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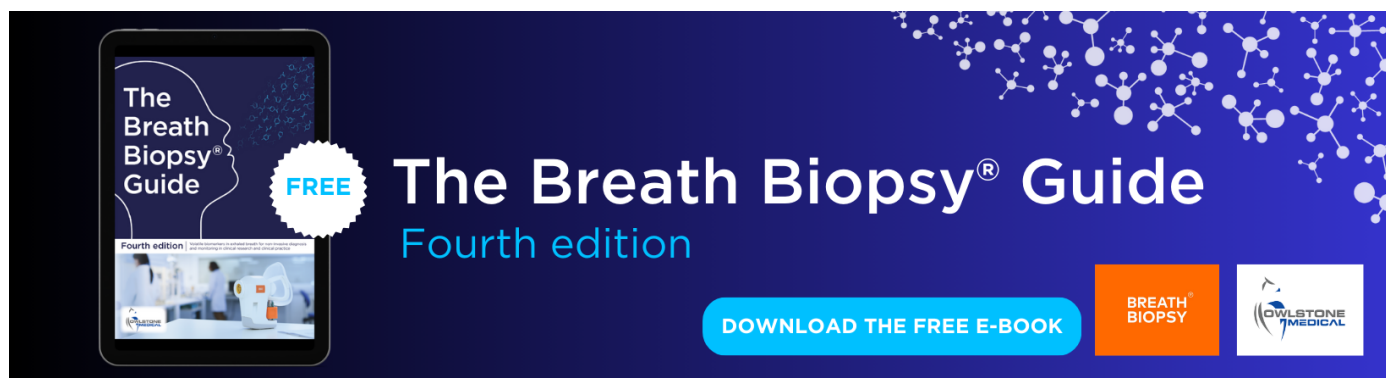
Variation and control of soil organic carbon and other nutrients in permafrost regions on central Qinghai-Tibetan Plateau

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Variation and control of soil organic carbon and other nutrients in permafrost regions on central Qinghai-Tibetan Plateau

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Abstract

The variation and control of soil organic carbon (SOC) and other nutrients in permafrost regions are critical for studying the carbon cycle and its potential feedbacks to climate change; however, they are poorly understood. Soil nutrients samples at depths of 0–10, 10–20, 20–30, and 30–40 cm, were sampled eight times in 2009 in alpine swamp meadow, alpine meadow and alpine steppe in permafrost regions of the central Qinghai-Tibetan Plateau. SOC and total nitrogen (TN) in the alpine swamp meadow and meadow decreased with soil depth, whereas the highest SOC content in the alpine steppe was found at depths of 20–30 cm. The vertical profiles of total and available phosphorus (P) and potassium (K) were relatively uniform for all the three grassland types. Correlation and linear regression analyses showed that soil moisture (SM) was the most important parameter for the vertical variation of SOC and other soil nutrients, and that belowground biomass (BGB) was the main source of SOC and TN. The spatial variations (including seasonal variation) of SOC and TN at plot scale were large. The relative deviation of SOC ranged from 7.18 to 41.50 in the alpine swamp meadow, from 2.88 to 35.91 in the alpine meadow, and from 9.33 to 68.38 in the alpine steppe. The spatial variations in the other soil nutrients varied among different grassland types. The most important factors for spatial variations (including seasonal variation) of SOC, TN, total P, available P, and both total and available K were: SM, SM and temperature, SM, air temperature, and SM and BGB, respectively. The large variation in the three grassland types implies that spatial variation at plot scale should be considered when estimating SOC storage and its dynamics.

Keywords: permafrost, alpine grassland, belowground biomass, soil moisture, soil temperature

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1. Introduction

Soil organic carbon (SOC) is the largest terrestrial pool of carbon; it plays a key role in the carbon cycle and is therefore important in global climate models (Davidson and Janssens 2006). In permafrost regions of the northern hemisphere,

soil is a critical terrestrial carbon pool because it contains approximately 1670 Pg (1 Pg = 10^{15} g) of SOC, which accounts for approximately 50% of the estimated global belowground organic carbon pool (Tarnocai *et al* 2009). SOC in permafrost regions is expected to undergo drastic changes with predicted global warming (Gruber *et al* 2004, Schuur *et al* 2008, Schädel *et al* 2013). These changes in SOC could amplify global warming by releasing methane and carbon dioxide, which are powerful greenhouse gases (Schuur *et al* 2009). Therefore, studying the spatial distribution, temporal dynamics, and control of SOC in permafrost regions is critical for global climate predictions.

The Qinghai-Tibetan Plateau (QTP) is the largest high-altitude permafrost region on earth, with 54.3% of its total area affected by permafrost (Cheng 2005). Recent studies have found that global warming has caused permafrost degradation in the QTP over the past several decades (Wu and Zhang 2010). Permafrost degradation will have a strong influence on alpine ecosystems on timescales ranging from seasons to decades, leading to severe changes in soil water–heat transmission regimes (Chen *et al* 2012b). Alpine grasslands (alpine steppe and alpine meadow) are the region's dominant ecosystems, covering 60% of its total area (Li and Zhou 1998). They store 23.2 Pg SOC, which represents 23.4% of China's total SOC pool and 2.4% of the global SOC pool (Wang *et al* 2002). However, permafrost degradation and overgrazing have caused considerable losses of SOC and other soil nutrients (such as nitrogen, phosphorus and potassium) in heavily degraded alpine grasslands over the past 25–45 years (Wang *et al* 2007, Yang *et al* 2009), resulting in significant modifications in the carbon cycle and the cycles of other soil nutrients (Baumann *et al* 2009). This makes it essential to gain a better understanding of the main factors influencing the distribution and dynamics of SOC and other soil nutrients in the grasslands of the QTP.

Many scholars around the world have been concerned by the change in SOC storage in the QTP (Wang *et al* 2002, Zhang *et al* 2007, Yang *et al* 2008, Baumann *et al* 2009, Tan *et al* 2010, Wu *et al* 2012, Dörfer *et al* 2013). While there have been some studies on the spatial distribution and temporal dynamics of SOC storage in large scale (Zhang *et al* 2007, Tan *et al* 2010), variation and the factors controlling SOC in small scale (e.g. plot-scale) have not been well investigated. In addition to the quality and quantity of litter input, SOC is influenced by external factors such as air temperature, precipitation, vegetation and the soil environment (Ravindranath and Ostwald 2008), and by internal factors that vary seasonally such as microbial biomass and activity (Kawahigashi *et al* 2003). Therefore, variation in other soil nutrients should also be considered in order to understand the variation of SOC. The Beiluhe Basin is located in the source areas of several large rivers on the QTP, including the Yangtze and Yellow Rivers (Wang and Wu 2013). The variations of SOC and other nutrients in the shallow active layer (top layer of soil that thaws during the summer and freezes again during the autumn) of the permafrost regions in this basin is critical for the stability of high-cold ecosystem, thereby playing an important role in

regulating river flow, the productivity of local grazing grasslands and carbon sequestration (Wang *et al* 2002, Wang and Wu 2013). In this study, data on SOC, total nitrogen (TN), total and available phosphorus (P) and potassium (K) were collected eight times between May and October of 2009 from plots with three alpine grassland types (alpine swamp meadow, alpine meadow and alpine steppe) in the Beiluhe Basin. Our objectives were: (1) to detect vertical and spatial patterns of SOC, TN, total and available P and K; and (2) to determine how external factors affect the vertical and spatial variations (including seasonal variation) of SOC and other soil nutrients.

2. Materials and methods

2.1. Study location and plot description

The study was conducted in the Beiluhe region in the hinterland of the QTP, China. Three plots (BLH1, BLH2 and BLH3, 30 m × 30 m for each plot) were selected nearby the Beiluhe Station (full name is Beiluhe Observation and Research Station on Frozen Soil Engineering and Environment in Qinghai-Tibet Plateau), which located on both sides of the Qinghai-Tibet railway (figure 1). The region has thin air and low pressure with a semi-arid climate of cold and dry weather over four indistinct seasons (Zhao *et al* 2006). Mean annual radiation, air temperature and wind velocity are 6258 MJ m⁻², −3.2 °C and 4.6 m s⁻¹, respectively (Chen *et al* 2012a). The mean annual precipitation is about 424 mm, 80% of which falls during the growing season (from May to September) (Wang and Wu 2013). The thickness of the active layer is maximum thaw depth in permafrost areas, which ranges from 1.5 to 4.2 m in this region. Mean daily temperature and precipitation during sampling periods of 2009 are presented in figure 2.

The area of Beiluhe Basin is about 7949 km², with 94% of total area covered by the grassland. Based on 1:1000 000 scale vegetation distribution map of China (the data set was provided by Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China, <http://westdcwestgis.ac.cn>), grassland types of alpine meadow and alpine steppe were grouped in this basin. And the alpine swamp meadow type was separated by NDVI value from Thematic Mapper remote sensing data (acquired on July 16, 2010), and then was checked by high resolution satellite images at Google Earth. The areas of alpine swamp meadow, alpine meadow and alpine steppe were 96, 3090 and 4300 km², respectively. The grassland types of BLH1, BLH2 and BLH3 were alpine swamp meadow, alpine meadow and alpine steppe, and their vegetative coverage in August were about 87%, 57% and 38%, respectively. Representative plants were *Kobresia tibetica*, *K robusta* and *Aster souliei* in BLH1, *K pygmaea*, *Carex moorcroftii*, *Leontopodium ochroleucum* and *Poa poophagorum* in BLH2, *Stipa purpurea*, *Carex rigescens*, *Oxytropis melanocalyx* in BLH3 (Chen 2010, Chen *et al* 2012a). According to the Chinese soil classification system (soil types from the WRB classification, IUSS

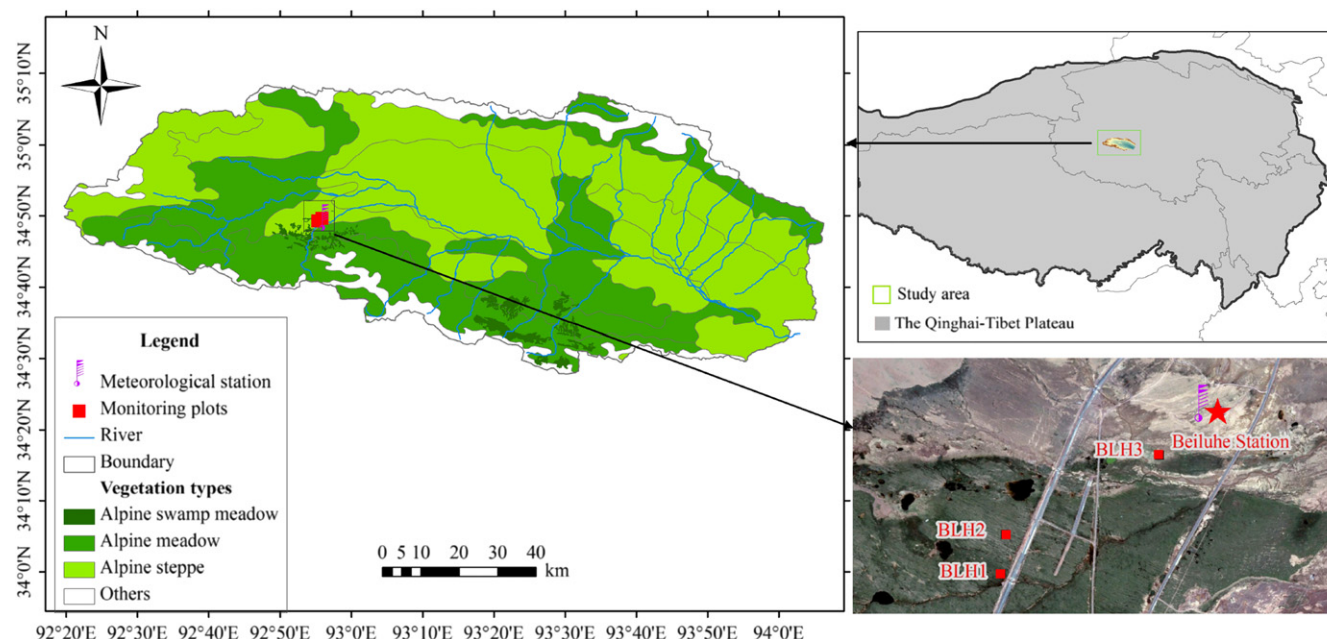


Figure 1. Location of the study area in the Beiluhe Basin on the central of Qinghai-Tibetan Plateau, China. Monitoring plots of BLH1, BLH2 and BLH3 located in alpine swamp meadow, alpine meadow and alpine steppe, respectively.

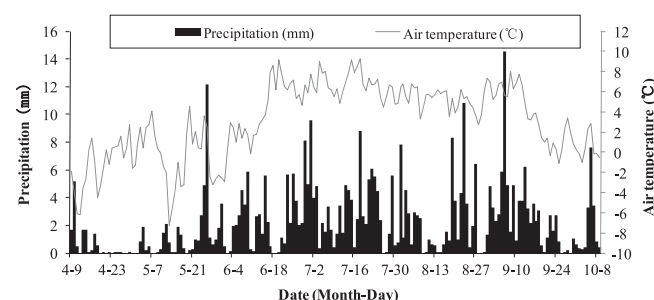


Figure 2. Mean daily temperature and precipitation during vegetation growing season of 2009.

Working Group WRB 2006, are given in parentheses), the soil types of the BLH1, BLH2 and BLH3 are Calcaric Matti-Gelic Cambosols (Calcic Kastanozem), Calcic Hapli-Gelic Cambosols (Haplic Calcisols) and Calcrine Gelic-Sandic Primosols (Gelic Arenosols), respectively (Zhao *et al* 2006).

2.2. Data collection

Meteorological data were recorded by a nearby meteorological station of the Beiluhe Station (figure 1), including radiation, air temperature and relative humidity, atmospheric pressure, precipitation, wind velocity and wind direction. Soil temperature data were recorded at one hour intervals by a data-logger (CR1000, Campbell) from five soil temperature probes at depths of 5, 10, 20, 30 and 40 cm that were embedded in each plot in October 2008.

Soil and biomass samples were collected from depths of 0–40 cm where 90% of roots in alpine grasslands of the QTP are concentrated (Yang *et al* 2009), and thus where SOC and other soil nutrients are subject to change. On May 9, three 50 × 50 cm quadrats were selected randomly in each plot, and

all plants were harvested to measure aboveground biomass (AGB). At each quadrat, belowground biomass (BGB) samples were sampled in five soil cores (4.8 cm in diameter) at depths of 0–10, 10–20, 20–30, and 30–40 cm, passed through sieve with 0.2 cm pore size after removing rocks, and then cleaned repeatedly. All materials of AGB and BGB were dried (24 h at 80 °C) and weighed. Soil samples for SOC and other nutrients analysis were collected from each quadrat by combining five soil cores in an X-shaped pattern, which were subdivided into 0–10, 10–20, 20–30, and 30–40 cm sections (Chen *et al* 2012b), and then packed in plastic bags and brought to the laboratory. Soil moisture (SM) was measured gravimetrically after 24 h drying at 105 °C. Sampling quadrats on June 9, July 9, July 25, August 9, August 25, September 9 and October 5 were selected near the initial quadrat on May 9 for each plot. In addition, three replicates of volumetric soil samples for each soil depth from each quadrat were collected using a cutting ring (volume of 100 g cm⁻³) to determine bulk density.

Soil samples for SOC and other nutrients analysis were air-dried at room temperature and were sieved at 2 mm to remove roots, litter and stone. One aliquot was further ground to pass a 1 mm sieve and analyzed for available P and available K contents, and a subsample was further ground to pass a 0.25 mm sieve and analyzed for SOC, TN, total P and total K contents. All soil samples were analyzed simultaneously in the Analytical Testing Center of Northwest Institute of Plateau Biology, Chinese Academy of Sciences. SOC and TN were determined by dichromate oxidation using the Walkley–Black procedure (Nelson and Sommers 1982) and the micro-Kjeldhal procedure (ISSCAS (Institute of Soil Sciences, Chinese Academy of Sciences) 1978), respectively. Total and available P were measured by the molybdenum–antimony anti-spectrophotometric method after H₂SO₄–

HClO₄ digestion for total P, and with NaHCO₃ extraction for available P. Total and available K were measured by flame photometry after HF–HClO₄ digestion for total K, and with NH₄OAc extraction for available K (Liu *et al* 2012a).

2.3. Data analysis

The calculation of SOC density for each soil layer (0–10, 10–20, 20–30 and 30–40 cm) was obtained using equation (1) (Liu *et al* 2012b):

$$\text{SOCD} = \sum_{i=1}^n h_i \times \text{BD}_i \times \text{SOC}_i \times (1 - C_i) / 100, \quad (1)$$

where SOCD, h_i , BD_i , SOC_i , and C_i are SOC density (kg m^{-2}), soil thickness (cm), bulk density (g cm^{-3}), SOC (g kg^{-1}), and volume percentage of the soil particles fraction > 2 mm at layer i , respectively. The calculation of TN density was described in an analogously. The pools of SOC or TN were calculated by area of each grassland type and their densities, which were then summed.

Multiple linear stepwise regression and correlation analyses were conducted to evaluate the relationships between dependent variables (SOC and other soil nutrients) and independent variables (soil and air temperature, precipitation, AGB and BGB). A general linear mode was used to describe the effects of the dependent parameters (*vide supra*) on the independent variables. These single condition models were used to investigate the impact of each dependent variable based on correlation analysis and multiple linear model explanation. Meteorological and soil temperature data used for analyses were the half-month mean values of the data prior to each sampling time. Comparisons of variables between different grasslands were tested by one-way ANOVA analysis and LSD test. All statistical analyses were conducted using SPSS software (version 11.5). The $P < 0.05$ level was considered to be significant.

3. Results

3.1. Vertical profiles distributions of SOC and other soil nutrients

Both SOC and TN decreased with soil depth in the alpine swamp meadow and alpine meadow, whereas their profiles were more complex in the alpine steppe (figure 3). In the alpine steppe, the highest and lowest SOC contents were found at depths of 20–30 and 30–40 cm, respectively; and the highest and lowest TN contents were found at depths of 0–10 and 10–20 cm, respectively. Unlike SOC and TN, the vertical profiles of total and available P and K were relatively uniform for each grassland type.

The mean SOC and TN contents for eight sampling times at depth of 0–10 cm were 19.16 ± 6.67 and $1.79 \pm 0.46 \text{ g kg}^{-1}$, 11.02 ± 2.79 and $1.14 \pm 0.24 \text{ g kg}^{-1}$, 3.42 ± 2.73 and $0.70 \pm 0.22 \text{ g kg}^{-1}$ in the alpine swamp meadow, alpine meadow, alpine steppe, respectively. The highest and lowest contents of SOC and TN at each soil depth were observed in

the alpine swamp meadow and alpine steppe, respectively (figure 3). Total P and K at each soil depth were significant higher in alpine swamp meadow and alpine meadow compared to those in alpine steppe. The only significant difference for available P was between alpine swamp meadow and alpine meadow at 0–10 cm depth. The highest and lowest available K contents at each soil depth were observed in alpine meadow and alpine steppe, respectively.

Mean SOC and TN densities were 7.43 ± 1.25 and $0.78 \pm 0.17 \text{ kg m}^{-2}$, 3.90 ± 0.75 and $0.47 \pm 0.07 \text{ kg m}^{-2}$, 2.09 ± 1.14 and $0.33 \pm 0.03 \text{ kg m}^{-2}$ for the entire 0–40 cm top layer of soil in the alpine swamp meadow, alpine meadow and alpine steppe, respectively. Within the study area, the mean SOC and TN storage at a depth of 0–40 cm was $21.74 \pm 6.92 \text{ Tg}$ ($1 \text{ Tg} = 10^{12} \text{ g}$) and $2.96 \pm 0.25 \text{ Tg}$, respectively.

Mean soil C:N ratios (mass ratio) ranged from 6.88 to 10.62 and exhibited a decreasing trend with soil depth in alpine swamp meadow and alpine meadow. However, the C:N ratios ranged from 4.33 to 8.82 in the alpine steppe, which exhibited a increasing trend with soil depth at 0–30 cm soil layer (figure 4). The highest and lowest ratios of C:N at most soil depth were observed in the alpine swamp meadow and alpine steppe, respectively. However, the significant differences were only found at 0–10 cm and 30–40 cm depth between alpine swamp meadow and alpine steppe (figure 4). In addition, there was a decreasing trend of BGB in the soil profiles of three grassland types (figure 5).

3.2. Spatial variations of SOC and other soil nutrients

Mean and standard deviation of SOC and other soil nutrients at different sampling times for each grassland type were shown in table 1. There was large variation of SOC and TN in three grassland types. The relative deviation of SOC ranged from 7.18 to 41.50 in the alpine swamp meadow, from 2.88 to 35.91 in the alpine meadow, and from 9.33 to 68.38 in the alpine steppe. The relative deviation of TN ranged from 3.05 to 34.39 in the alpine swamp meadow, from 0.84 to 21.94 in the alpine meadow, and from 0.54 to 16.22 in the alpine steppe. There was relatively small variation for total P and K, there was large variation for available P and K.

3.3. Relationships of SOC and other soil nutrients with environmental factors

Significant positive correlations of SM and BGB with SOC and TN explained the most variation in the vertical profiles of SOC and TN from the stepwise linear regression analysis (table 2). There was a significant negative correlation between total P and soil temperature, and a significant positive correlation between total P and SM, which was the most important parameter for the vertical profile of total P. The influence factors for the vertical profile of total K were same as those for total P. There was a significant positive correlation between available K and SM, and SM was the most important parameter for the vertical profile of available K from the stepwise linear regression analysis. However, there

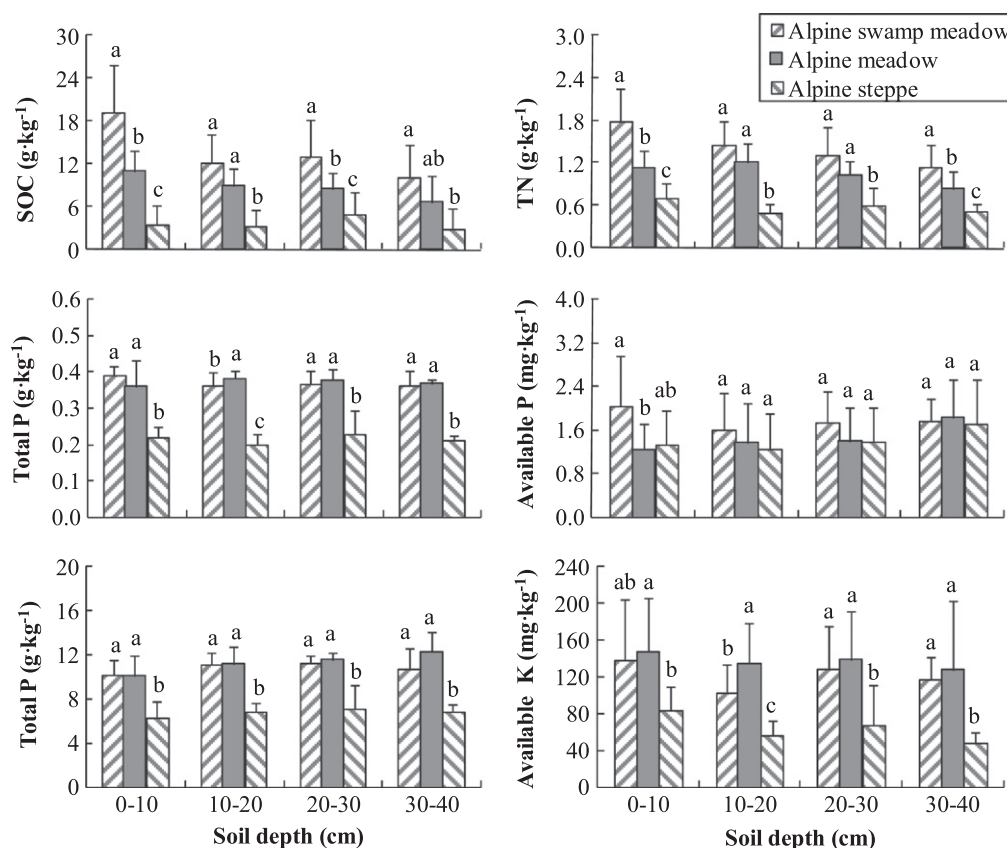


Figure 3. Mean contents and standard deviation (error bar) of soil organic carbon (SOC), total nitrogen (TN), total phosphorus (P), available P, total potassium (K) and available K for eight sampling periods throughout the year of 2009. Bars with the same letters indicate means within the same soil depth that are not significantly different.

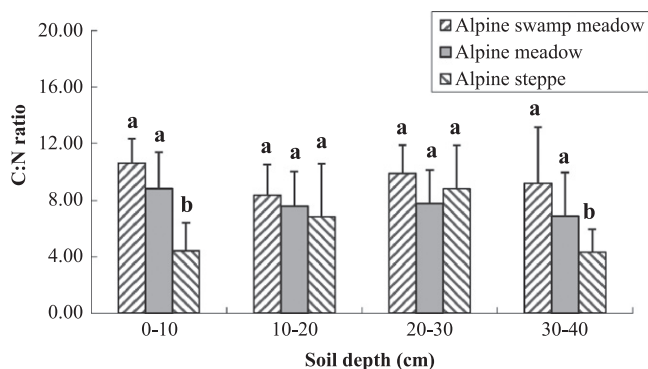


Figure 4. Variations of C:N ratios among the soil profiles for different grassland types.

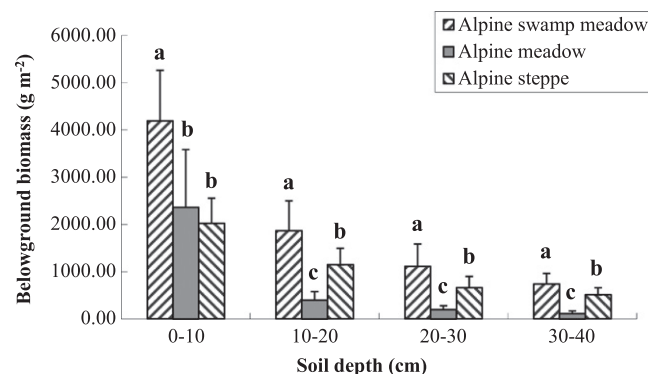


Figure 5. Variations of belowground biomass among the soil profiles for different grassland types.

were no significant correlations between available P and the environmental variables.

SOC was significantly positively correlated with SM and BGB, and SM accounted for most (55%) of the spatial variations of SOC from the stepwise linear regression analysis (table 3). There was a significant positive correlation between TN and SM or BGB, and a significant negative correlation between TN and soil temperature. SM and temperature were the most important parameters for the spatial variation of TN, accounting for 72% of the variation. There were significant positive relationships between total P and SM, available P and air temperature. SM and temperature were the most important

parameters for the spatial variation of total and available P, respectively. Both total and available K were significantly positively correlated with SM, and SM and BGB were the most important parameters for their spatial variation.

4. Discussion

Positive correlations of SM and BGB with SOC (table 2) indicate that BGB of roots was the main source of SOC (Jobbágy and Jackson 2000, Yang *et al* 2010), and that SM

Table 1. Mean and standard deviation of SOC and other soil nutrients at different sampling times for each grassland type.

Grassland type	Sampling time	SOC g kg ⁻¹	TN g kg ⁻¹	Total P g kg ⁻¹	Available P mg kg ⁻¹	Total K g kg ⁻¹	Available K mg kg ⁻¹
Alpine swamp meadow	May-8	19.74 ± 8.99	1.77 ± 0.62	0.36 ± 0.03	2.21 ± 0.98	11.00 ± 0.26	112.12 ± 54.26
	June-5	12.95 ± 4.05	1.55 ± 0.15	0.37 ± 0.03	1.23 ± 0.22	9.63 ± 0.54	82.96 ± 11.08
	July-9	11.21 ± 4.41	1.13 ± 0.25	0.36 ± 0.01	1.44 ± 0.30	10.78 ± 0.46	122.01 ± 29.87
	July-25	10.99 ± 6.20	1.14 ± 0.36	0.32 ± 0.05	1.48 ± 0.60	10.68 ± 1.52	73.02 ± 28.19
	August-9	11.59 ± 1.92	1.09 ± 0.23	0.36 ± 0.02	2.05 ± 0.16	11.50 ± 0.67	117.99 ± 17.03
	August-25	17.84 ± 9.62	1.95 ± 0.26	0.41 ± 0.02	2.05 ± 0.52	10.60 ± 1.41	121.43 ± 32.01
	September-10	12.28 ± 4.00	1.41 ± 0.28	0.38 ± 0.02	2.60 ± 0.79	12.03 ± 1.12	173.54 ± 36.33
	October-5	15.01 ± 5.01	1.56 ± 0.53	0.39 ± 0.03	1.25 ± 0.25	10.68 ± 2.10	173.58 ± 40.09
Alpine meadow	May-8	8.06 ± 2.51	1.17 ± 0.13	0.38 ± 0.02	0.92 ± 0.33	12.03 ± 1.39	106.40 ± 16.85
	June-5	7.41 ± 2.00	1.17 ± 0.47	0.37 ± 0.01	0.98 ± 0.20	10.88 ± 0.62	127.99 ± 63.50
	July-9	8.57 ± 2.30	0.83 ± 0.17	0.37 ± 0.01	1.21 ± 0.51	10.58 ± 0.61	194.96 ± 54.62
	July-25	10.30 ± 3.02	1.01 ± 0.12	0.35 ± 0.01	0.87 ± 0.24	11.78 ± 0.38	94.43 ± 34.82
	August-9	11.99 ± 1.17	1.02 ± 0.37	0.38 ± 0.01	1.88 ± 0.28	11.13 ± 0.72	102.32 ± 20.91
	August-25	7.03 ± 4.47	1.06 ± 0.12	0.42 ± 0.02	2.05 ± 0.42	11.88 ± 2.37	169.34 ± 35.51
	September-10	10.57 ± 3.46	1.12 ± 0.35	0.32 ± 0.09	1.98 ± 0.58	11.08 ± 3.66	104.47 ± 28.27
	October-5	6.66 ± 1.60	1.17 ± 0.17	0.38 ± 0.01	1.49 ± 0.87	11.00 ± 1.69	193.63 ± 56.43
Alpine steppe	May-8	1.44 ± 0.65	0.53 ± 0.12	0.20 ± 0.02	0.77 ± 0.76	7.38 ± 0.15	53.84 ± 13.99
	June-5	1.41 ± 0.99	0.56 ± 0.26	0.21 ± 0.02	0.72 ± 0.25	6.60 ± 0.24	66.83 ± 40.26
	July-9	2.57 ± 1.05	0.65 ± 0.18	0.20 ± 0.01	1.31 ± 0.40	7.63 ± 0.68	77.98 ± 10.54
	July-25	3.79 ± 1.56	0.49 ± 0.08	0.18 ± 0.02	1.59 ± 0.39	7.30 ± 0.32	51.43 ± 6.01
	August-9	5.81 ± 3.29	0.62 ± 0.13	0.21 ± 0.02	1.97 ± 0.31	7.68 ± 0.19	67.71 ± 33.20
	August-25	6.12 ± 4.27	0.59 ± 0.23	0.23 ± 0.02	1.88 ± 0.09	6.13 ± 0.64	36.24 ± 11.20
	September-10	5.51 ± 2.35	0.62 ± 0.28	0.21 ± 0.01	1.81 ± 1.10	4.68 ± 1.74	68.33 ± 15.86
	October-5	2.25 ± 2.18	0.61 ± 0.30	0.27 ± 0.07	1.21 ± 0.40	6.98 ± 2.24	87.43 ± 52.48

The abbreviations for soil organic carbon, total nitrogen, phosphorus and potassium are SOC, TN, P and K.

Table 2. Results from correlation analyses and stepwise linear regressions of mean soil chemical properties (site averages) and soil temperature (ST), soil moisture (SM) and below ground biomass (BGB) at four soil depth increments (0–10, 10–20, 20–30, 30–40 cm) for three grassland types ($n = 12$).

	Correlation			Stepwise linear regression		
	ST	SM	BGB	Equation	R^2	P -value
SOC	−0.40	0.89 ^b	0.63 ^a	SOC = 34.91SM + 1.60BGB − 1.00	0.93	<0.01
TN	−0.43	0.91 ^b	0.58 ^a	TN = 3.07SM + 0.11BGB + 0.21	0.93	<0.01
Total P	−0.62 ^a	0.97 ^b	0.15	Total P = 0.70SM + 0.17	0.93	<0.01
Available P	−0.49	0.51	0.25	—	—	—
Total K	−0.75 ^b	0.89 ^b	−0.09	Total K = 18.44SM + 5.61	0.80	<0.01
Available K	−0.41	0.89 ^b	0.22	Available K = 294.25SM + 43.33	0.79	<0.01

The abbreviations for soil organic carbon, total nitrogen, phosphorus and potassium are SOC, TN, P and K.

The levels of significance for the correlations are

^a $P < 0.05$ and

^b $P < 0.01$.

was an important environmental factor influencing the distribution of BGB (Liu *et al* 2012b) and microbial decomposition. The decrease in SOC in the alpine swamp meadow and alpine meadow with soil depth agrees with results of other studies in the QTP (Yang *et al* 2010, Liu *et al* 2012b). As a main source of SOC, BGB decreased with soil depth (figure 5) and it agrees with the results in the grassland of the permafrost regions of the central QTP (Chen 2010). However, the vertical profile of SOC was relatively complex in the alpine steppe, and the highest SOC content was found at a depth of 20–30 cm. SOC is controlled by the balance of

carbon inputs from plant production and outputs through microbial decomposition (Jobbágy and Jackson 2000). The low SOC content in the top 20 cm of soil may be the result of low vegetative coverage and litter return on the alpine steppe, coupled with high microbial decomposition rates and intense wind erosion. The vertical profile of TN and its controlling factors were similar to SOC, which indicates that they came from the same sources. In addition, the relatively uniform vertical profiles of total and available P and K in all three grassland types were different from those in the Northeastern region of the QTP (Liu *et al* 2012b). This implies that these

Table 3. Results from correlation analyses and stepwise linear regressions of mean soil chemical properties and soil temperature (ST), soil moisture (SM) and below ground biomass (BGB) at a depth of 0–40 cm, and air temperature (AT) for all three grassland types combined at eight sampling periods ($n = 24$).

	Correlation				Stepwise linear regression		
	AT	ST	SM	BGB	Equation	R^2	P -value
SOC	0.06	−0.24	0.74 ^b	0.50 ^a	SOC = 33.60SM + 1.45	0.55	<0.01
TN	−0.19	−0.46 ^a	0.75 ^b	0.43 ^a	TN = 2.72SM − 0.05ST + 0.76	0.72	<0.01
Total P	−0.11	−0.33	0.87 ^b	0.09	Total P = 0.65SM + 0.18	0.76	<0.01
Available P	0.47 ^a	0.38	0.29	0.19	Available P = 0.08AT + 1.19	0.22	<0.05
Total K	0.04	−0.24	0.88 ^b	0.08	Total K = 20.10SM − 0.24BGB + 6.49	0.84	<0.01
Available K	−0.08	−0.18	0.66 ^b	−0.17	Available K = 358.25SM − 8.46BGB + 72.02	0.64	<0.01

The abbreviations for soil organic carbon, total nitrogen, phosphorus and potassium are SOC, TN, P and K. The levels of significance for the correlations are

^a $P < 0.05$ and

^b $P < 0.01$.

soil nutrients are controlled by the parent material, texture and other external factors in the Beiluhe Basin rather than quantity of BGB in different soil layers. Moreover, SM was an important environmental factor for retaining soil nutrients and for influencing the vertical profiles of SOC and other soil nutrients. BGB is the main source of SOC and TN.

The overall C:N ratios for this study were low, and were similar to results of large scale in the central QTP (Yang *et al* 2010). The C:N ratios ranged from 6.88 to 10.62 in alpine swamp meadow and alpine meadow (figure 4), which was consistent with previous results in the Eastern QTP in which C:N ratio ranged from 6 to 14 (Xue *et al* 2009) and from 6 to 11 (Liu *et al* 2012b). Compared to alpine swamp meadow and alpine meadow, the C:N ratios in alpine steppe were relatively low. This is because there was low vegetative coverage and litter return on, coupled with high microbial decomposition rates in alpine steppe, which may be the cause of lower C:N ratios (Liu *et al* 2012b). C:N ratios exhibited a decreasing trend with soil depth in alpine swamp meadow and alpine meadow (figure 4), which was consistent with previous study results in Nordic forest soils (Callesen *et al* 2007) and in the QTP (Yang *et al* 2010, Liu *et al* 2012b). Generally, there is more recalcitrant material with slower decomposition rates and lower C:N ratios in deep soil than in topsoil (Trumbore 2000). However, there was increasing trend with soil depth at the depth of 0–30 cm soil layer in alpine steppe. The low C:N ratios in top soil (0–10 and 10–20 cm) reflected that a few organic matter returns on and high decomposition rates in the surface soil of alpine steppe. Although there was a decreasing trend of BGB (most consisted of thick root of *Oxytropis melanocalyx*) in the soil profiles (figure 5), there was no significant difference of fine root. The approximate amount of organic matter (e.g. fine root) input in the 0–10 cm, 10–20 cm and 20–30 cm soil layer, while decreased decomposition rate and wind erosion rate as soil depth increased, caused an increasing trend of C:N ratios.

Although SOC was significantly positively correlated with SM and BGB, BGB was excluded in the stepwise linear regression (table 3), indicating that SM was the dominant controlling factor for spatial variation of SOC at a depth of

0–40 cm. Similar relationships between SM and SOC previously found at large scale spatial pattern in the QTP (Baumann *et al* 2009, Yang *et al* 2010, Liu *et al* 2012b) have been attributed to higher SM that could lead to higher plant productivity and substrate availability, and then to higher SOC (Reichstein and Beer 2008). Seasonal patterns in nutrient uptake by vegetation, litterfall and mineralization of organic matter could lead to seasonal variations in soil nutrients (Lundell 1987). The seasonal variations of SOC and other soil nutrients should not be neglected in this study, because the samples collected from different period of 2009. Seasonal variations of SOC and other soil nutrients are considered to be the result of short-term effects of environmental factors, and their spatial pattern are considered to be the result of long-term effects. Therefore, the variation of SOC in this study was a comprehensive influence of short-term and long-term effects, and was controlled by SM. However, there were no significant relationships between SOC and air or soil temperature, indicating that substrate quality and quantity as well as moisture were more important than temperature in litter decomposition in the permafrost regions of the QTP (Baumann *et al* 2009). In addition, results from a study on forest mineral soils also suggested there were no direct influence of temperature limitations on microbial activity and no stimulation of decomposition by increased temperature alone (Giardina and Ryan 2000). Of the three variables that had a significant correlation with TN, soil temperature and moisture (but not BGB) were the dominant factors and controlled the spatial variation of TN. As for short-term effects of environmental factors, the nitrogen mineralization rate has been found to increase exponentially with temperature during laboratory incubations (Dalias *et al* 2002). Likewise, SM can significantly affect nitrification and mineralization rates (Sierra 1997, Paul *et al* 2003, Wang *et al* 2006), and it can also affect the biological process of the uptake of nitrogen by plants (da Silva and Kay 1997). At large scale (long-term effects), TN content was controlled by climate, vegetation, and soil texture (Brady and Weil 2004, Yang *et al* 2007), and all of those environmental factors are related to soil temperature and moisture. Soil texture is a critical factor for water

retention in the soil (Liu *et al* 2012b). Although SM appeared to be the most important parameter for spatial variation of total P in our study, soil texture was the main controlling factor because there was small variation (low relative deviation) for total P. In addition, both total and available K were positively correlated with SM, which directly influences litter decomposition (Baumann *et al* 2009), and alternate drying–wetting could cause contraction or expansion of clay mineral. Therefore, SM is an important parameter that affects K fixation and release (Liang *et al* 2002). In addition to SM, BGB was also an important parameter for the spatial variation of K. However, more research is needed on the relationship between K and BGB in the QTP.

To accurately estimate SOC storage is critical for study the carbon dynamics in the QTP and its potential feedbacks to global climatic change. However, previous studies have demonstrated that SOC storage was inevitably subject to many uncertainties, including differences in sampling methods, biased data and scale (Wang *et al* 2002 and 2003, Liu *et al* 2012b). Variations at plot scale were also important factors for estimating SOC storage from the results of this study. In order to eliminate influences of seasonal variation, we recommend the sampling occur at the same month in different years. It's important to note that the spatial variations at the plot scale also should be considered to estimate SOC storage. In addition, many recently studies reported that there were significant effects of experimental warming on the temperature and moisture patterns in the shallow soil of the active layer on the QTP (Chen 2010, Wang and Wu 2013, Yang *et al* 2014). Under background of global climate warming, quantifying the relationships between SOC, TN and soil temperature and moisture in this study could provide a basic data to forecast the changes of SOC and TN on the QTP.

5. Conclusions

We conclude that SM is the most important parameter to influence the vertical profiles of SOC and other soil nutrients, and that BGB is the main source of SOC and TN. SM was also the most important factor for the spatial variation of SOC at plot scale. Degradation of permafrost in the QTP with global warming would lead to severe changes in SM conditions, and these changes would have serious impacts on SOC and the dynamics of other soil nutrients. In addition, the spatial variations of soil nutrients at the plot scale also should be considered to estimate SOC storage.

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