C to 16°C passing from 4,000 to 3,000 m during incubation period (mid-July to mid-September, Fig. 1). The area of alpine meadow had 2,580 h of sunshine and more than 270 frost days per year. The vegetation of SF and NF slope were similar at each altitude. The species number and aboveground biomass along altitude changed from 20 to 30 and from 150 to 350 g/m^2, respectively. Other details of the sites were shown in Table 1.

Experimental design and sampling

A total of 16 sampling plots were selected, including six on SF slope and six on NF slopes, which were located at 3,000 and 3,500 m; additionally, two plots located on SF slopes and two plots located on NF slopes were selected at the 4,000-m site. In the middle of July, one plot (20×20 m) was

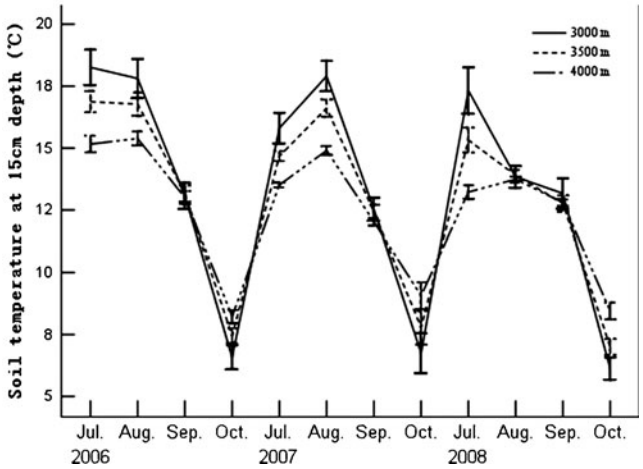

Fig. 1 Average soil temperature at 15 cm depth and at three altitudes from July to October during the studied period. Data are the means of 3 years. *Bars* represent standard errors

selected at each site for monitoring soil N mineralization and nitrification rates using an in situ closed-top tube incubation method (Adams and Attiwill 1986). In each plot, five random points were chosen for sampling. After removing the vegetation and litter, three PVC tubes (15 cm long×4.3 cm inner diameter) were driven into the mineral soil of each sample point with more than 1 m interval between each tube. The top of PVC tubes were then capped with polyethylene film. At the same time, three soil cores (3.8 cm inner diameter×15 cm in depth) were collected near to each PVC tube and composited for determining the initial NH_4^+–N and NO_3^-–N concentrations before incubation, and the other soil physical and chemical properties (Table 2). All PVC tubes were retrieved after a 60-day incubation in the field. Therefore, 15 soil samples and 15 PVC tubes were obtained at each sampling time in each plot from 2006 to 2008. After removing the coarse roots and gravel, the soil samples were sealed in plastic bags, kept cool while returned to the laboratory, and then stored in a refrigerator until analyzed. In the middle of August, when the biomass had reached its maximum (Luo et al. 2006), five 0.25-m^2 quadrats were randomly selected in each plot and the number of species recorded. The plants were clipped at ground level and dried at 80°C for 72 h, and weighed to determine total aboveground biomass.

Soil physical and chemical properties analysis

All soil samples were passed through a 2-mm sieve before analysis. Soil pH was measured with a glass electrode (soil to solution=1:2.5, using 1 M KCl). SOC was measured by the dichromate oxidation method (Kalembasa and Jenkinson 1973). Soil TN was measured by the Kjeldahl digestion method (Jackson 1973), using Vapodest Rapid Distillation Systems (EW 78871-05, Gerhardt Corp., Germany). Soil water content (WC) was measured gravimetrically, drying soil (50 g) in an oven at 105°C for 24 h; measurements of soil WC were repeated three times during soil incubation.

Available N (AN), which includes NH_4^+–N and NO_3^-–N, was determined on 10 g of soil, which were extracted with 2 M KCl for 1 h and filtered through a washed (50 mL 2 M KCl) quantitative filter paper. The soil filtrate was analyzed for NH_4^+–N at 660 nm electrofilter and for NO_3^-–N at 540 nm electrofilter on Flow Solution® IV (OI Analytical Corporation, USA) using alkaline phenol (USEPA 1983a) and cadmium reduction (USEPA 1983b) techniques, respectively. The SOC, TN, and AN data are presented on a dry weight basis. Nitrogen mineralization was calculated as soil NH_4^+–N+NO_3^-–N concentration at 60-day minus NH_4^+–N+NO_3^-–N concentration at time zero. Net nitrification was calculated as soil NO_3^-–N concentration at 60-day minus NO_3^-–N concentration at time zero.

Data analysis

Analysis by general linear model (GLM) showed that both year and year×altitude did not significantly affect in situ N

Table 1 Characteristics of the three altitudes alpine meadow soils located on the eastern Qinghai–Tibetan Plateau

Altitude (m)	Position	Slope (°)	Aboveground biomass (g/m^2)	Dominant species
3,000	NF slope	20–30	260	*Kobresia* sp., *Festuca ovina*, *Poa poophagorum*, *Roegneria nutans*, *Agrostis* sp., and *Saussurea* sp.
	SF slope		208	*Kobresia* sp., *F. ovina*, *P. poophagorum*, *Agrostis* sp., *Saussurea* sp., and *Anemone rivularis*
3,500	NF slope	25–35	196	*Kobresia* sp., *F. ovina*, *P. poophagorum*, *R. nutans*, *Agrostis* sp., *Saussurea* sp., and *A. rivularis*
	SF slope		332	*Kobresia* sp., *F. ovina*, *P. poophagorum*, *R. nutans*, *Agrostis* sp., *Saussurea* sp., and *A. rivularis*
4,000	NF slope	30–40	112	*Kobresia* sp., *R. nutans*, *Agrostis* sp., *Saussurea* sp., and *A. rivularis*
	SF slope		156	*Kobresia* sp., *F. ovina*, *R. nutans*, and *Saussurea* sp.

NF north facing, *SF* south facing

Table 2 Physical and chemical characteristics of the 0–15 cm soil taken from two positions at each of three altitudes during the 2006–2008 period

Altitude (m)	Position	WC (%)	pH	SOC (g/kg)	TN (g/kg)	NH_4^+–N (mg/kg)	NO_3^-–N (mg/kg)	AN (mg/kg)	C/N ratio
3,000	NF slope	39.9 (1.74)Za	6.3 (0.09)Xb	49.3 (0.66)Za	4.2 (0.05)Zb	7.5 (0.29)Za	8.7 (0.37)Yb	16.2 (0.38)Yb	11.4 (0.10)Ya
	SF slope	28.3 (1.27)zb	7.5 (0.13)xa	45.3 (0.88)zb	4.4 (0.07)za	7.6 (0.29)za	17.2 (0.87)xa	24.7 (0.87)xa	10.0 (0.11)zb
3,500	NF slope	56.7 (2.23)Ya	5.3 (0.02)Zb	57.1 (0.73)Yb	4.4 (0.05)Yb	11.6 (0.40)Xb	4.4 (0.20)Zb	16.2 (0.51)Yb	12.5 (0.09)Xa
	SF slope	50.4 (2.14)yb	5.6 (0.05)ya	77.6 (1.27)xa	6.0 (0.09)xa	18.7 (0.74)xa	7.3 (0.63)za	26.0 (1.14)xa	12.6 (0.11)ya
4,000	NF slope	78.1 (2.23)Xa	5.6 (0.05)Ya	78.2 (0.90)Xa	6.1 (0.07)Xa	9.8 (0.62)Yb	14.4 (0.87)Xa	24.2 (1.12)Xb	12.6 (0.15)Xb
	SF slope	59.6 (1.59)xb	5.7 (0.07)ya	68.0 (1.06)yb	4.92 (0.07)yb	14.4 (0.92)ya	13.5 (0.67)ya	27.9 (1.15)xa	13.3 (0.16)xa

Values are means (SE), $n=90$ for all soil properties except for WC and pH where $n=30$. The significant differences between NF slope and SF slope are indicated with a and b at each altitude. The significant differences of the NF slopes are indicated with X, Y, and Z and those of SF slopes with x, y, and z among different altitudes. All differences are significant at level of $P<0.05$, based on LSD comparison

NF north facing, *SF* south facing, *WC* water content, *SOC* soil organic C, *TN* total N, *AN* available N

mineralization ($P=0.06$ and $P=0.12$, respectively) and nitrification ($P=0.07$ and $P=0.34$), respectively; thus all indices are the mean of 3 years. Independent sample *t* tests were employed to analyze the differences of all indices between SF and NF slopes at each altitude. One-way ANOVA was used to analyze the difference of all indices at each position among altitudes. Post hoc tests for each variable were made using LSD comparisons. Pearson correlation analysis was used to determine the correlation between all the measured parameters. Significant differences for all statistical tests were evaluated at the level of $P\leq0.05$ unless noted. All data analyses were conducted with the SPSS software (SPSS for Windows, Version 13.0, Chicago, IL, USA).

Results

Soil chemical properties related to altitude and position

Using 3-year mean values, the analysis of variance showed that SOC and TN contents significantly ($P<0.05$) increased with altitude on NF slopes (Table 2). The soil parameters WC, AN, and C/N ratio increased with altitude on both NF and SF slopes (Table 2). The pH and NO_3^-–N content were the lowest at the 3,500 m site at both slope positions (Table 2). The maximum soil pH value was 7.46 on an SF slope position, and the minimum was 5.31 on an NF slope position. Soil C/N ratio showed a narrow range varying from 10 to 13 and increased at two slope positions with altitude. Soil WC was significantly higher ($P<0.001$) on the NF slopes than the SF slopes at each altitude and soil WC of two slope positions significantly increased ($P<0.01$) by increasing altitude (Table 2). It showed that NF slopes were always wetter than SF slopes at each altitude. Soil pH and the content of NH_4^+–N and AN were greater on SF slope positions than NF slope positions (Table 2) at all altitudes. The concentrations of SOC and TN were significantly and positively correlated with concentrations of NH_4^+–N ($R=0.55$, $P<0.01$ and $R=0.54$, $P<0.01$, respectively) and AN ($R=0.35$, $P<0.01$ and $R=0.49$, $P<0.01$, respectively) and with each other ($R=0.93$, $P<0.001$; Table 3).

Soil N mineralization and nitrification with altitude and position

ANOVA analysis showed that both soil N mineralization and nitrification rates were significantly greater ($P<0.05$) on both slope positions at 3,000 m compared to 3,500 and 4,000 m altitudes (Fig. 2a, b). The soil N mineralized rates over the 60-day period were 8.5, 5.3, and 3.8 mg N/kg soil for the 3,000, 3,500, and 4,000 m in the NF slope position, and 16.1, 8.4, and 8.0 mg N/kg soil in the SF slope position, respectively (Fig. 2a). Soil N mineraliza-

Table 3 Pearson's correlation coefficients among soil properties in alpine meadow soil on the eastern Qinghai–Tibetan Plateau

Parameters	SOC	TN	NH_4^+–N	NO_3^-–N	AN	C/N ratio	pH	Nm
TN (g/kg)	0.93[a]							
NH_4^+ (mg/kg)	0.55[a]	0.54[a]						
NO_3^- (mg/kg)	−0.04	0.14[a]	−0.12[a]					
AN (mg/kg)	0.35[a]	0.49[a]	0.60[a]	0.72[a]				
C/N ratio	0.58[a]	0.29[a]	0.11[a]	−0.30[a]	−0.16[a]			
pH	−0.52[a]	−0.29[a]	−0.30[a]	0.49[a]	0.19[b]	−0.68[a]		
Nm (mg/kg)	−0.21[a]	−0.07	−0.15[a]	0.21[a]	0.05	−0.38[a]	0.44[a]	
Nn (mg/kg)	−0.16[a]	−0.01	0.06	0.13[b]	0.16[a]	−0.33[a]	0.49[a]	0.86[a]

Nm N mineralization, *Nn* N nitrification, *SOC* soil organic C, *TN* total N, *AN* available N

[a]Correlation is significant at the 0.01 level

[b]Correlation is significant at the 0.05 level

tion rate of the SF slope was almost two times that of NF slope. The nitrification rates were 8.9, 6.1, and 5.3 mg N/kg soil/60 days for the 3,000, 3,500, and 4,000 m in the NF slope position, and 17.2, 9.7, and 8.6 mg N/kg soil/60 days in the SF slope position, respectively (Fig. 2b). Both soil N mineralization and nitrification rates in two slope positions decreased by increasing altitude and these differences were significant ($P<0.05$) except for 4,000 m altitude.

Average soil N mineralization and nitrification rates for three altitudes were 7.1 and 7.8 mg N/kg soil for the NF slopes, respectively, and 11.8 and 12.9 mg N/kg soil for the SF slopes, respectively. Both soil N mineralization and nitrification rates on SF slopes were greater than on NF slope among 3 years. Independent sample *t* test showed that soil N mineralization and nitrification rates were significantly different ($P<0.01$) between NF and SF slopes at the two lower altitudes (Fig. 2a, b).

Discussion

Soil properties with altitude and position

By increasing altitude temperature will typically decrease and the corresponding precipitation will increase (Barry 1981; Ineson et al. 1998), thus directional positions are a main factor for the differences in climate distribution. The SF slope was warmer/drier than the NF slope due to differences in micrometeorological conditions (Du et al. 2003). In our study, the soil WC explained 16.6% of the variance. The difference of soil WC between NF and SF slopes are mainly attributed to the position. Soil pH is a function of parent material, time of weathering, vegetation, and climate (Smith et al. 2002). The mean soil pH value decreased from 3,000 to 3,500 m but did not increase from 3,500 to 4,000 m, thus confirming previous reports (Stanko-Golden et al. 1992; Dahlgren et al. 1997). Since time of weathering and vegetation type are similar among experimental sites in the alpine meadow (Table 1), the decrease in soil pH could be due to the increase of basic cations leaching at the higher altitude due to the greater soil WC (Smith et al. 2002). At the same time, soil pH value of SF slopes were significantly ($P<0.001$) higher than those of NF slopes except at 4,000 m (Table 2) probably due to the greater soil WC in the NF slope. Our result showed that soil from the low altitude was slightly alkaline and that from the high altitude was slightly acidic.

The contents of SOC and TN increased by increasing altitude on NF slopes probably due to the greater soil WC (Table 2) and lower soil temperatures (Fig. 1), which would retard the decomposition of litter. Consequently there is a longer residence time of N in the litter and a decrease in soil N losses at higher than lower altitudes (Smith et al. 2002; Kato et al. 2006). It may be that soil periodically become

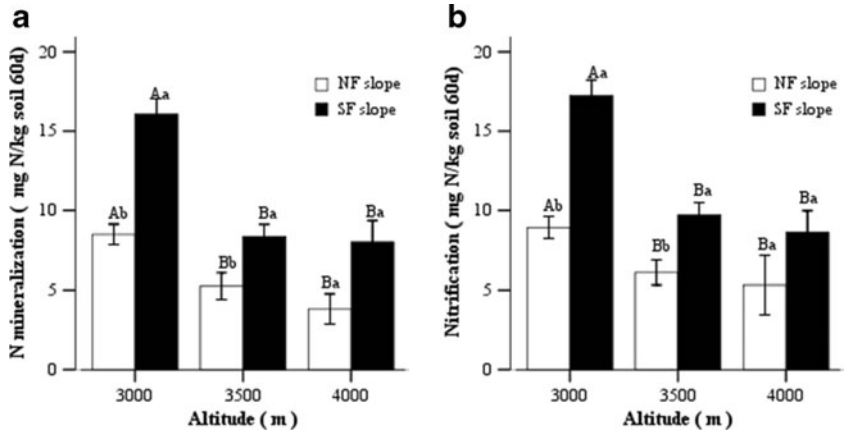

Fig. 2 N mineralization (**a**) and nitrification (**b**) were measured using in situ close-top tube at three altitudes and two slopes during a 60-day incubation (0–15 cm) period. Data are the means of 3 years. *Bars* represent standard errors. Significant differences are shown in *capital letters* for each position (NF and SF slopes) across altitudes and *lower case letters* between the NF and SF slopes at each altitude. Based on LSD comparison ($P\leq0.05$)

anaerobic and soil N mineralization rate is slowed by increasing altitude. In addition, lower soil temperatures contributed to the accumulation of SOC and TN (Ji 1996). However, the maximum SOC and TN existed at the 3,500-m site (Table 2) on an SF slope, thus other factors may be controlling microbial activity since this site has intermediate soil temperature and soil WC values (Smith et al. 2002; Kato et al. 2006). In addition, SF slope at 3,500 m showed the highest plant productivity (Table 1).

Soil N mineralization with altitude and position

Soil temperature and soil WC explained more than 90% of the variation in laboratory N mineralization measurements made by Goncalves and Carlyle (1994). Powers (1990), Goncalves and Carlyle (1994), and Ineson et al. (1998) reported that temperature and precipitation influenced rates and patterns of soil N mineralization. Marrs et al. (1988) found that soil net N transformations decreased with altitude in tropical rain forests in Costa Rica. Their results indicated that reduced rates of these processes occurred at higher altitudes because of higher soil WC of the mountain soils. Powers (1990) found the highest rates of soil net N transformations at intermediate altitudes in forest soil in northern California, probably because soil water availability limited soil net N transformations at the low-elevation sites, while low soil temperatures limited the process at the higher altitudes. In our study both of these factors varied with altitudes, with soil WC increases, and soil temperature decreases by increasing altitude (Table 2 and Fig. 1). Soil N mineralization rate was regulated by soil WC in the slope positions and by both soil WC and temperature at altitudes.

Soil nitrification with altitude and position

Soil nitrification rates were probably autotrophic in these soils (Matson et al. 2002; Liu et al. 2007). This process can control N losses by leaching and gaseous N losses (Liu et al. 2007). In our study, soil nitrification rate showed similar trends as soil N mineralization rate decreased by increasing altitude and being higher in SF than NF slopes. Soil nitrification rate decreased by increasing soil WC (Breuer et al. 2002), probably due to appearance of anaerobic microsites with restricted oxygen diffusion into the soil. However, a positive relationship between soil nitrification rate and soil WC has been also observed due to the fact that microbial activity can increase within a certain range of soil WC (Stark and Firestone 1995; Ingwersen et al. 1999). Our study showed a positive relationship of soil nitrification rate with soil temperature and a negative relationship with soil WC. The aerobic nitrifying bacteria are limited by soil temperature and by the presence of anaerobic microsites. The response of soil nitrification to the increase in soil temperature was higher than the response of soil N mineralization in the NF slope, suggesting that soil nitrification rate may be more sensitive to soil temperature than N mineralization. In addition, soil nitrification was significantly greater ($P<0.01$) on SF slopes than NF slopes at each altitude except at 4,000 m ($P>0.05$, Fig. 2b), and this suggests that the effect of temperature was masked by soil WC.

Both soil N mineralization and nitrification rates were significantly and positively correlated with pH as already shown by as Kemmitt et al. (2006), since soil acidity limits soil microbial activity. Soil pH may locally be an important regulator of soil N mineralization and nitrification, but it is generally not a good predictor of regional differences (Robertson 1982). Soil N mineralization and nitrification rates were significantly and negatively correlated with soil C/N ratio, confirming what was reported by Menyailo and Huwe (1999). It is well established that low C/N ratio can stimulate N mineralization and nitrification. Indeed, available N was significantly and positively correlated with soil N mineralization and nitrification rates.

Conclusion

Soil N mineralization and nitrification rates decreased by increasing altitudes and were higher in the SF than in the NF slope. Both soil temperature and soil WC were the key controlling factors for soil N mineralization and nitrification rates across altitude, and soil WC was the main regulating factor when different slopes were compared in these alpine meadows. In addition, soil nitrification rate was higher than soil N mineralization rate at two positions across altitudes. Increased soil N mineralization rate may support enhanced soil nitrification rate. Thus the mechanisms and controlling factors of high nitrification rates should be the subject of future researches.

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References

Adams JM, Faire H, Faire-Richard L, Mcglade JM, Woodward FI (1990) Increases in terrestrial carbon storage from the last glacial maximum to the present. Nature 348:711–714

Adams MA, Attiwill PM (1986) Nutrient cycling and nitrogen mineralization in eucalypt forests of south-eastern Australia. II. Indices of nitrogen mineralization. Plant Soil 92:341–362. doi:10.1007/BF02372483

Alef K, Beck TH, Zelles L, Kleiner D (1988) A comparison of methods to estimate microbial biomass and N-mineralization in agricultural and grassland soils. Soil Biol Biochem 20:561–565. doi:10.1016/0038-0717(88), 90073-9

Barry RG (1981) Mountain weather and climate. Methuen, London

Baumann F, He JS, Schmidt K, Kuhn P, Scholten T (2009) Pedogenesis, permafrost, and soil moisture as controlling factors for soil nitrogen and carbon contents across the Tibetan Plateau. Global Change Biol 12:3001–3017. doi:10.1111/j.1365-2486.2009.01953.x

Breuer L, Kiese R, Butterbach-Bahl K (2002) Temperature and moisture effects on nitrification rates in tropical rain forest soils. Soil Sci Soc Am J 66:834–844

Cao GM, Tang YH, Mo WH, Wang YS, Li YN, Zhao XQ (2004) Grazing intensity alters soil respiration in an alpine meadow on the Tibetan plateau. Soil Biol Biochem 36:237–243. doi:10.1016/j.soilbio.2003.09.010

Casals P, Romanya J, Cortina J, Fons J, Bode M, Vallejo VR (1995) Nitrogen supply rate in Scots pine (*Pinus sylvestris* L.) forests of contrasting slope aspect. Plant Soil 168–169:67–73. doi:10.1007/BF00029314

Dahlgren RA, Boettinger JL, Huntington GL, Amundson RG (1997) Soil development along an elevational transect in the western Sierra Nevada, California. Geoderma 78:207–236. doi:10.1016/S0016-7061(97)00034-7

Dalal RC, Meyer RJ (1987) Long-term trends in fertility of soils under continuous cultivation and cereal cropping in Southern Queensland. VII. Dynamics of nitrogen mineralization potentials and microbial biomass. Aust J Soil Res 25:461–472

Du GZ, Qin GL, Li ZZ, Liu ZH, Dong GS (2003) Relationship between species richness and productivity in an alpine meadow plant community. Acta Phytoecologica Sinica 27:125–132, in Chinese with English abstract

Fisk MC, Schmidt SK (1995) Nitrogen mineralization and microbial biomass nitrogen dynamics in three alpine tundra communities. Soil Sci Soc Am J 59:1036–1043

Floate MJS (1970) Decomposition of organic materials from hill soils and pastures. III. The effect of temperature on the mineralization of carbon, nitrogen and phosphorus from plant materials and sheep faeces. Soil Biol Biochem 2:187–196. doi:10.1016/0038-0717(70)90006-4

Frank AB, Liebig MA, Hanson JD (2002) Soil carbon dioxide fluxes in northern semiarid grasslands. Soil Biol Biochem 34:1235–1241. doi:10.1016/S0038-0717(02)00062-7

Frankenberger WT, Abdelmagid HM (1985) Kinetic parameters of nitrogen mineralization rate of leguminous crops incorporated into soil. Plant Soil 87:257–271. doi:10.1007/BF02181865

Garten CT Jr, Huston MA, Thoms CA (1994) Topographic variation of soil nitrogen dynamics at Walker Brance Watershed, Tennessee. Forest Sci 40:497–512

Goncalves JLM, Carlyle JC (1994) Modelling the influence of moisture and temperature on net nitrogen mineralization in a forested sandy soil. Soil Biol Biochem 26:1557–1564. doi:10.1016/0038-0717(94)90098-1

Hart SC, Perry Dnge A (1999) Transferring soils from high-to low-elevation forests increases nitrogen cycling rates: climate change implications. Global Change Biol 5:23–32. doi:10.1046/j.1365-2486.1998.00196.x

Hutchinson GL (1995) Biosphere-atmosphere exchange of gaseous N oxides. In: Lal R, Kimble J, Levine E, Stewart BA (eds) Soils and global change. CRC Press, Boca Raton, pp 219–236

Ineson P, Taylory T, Harrison AF, Poskitt J, Benham DG, Tipping E, Woof C (1998) Effects of climate change on nitrogen dynamics in upland soils. 1. A transplant approach. Global Change Biol 4:143–152. doi:10.1046/j.1365-2486.1998.00118.x

Ingwersen J, Butterbach-Bahl K, Gasche R, Richter O, Papen H (1999) Barometric process separation: new method for quantifying nitrification, denitrification and nitrous oxide sources in soils. Soil Sci Soc Am J 63:117–128

Jackson ML (1973) Soil chemical analysis. Prentice-Hall, New Delhi

Ji Z (1996) Periglacial wetland and its environment effect and ecological construction in China. J Glac Geocryol 18:274–280, in Chinese with English abstract

Kalembasa SJ, Jenkinson DS (1973) A comparative study of titrimetric and gravimetric methods for the determination of organic carbon in soil. J Sci Food Agr 24:1085–1090. doi:10.1002/jsfa.2740240910

Kato T, Tang YH, Gu S, Hirota M, Du MY, Li YN, Zhao XQ (2006) Temperature and biomass influences on interannual changes in CO_2 exchange in an alpine meadow on the Qinghai-Tibetan Plateau. Global Change Biol 12:1285–1298. doi:10.1111/j.1365-2486.2006.01153.x

Keeney DR (1980) Prediction of soil nitrogen availability in forest ecosystems: a literature review. Forest Sci 26:159–171

Kemmitt SJ, Wright D, Goulding KWT, Jones DL (2006) pH regulation of carbon and nitrogen dynamics in two agricultural soils. Soil Biol Biochem 38:898–911. doi:10.1016/j.soilbio.2005.08.006

Kitanyanma K, Aiba SI, Lee NM, Ohsawa M (1998) Soil nitrogen mineralization rates of rainforests in a matrix of elevations and geological substrates on Mount Kinabalu, Borneo. Ecol Res 13:301–312. doi:10.1046/j.1440-1703.1998.00264.x

Knoepp JD, Swank WT (1998) Rates of nitrogen mineralization across an elevation and vegetation gradient in the southern Appalachians. Plant Soil 204:235–241. doi:10.1023/A:1004375412512

Liu Y, Chen JS, Liu Q, Wu Y (2007) Nitrification and denitrification in subalpine coniferous forests of different restoration stages in western Sichuan, China. Front For China 2:260–265. doi:10.1007/s11461-007-0042-z

Luo YJ, Qin GL, Du GZ (2006) Importance of assemblage-level thinning: a field experiment in an alpine meadow on the Tibet plateau. J Veg Sci 17:417–424

Marion GM, Black CH (1987) The effect of time and temperature on nitrogen mineralization in arctic tundra soils. Soil Sci Soc Am J 51:1501–1508

Marrs RH, Proctor J, Heaney A, Mountford MD (1988) Changes in soil nitrogen-mineralization and nitrification along an altitudinal transect in tropical rain forest in Costa Rica. J Ecol 76:466–482

Matson P, Lohse KA, Hall SJ (2002) The globalization of nitrogen deposition: consequences for terrestrial ecosystems. Ambio 31:113–119

Menyailo OV, Huwe B (1999) Activity of denitrification and dynamics of N_2O release in soils under six tree species and grassland in central Siberia. J Plant Nutr Soil Sci 162:533–538

Morecroft MD, Marrs RH, Woodward FI (1992) Altitudinal and seasonal trends in soil nitrogen mineralization rate in the Scottish Highlands. J Ecol 80:49–56

Nadelhoffer KJ, Giblin AE, Shaver GR, Launder JA (1991) Effects of temperature and substrate quality on element mineralization in six arctic soils. Ecology 72:242–253. doi:10.2307/1938918

Powers RF (1990) Nitrogen mineralization along an altitudinal gradient: interactions of soil temperature, moisture, and substrate quality. Forest Ecol Manag 30:19–29. doi:10.1016/0378-1127(90)90123-S

Robertson GP (1982) Nitrification in forested ecosystems. Phil T Roy Soc B 296:445–457

Ross DJ, Campbell IB, Bridger BA (1979) Biochemical activities of organic soils from sub-antarctic tussock grasslands on Campbell Islands. 1. Oxygen uptakes and nitrogen mineralization. New Zeal J Sci 22:161–171

Shi XM, Li XG, Long RJ, Singh BP, Li ZT, Li FM (2010) Dynamics of soil organic carbon and nitrogen associated with physically separated fractions in a grassland-cultivation sequence in the Qinghai-Tibetan plateau. Biol Fertil Soils 46:103–111. doi:10.1007/s00374-009-0414-7

Smith JL, Halvorson JJ, Jr HB (2002) Soil properties and microbial activity across a 500 m elevation gradient in a semi-arid environment. Soil Biol Biochem 34:1749–1757. doi:10.1016/S0038-0717(02)00162-1

Sprent JI (1987) The ecology of the nitrogen cycle. Cambridge University Press, Cambridge

Stanko-Golden KM, Fitzgerald JW, Swank WT (1992) Sulfur processing in soil from high and low elevation forests in the Southern Appalachians of the United States. Soil Biol Biochem 24:693–702. doi:10.1016/0038-0717(92)90048-3

Stark JM, Firestone MK (1995) Mechanisms for soil moisture effects on activity of nitrifying bacteria. Appl Environ Microb 61:218–221

Strader RH, Binkley D, Wells CG (1989) Nitrogen mineralization in high elevation forests of the Appalachians. I. Regional patterns in southern spruce-fir forests. Biogeochemistry 7:131–145. doi:10.1007/BF00004125

Swift MJ, Heal OW, Anderson JM (1979) Decomposition in terrestrial ecosystems. Blackwell Scientific Publications, Oxford

Tang MC, Li CQ, Zhang J (1986) The climate change of Qinghai-Xizang plateau and its neighborhood. Plateau Meteor 631:39–49. doi:10.1016/j.soilbio.2003.09.010

Tian YQ, Ouyang H, Song MH, Niu HSH, Hu QW (2008) Distribution characteristics and influencing factors of soil organic carbon in alpine ecosystems on the Tibetan Plateau transect. China Front Agric China 2:404–409. doi:10.1007/s11703-008-0050-2

USEPA (1983a) Methods for chemical analysis of water and waste. Determination of nitrogen as ammonia. Method 350.1

USEPA (1983b) Methods for chemical analysis of water and waste. Determination of nitrate/nitrite by automated cadmium reduction. Method 353.2

Von Lutzow M, Kogel-KNabner I (2009) Temperature sensitivity of soil organic matter decomposition—what do we know? Biol Fertil Soils 46:1–15. doi:10.1007/s00374-009-0413-8

Wang GX, Qian J, Cheng GD, Lai YM (2002) Soil organic carbon pool of grassland soils on the Qinghai-Tibetan plateau and its global implication. Sci Total Environ 291:207–217

Wang GX, Wang YB, Li YS, Cheng HY (2007) Influences of alpine ecosystem responses to climatic change on soil properties on the Qinghai-Tibet Plateau, China. Catena 70:506–514. doi:10.1016/j.catena.2007.01.001

Zhang YQ, Tang YH, Jiang J, Yang YH (2007) Characterizing the dynamics of soil organic carbon in grasslands on the Qinghai-Tibetan Plateau. Sci China Earth Sci 50:113–120. doi:10.1007/s11430-007-2032-2