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Patterns and environmental controls of soil organic carbon and total nitrogen in alpine ecosystems of northwestern China

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ABSTRACT

Soil carbon (C) and nitrogen (N) in alpine ecosystems are of special interest because of high concentration and potential feedbacks to climate changes. Alpine ecosystems of the Qilian Mountains in the northern margin of the Tibetan Plateau are characterized by complex topography, suggesting large variability in the spatial distribution of soil C and N. However, the patterns and environmental controls on C and N storage are not well understood. This study was conducted to determine the soil organic carbon (SOC) and total nitrogen (TN) stocks under different vegetation types and environmental conditions in a typical catchment in the Qilian Mountains, and explore their environmental control factors. The results showed that SOC and TN stocks varied significantly with vegetation type, ranging from 9.50 to 31.09 and 1.07 to 3.14 kg m^{-2}, respectively, at 0–50 cm soil depth. SOC storage in grasslands on sunny slopes and in *Picea crassifolia* forest together accounted for about 80% of the total SOC storage in the catchment due to the extensive distribution area of these vegetation types. SOC stocks in grasslands on sunny slopes and in *P. crassifolia* forest were generally higher than their counterparts in other regions. SOC stocks on shady slopes were mainly regulated by elevation-induced differences in temperature and precipitation, with temperature being the most important factor influencing the distribution of SOC. For the whole catchment, the distribution of SOC stocks was significantly affected by topographic aspect and elevation; aspect and elevation together explained 97.5% of the overall variation in SOC stocks at a soil depth of 0–50 cm, and aspect alone explained 68.2% of the overall variation. These results confirmed that topography was the most significant factor controlling the distribution patterns of SOC in alpine ecosystems.

1. Introduction

A large percentage of organic carbon (C) is stored in soils, and even small changes in soil C inventories could significantly alter CO_2 concentrations in the atmosphere and contribute to global climate change (Stockmann et al., 2013). The fluxes of soil C into and out of soils vary in response to many environmental factors and are sensitive to changes in climate and local environment. The cycles of C and nitrogen (N) interact closely, and it has been established that the cycling rate of soil C is strongly linked to N availability, especially in N-limited ecosystems (Singh et al., 2010; Yang et al., 2011; Gärdenäs et al., 2011). Thus, accurate assessments of patterns and environmental controls on soil C and N storage at both regional and global scales are essential for predicting and mitigating feedbacks of soil C to global environmental change (Jobbágy and Jackson, 2000; Yang et al., 2008; Janssens and Luyssaert, 2009; Melillo et al., 2011).

Soils in mountainous areas, especially in alpine ecosystems, have received relatively little attention in the past, because of low anthropogenic activity and agronomic interest (Podwojewski et al., 2011). Recently, the interest in C and N cycles in alpine ecosystems has increased due to high C concentration and potential feedbacks to climate warming (Davidson and Janssens, 2006; Zimov et al., 2006; Yang et al., 2008; Bond-Lamberty and Thomson, 2010; Hoffmann et al., 2014a). However, large spatial heterogeneity in soil characteristics and relative scarcity of field observations perpetuate the extensive uncertainty about the patterns and environmental controls on soil C and N storage in alpine ecosystems (Van Miegroet et al., 2005; Zhang et al., 2008). In montane ecosystems, topography is the most significant factor in generating differences in ecosystem characteristics (Yimer et al., 2006; Zhang et al., 2008; Bennie et al., 2008; Hoffmann et al., 2014b; Huang et al., 2015). For example, topographic aspect strongly modifies the amount of solar radiation intercepted by a surface, and affects the microclimate and hydrothermal processes such as evapotranspiration (Badano et al., 2005; Yimer et al., 2006; Bennie et al., 2008; Sidari et al., 2008). Climatic gradients along elevations can also alter hydrothermal processes because of their effects on temperature and precipitation (Longbottom et al., 2014). Topographic factors may determine variability in

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vegetation patterns and the amount and nature of organic residues entering the soil, and result in large variation in the spatial distribution of soil C and N in montane ecosystems (Fuentes et al., 1984; Ganuza and Almendros, 2003; Tsui et al., 2004; Badano et al., 2005; Yimer et al., 2006).

The Qilian Mountains, located in the northern margin of the Tibetan Plateau, are the source of several key inland rivers in northwestern China, including Heihe, Shiyang, and Shule. The mountains were designated as a National Nature Reserve in 1988 for their key role in maintaining regional ecological security. The mountains represent a semiarid montane ecosystem, and are characterized by complex topography with elevations ranging from 2000 to 5500 m. Large differences among aspects and steep elevation gradients resulted in high variability in vegetation and soil patterns. Along the elevation gradient, grasslands, forests, alpine shrublands, and alpine meadows are distributed on shaded north-facing slopes. Sunny south-facing slopes are mainly occupied by grasslands. Grasslands and forests are the main vegetation types (Wang et al., 2001). The unique ecological gradients, together with a relative lack of human disturbance, make the Qilian Mountains an ideal region for investigating the patterns and environmental controls of soil C and N storage in alpine ecosystems.

Few soil studies have been conducted in this region. Accurate estimates of soil C and N storage are lacking due to limited soil survey and high spatial variability of soils in this region. Thus, the objectives of the present study were to determine for the Qilian Mountains: (1) soil organic carbon (SOC) and total nitrogen (TN) stocks under different vegetation types and environmental conditions; and (2) the main environmental parameters that control the distribution of SOC and TN.

2. Methods

2.1. Study area

The study area is located in the Pailugou watershed (100°17′E, 38°24′N) in the Xishui Forest Reserve in the Qilian Mountains. The area is situated near Zhangye City, Gansu Province, in northwestern China. The catchment covers an area of 2.95 km^2, with high variability in elevation ranging from 2650 to 3800 m, and with ecosystems typical of the region. Due to the range of conditions, the area is well-suited for investigating the patterns and environment controls of soil C and N in the Qilian Mountains. The Pailugou watershed is characterized by a semiarid climate, with a mean annual temperature (MAT) of about 2 °C and mean annual precipitation (MAP) of about 376 mm at the base of the mountains. The MAT decreases and MAP increases with elevation by about 4.3% per 100 m (He et al., 2012). Permanently and seasonally frozen soils are widespread at mid and high elevations.

Vegetation patterns in the catchment are closely related to topography and climate gradients, and represent a mosaic of grasslands, scrublands, and forests (He et al., 2012). In our study, we used the slope aspect to define the degree of shading at each study site: north-facing slopes were considered to be shaded, east- or west-facing slopes — semi-shaded, and south-facing slopes - sunny. In the Pailugou watershed, grasslands occupy mainly sunny, south-facing slopes at elevations from 2700 to 3000 m, and forests, dominated by the Qinghai spruce (*Picea crassifolia*), are found primarily on shaded, north-facing slopes at elevations between 2650 and 3300 m; alpine shrublands and alpine meadows are also found on shaded slopes at elevations from 3250 to 3650 m and 3600 to 3800 m, respectively (Wang et al., 2001). The main parent material is calcareous rock, which is overlaid by a relatively thin soil layer (<1 m deep) (Jiang et al., 2013). Differences in climate and vegetation patterns induced divergent soils properties. Soils are classified according to the Chinese classification system as Gray cinnamon, present on shaded slopes, and Chestnut, present on sunny slopes (Jiang et al., 2013). Both soil types exhibit coarse texture, with pH ranging from 7 to 8 (Jiang et al., 2013).

2.2. Experimental design, soil sampling, and vegetation survey

Estimates of SOC storage at regional scales are obtained primarily with three methods: the soil type, vegetation type, and the life zone (modeling) method (Yimer et al., 2006; Yang et al., 2007; Zhang et al., 2008). To represent the spatial heterogeneity of the area, the vegetation-type method was adopted in our study. Based on the topographic and vegetation characteristics, the catchment was divided into six primary vegetation zones (alpine meadow, alpine shrubland, *P. crassifolia* forest, shrubland, grassland on shady slopes, and grassland on sunny slopes). Within each vegetation zone, sample plots were established in mid-August of 2013 to investigate soil, vegetation, and environmental parameters (Table 1). Sample plots were chosen to represent the distribution of environmental site characteristics. Sample plots were located within shady, semi-shady, and sunny aspects, at elevations ranging from 2650 to 3700 m, and on slopes ranging from 7 to 35°, and represented almost all of the typical aspects, elevations, slopes, and vegetation types of the study area, giving a total of 33 sample plots. A total of 396 soil samples were collected from 99 sampling locations within the sample plots. Details of the survey are as follows:

(1) Grassland. Three sample plots of 20 × 20 m^2 were randomly located at each of sunny and shady slopes at elevations of approximately 2750 and 2900 m. Within each plot, three soil profiles were randomly excavated (after removing the surface litter layer), and soil samples were collected at depths of 0–5, 5–15, 15–30, and 30–50 cm. In addition, undisturbed soil cores were obtained from each layer for the measurements of bulk density using a standard container with the volume of

Table 1
Description of vegetation types in the catchment.

Aspect	Vegetation types	Area (×10^6 m^2)	Plot number	Slope (°)	Elevation (m)	Dominant vegetation species and cover (%)
Shady slope	Alpine meadow	0.213	3	25–30	3700	*Caragana jubata* (38.54), *Polygonum viviparum* (23.41), *Carex tristachya* (18.26), *Salix gilashanica* (12.93)
	Alpine shrubland	0.076	3	28–34	3500	*Salix gilashanica* (60.52), *Caragana jubata* (21.67), *Rhododendron anthopogonoides* (10.38)
	Picea crassifolia forest	1.119	3 3 3 3	25–33 23–30 20–31 19–28	3200 3000 2800 2650	Understory species: *Polygonum viviparum*, *Saussurea hmuilis*, *Carex scabriostris*, *Thuidium delicatulum*, *Hypnum cupressiforme*
	Grassland on shady slopes	0.103	3 3	9–12 7–11	2950 2750	*Carex tristachya* (48.75), *Iris lactea* (25.22), *Stipa purpurea* (13.63), *Stipa przewalskyi* (9.31)
Semi-shady slope	Shrubland	<0.001	3	14–21	2950	*Potentilla fruticosa* (45.89), *Carex tristachya* (25.32), *Polygonum viviparum* (15.74)
Sunny slope	Grassland on sunny slopes	1.18	3 3	24–35 20–32	2950 2750	*Agropyron cristatum* (56.04), *Stipa purpurea* (18.60), *Kobresis humilis* (15.75)

Note: north-facing slopes were defined as shaded, east- or west-facing slopes were defined as semi-shaded, and south-facing slopes were defined as sunny.

100 cm^3. Finally, ten quadrats of 1 × 1 m^2 were randomly selected to investigate percent grass cover and species composition.

(2) Forest. Three sample plots of 30 × 30 m^2 were randomly located on shaded slopes at each of four elevations of approximately 2650, 2800, 3000, and 3200 m for a total of 12 sample plots. In each plot, the height, diameter at breast height (DBH), and stand density of trees were measured. Percent cover and species composition of understory vegetation were investigated separately in ten quadrats of 1 × 1 m^2. Soil sampling was the same as that described for grassland.

(3) Shrubland. Three sample plots of 20 × 20 m^2 were randomly located on semi-shaded slopes at elevation of 2950 m. In each plot, the height, density, and cover for each shrub species were recorded to determine species abundance and composition. Ten quadrats of 1 × 1 m^2 were randomly selected to determine percent cover and species composition of the herbaceous layer. Soil sampling was the same as that described for grassland.

(4) Alpine shrubland. Three sample plots of 20 × 20 m^2 were randomly located on shaded slopes at the elevation of 3450 m. Only a few herb species were present under the shrub canopy, so we investigated the species composition of shrubs alone. Vegetation survey and soil sampling were the same as those described for shrubland.

(5) Alpine meadow. For the alpine meadow on shaded slopes, three sample plots of 20 × 20 m^2 were randomly located at the elevation of 3700 m. Vegetation survey and soil sampling were the same as those described for shrubland.

2.3. Determination of environmental factors

Geographic coordinates and elevations of each plot were obtained using a global positioning system (GPS) with differential correction, and slope gradient and slope aspect were determined with a compass. The areas of each vegetation type were determined using QuickBird satellite data with a 0.61 m ground resolution at nadir (acquired on 8 August 2006) (He et al., 2012). In addition, a Digital Elevation Model (DEM) was used to obtain vegetation distribution data at different elevations and directs, and the slope, aspect, and elevation parameters were derived from this data source (He et al., 2012).

Data on annual precipitation from 1994 to 2008 were collected at elevations of 2650–3800 m in 100-m intervals with standing tipping-bucket pluviographs (He et al., 2012). The MAP of the plots was estimated from a regression formula for precipitation as a function of elevation (Fig. 1). Based on available long-term field temperature records, a temperature decrease of 0.58 °C per 100 m increase in elevation (Wang et al., 2001) was used to calculate MAT of the plots.

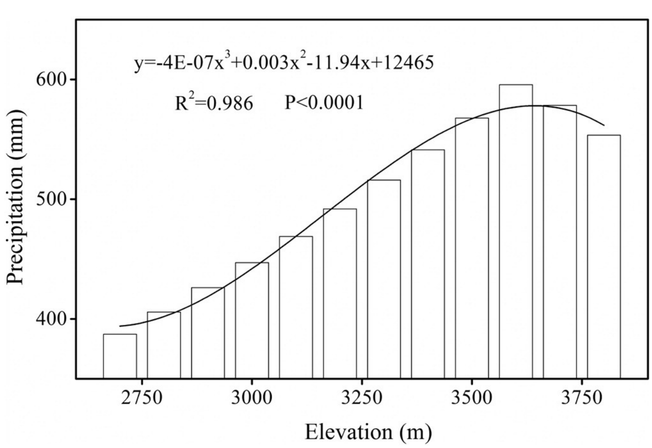

Fig. 1. The change of mean annual precipitation (MAP) with elevation, and the regression formula for precipitation as a function of elevation.

2.4. Soil analysis

Soil samples were air-dried, and then passed through a 2 mm soil sieve; gravels (> 2 mm) were weighed to obtain the volumetric percentage of coarse fragments. Soil bulk density was calculated as the ratio of undisturbed cores, oven-dried at 105 °C for 8 h, to the container volume. Soil texture was determined by laser diffraction using a Mastersizer 2000 (Malvern Instruments, Malvern, England) (Liu et al., 2005). Subsamples for SOC and TN analyses were finely ground to pass through a 0.10 mm sieve. SOC was determined by the $K_2Cr_2O_7$–H_2SO_4 oxidation method of Walkley–Black (Nelson and Sommers, 1982). TN was measured with the Kjeldahl method (Jackson, 1973).

2.5. Data analysis

We calculated SOC stocks (Eq. (1)) and TN stocks (Eq. (2)) for each soil layer using the following equations:

$$\mathrm{SOCD} = \sum_{i=1}^{n} H_i \times B_i \times \mathrm{SOC} \times \frac{(1-D_i)}{100} \quad (1)$$

$$\mathrm{TND} = \sum_{i=1}^{n} H_i \times B_i \times \mathrm{TN}_i \times \frac{(1-D_i)}{100} \quad (2)$$

where SOCD and TND were the SOC stocks (kg m^{-2}) and TN stocks (kg m^{-2}) of a soil profile; n was the number of layers considered; SOC$_i$. and TN$_i$ were the SOC concentration (g kg^{-1}) and TN concentration (g kg^{-1}) at layer i; H_i, B_i, and D_i were the thickness (cm), bulk density (g cm^{-3}), and volumetric percentage (%) of coarse fragments (>2 mm), respectively, at layer i.

SOC storage (at a soil depth of 0–50 cm) for each vegetation type was calculated with the following equation:

$$\mathrm{SOCS} = \mathrm{Area} \times \mathrm{ASOCD} \quad (3)$$

where SOCS, Area, and ASOCD were: SOC storage, soil area, and average SOC stocks (at a soil depth of 0–50 cm), respectively, for each vegetation type.

2.6. Statistical analysis

The differences in SOC and TN stocks, and in C:N ratios between different vegetation types were tested with one-way analysis-of-variance (ANOVA); a least-significant-difference test (LSD) was conducted when significant differences were detected by ANOVA. Ordinary least squares (OLS) regression was performed to evaluate the relationships between SOC stocks and environmental parameters (elevation, MAT and MAP) for shady slopes. Additionally, we employed a general linear model (GLM) to assess integrative effects of environmental parameters on the distribution of SOC stocks for both — shady slopes and the whole catchment. All statistical analyses were performed using the statistical software SPSS, ver. 17.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. SOC and TN

Generally, SOC stocks varied significantly with aspect, vegetation types, and elevation, and ranged from 9.50 to 31.09 kg m^{-2} across the sampled soil depth (0–50 cm) (Table 2). SOC stocks on sunny slopes were significantly lower than on shady and semi-shady slopes (Table 2). SOC stocks at 0–50 cm soil depth on shady slopes were (in kg m^{-2}) 18.83–31.09 in *P. crassifolia* forest, 30.50 in alpine shrubland, 25.61 in alpine meadow, 25.09 in shrubland, and 20.69–22.14 in grassland (Table 2). Grasslands on sunny slopes had the lowest SOC stocks among the studied vegetation types, ranging from 9.50 to 10.71 kg m^{-2}. However, with the largest distribution area, SOC storage

Table 2
Soil organic carbon (SOC) stocks and SOC storage at a soil depth of 0–50 cm for each vegetation type.

Vegetation types	Elevation (m)	SOC stocks(kg m^{-2})				SOC storage ($\times 10^6$ kg)
		0–5 cm	0–15 cm	0–30 cm	0–50 cm	
Alpine meadow	3700	3.42 ± 0.22ab	9.06 ± 0.84bc	16.70 ± 1.21bc	25.61 ± 2.31c	5.45
Alpine shrubland	3500	3.88 ± 0.56a	10.16 ± 0.68ab	20.27 ± 1.09a	30.50 ± 1.13ab	2.32
Picea crassifolia forest	3200	3.57 ± 0.39ab	10.04 ± 0.72ab	19.22 ± 0.96a	31.09 ± 1.46a	26.49
	3000	3.81 ± 0.31a	8.88 ± 0.97c	15.41 ± 1.29 cd	22.74 ± 1.54d	
	2800	3.29 ± 0.21ab	8.44 ± 0.68 cd	15.39 ± 1.21 cd	22.02 ± 2.11d	
	2650	3.00 ± 0.26b	7.59 ± 0.85d	13.69 ± 1.06de	18.83 ± 1.23e	
Grassland on shady slopes	2950	2.99 ± 0.16b	8.25 ± 0.34 cd	14.63 ± 0.67de	22.14 ± 0.94d	2.21
	2750	3.49 ± 0.39ab	8.50 ± 0.47 cd	13.39 ± 0.99e	20.69 ± 0.71de	
Shrubland	2950	3.37 ± 0.35a	9.07 ± 1.10a	16.62 ± 1.29a	25.09 ± 1.78bc	<0.01
Grassland on sunny slopes	2950	1.74 ± 0.06c	4.60 ± 0.13e	7.67 ± 0.48f	10.71 ± 0.56f	11.93
	2750	1.21 ± 0.11c	3.43 ± 0.14f	6.18 ± 0.25f	9.50 ± 0.36f	

Note: the data were expressed as mean ± standard error and values followed by different lower-case letters within columns are significantly different at $P < 0.05$.

in grasslands on sunny slopes accounted for about 25% of the total in the catchment, lower only than SOC in *P. crassifolia* forest (at about 55%); SOC in alpine meadow, alpine shrubland, grassland on shady slopes, and shrubland together accounted for about 20% of total SOC in the catchment. On shady slopes, SOC stocks exhibited significant variation, and initially increased with elevation and then tended to decline (Table 2, Fig. 2). The relationships between SOC stocks and elevation for shady slopes were confirmed with a regression analysis; the R^2 values increased with soil depth and were 0.15 for 0–5 cm, 0.67 for 0–15 cm, 0.82 for 0–30 cm, and 0.84 for 0–50 cm (Fig. 2).

Total N stocks ranged from 1.07 to 3.14 kg m^{-2} across the sampled soil profile (0–50 cm) (Table 3). Similarly to SOC, TN stocks in grasslands on sunny slopes were significantly lower than those on shady and semi-shady slopes. TN stocks were (in kg m^{-2}): 2.78–3.14 for *P. crassifolia* forest, 2.43 for shrubland, 2.30 for alpine meadow, 2.28–2.38 for grassland on shady slopes, and 1.76 for alpine shrubland (Table 3). In contrast to SOC, TN stocks were not significantly related to elevation.

3.2. Soil C:N ratios

The C:N ratios in all sampled soil depths differed significantly among vegetation types. In general, the C:N ratios were in the order of: *P. crassifolia* forest, alpine shrubland > shrubland, alpine meadow > grassland on both shady and sunny slopes (Table 3). The C:N ratios were 14.26–22.52 for *P. crassifolia* forest, 16.41–18.45 for alpine shrubland, 10.98–12.28 for shrubland, 10.91–11.57 for alpine meadow, 8.57–9.70 for grassland on shady slopes, and 7.50–9.71 for grassland on sunny slopes. Although in general the C:N ratios did not vary significantly with aspect and elevation, they tended to increase with elevation in *P. crassifolia* forests (Table 3).

3.3. The effects of environmental factors on SOC stocks on shady slopes

SOC stocks on shady slopes were significantly positively correlated with MAP and the relationships were characterized by linear functions (Fig. 3). The R^2 values of regression functions increased with soil depth and were 0.13, 0.44, 0.56 and 0.56 for the 0–5, 0–15, 0–30, and 0–50 cm depths, respectively. On shady slopes, SOC stocks also exhibited significant relationships with MAT, and initially increased with MAT and then declined (Fig. 3). Similarly to those of MAP, the R^2 values for SOC and MAT also increased with soil depth, and were 0.15, 0.67, 0.82 and 0.84 for 0–5, 0–15, 0–30, and 0–50 cm depths, respectively (Fig. 3). However, SOC stocks showed no significant relationships with soil texture (data not shown). MAT and MAP together explained

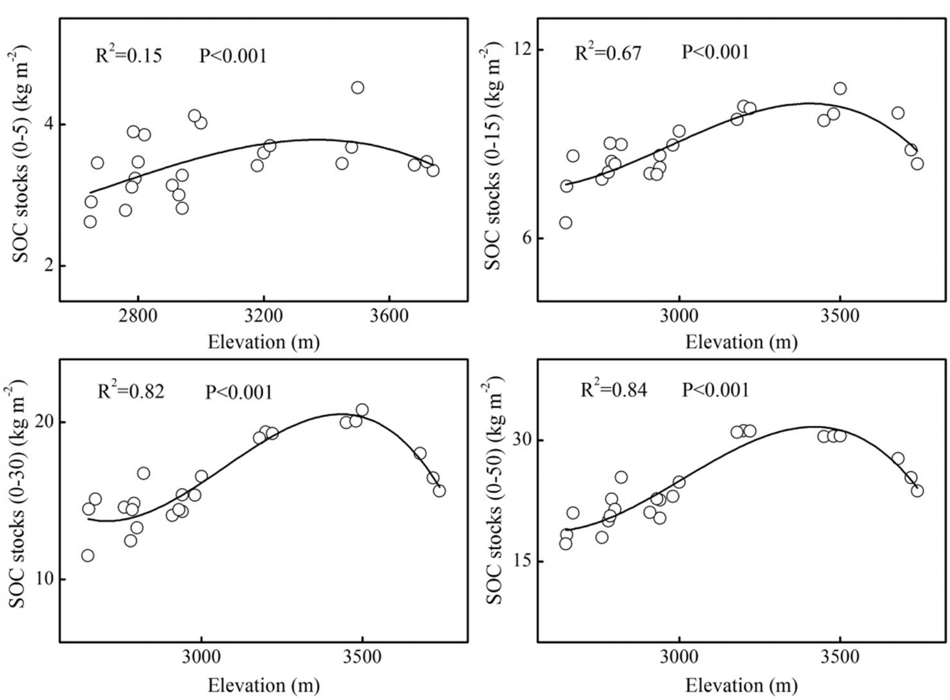

Fig. 2. Regression correlation of soil organic carbon (SOC) stocks with elevation at different depths for shady slopes.

Table 3
Soil total nitrogen (TN) stocks and carbon/nitrogen (C:N) ratios for each vegetation type.

Vegetation types	Elevation (m)	TN stocks(kg m^{-2})				C:N			
		0–5 cm	0–15 cm	0–30 cm	0–50 cm	0–5 cm	5–15 cm	15–30 cm	30–50 cm
Alpine meadow	3700	0.30 ± 0.01b	0.79 ± 0.06b	1.48 ± 0.09a	2.30 ± 0.13c	11.38 ± 0.10c	11.57 ± 0.46e	10.97 ± 0.02c	10.91 ± 0.17d
Alpine shrubland	3500	0.21 ± 0.02c	0.56 ± 0.01de	1.13 ± 0.02b	1.76 ± 0.04d	18.45 ± 0.89b	17.76 ± 0.36b	17.73 ± 0.51a	16.41 ± 0.11bc
Picea crassifolia forest	3200	0.17 ± 0.02de	0.66 ± 0.06cd	1.61 ± 0.18a	3.14 ± 0.23a	21.34 ± 2.46a	20.45 ± 2.33a	20.11 ± 2.80a	20.55 ± 1.57a
	3000	0.17 ± 0.01de	0.64 ± 0.02cd	1.50 ± 0.11a	2.78 ± 0.09ab	22.52 ± 3.03a	17.31 ± 2.55bc	16.64 ± 3.16ab	18.25 ± 3.09ab
	2800	0.17 ± 0.01de	0.66 ± 0.03cd	1.57 ± 0.05a	2.86 ± 0.12a	19.55 ± 3.38ab	16.22 ± 1.85bc	16.75 ± 2.02ab	17.65 ± 1.93ab
	2650	0.17 ± 0.03cde	0.67 ± 0.09c	1.60 ± 0.18a	2.89 ± 0.32a	17.43 ± 2.30b	14.26 ± 2.79d	15.37 ± 3.47b	15.64 ± 2.92bc
Grassland on shady slopes	2950	0.31 ± 0.02b	0.89 ± 0.03ab	1.61 ± 0.07a	2.38 ± 0.07bc	9.54 ± 0.25c	9.19 ± 0.07fg	8.82 ± 0.15c	9.69 ± 0.35de
	2750	0.36 ± 0.05a	0.92 ± 0.09a	1.49 ± 0.15a	2.28 ± 0.17c	9.70 ± 0.21c	9.05 ± 0.64fg	8.57 ± 0.37c	9.36 ± 0.66de
Shrubland	2950	0.32 ± 0.03b	0.92 ± 0.08a	1.70 ± 0.03a	2.43 ± 0.09bc	11.40 ± 0.21c	11.07 ± 0.62ef	10.98 ± 0.87c	12.28 ± 1.31d
Grassland on sunny slopes	2950	0.20 ± 0.02cd	0.54 ± 0.07e	0.93 ± 0.19bc	1.34 ± 0.2e	8.68 ± 0.31c	8.38 ± 0.31g	7.84 ± 0.32c	7.50 ± 0.31e
	2750	0.14 ± 0.01e	0.39 ± 0.01f	0.72 ± 0.03c	1.07 ± 0.07e	8.63 ± 0.46c	8.75 ± 0.46g	8.34 ± 0.34c	9.71 ± 1.14de

Note: the data were expressed as mean ± standard error; values followed by different lower-case letters within columns are significantly different at P < 0.05.

96.2%, 98%, and 96.6% of the overall variation in SOC stocks at soil depths of 0–15, 0–30, and 0–50 cm, respectively (Table 4). MAT alone, as the most important environmental factor, explained 57.4%, 58.7% and 59.6% of the variation in SOC stocks for the 0–15, 0–30, and 0–50 cm soil depths.

3.4. The effects of environmental factors on the distribution of SOC stocks for the whole catchment

The GLM suggested that aspect was the most important environmental factor for SOC stocks, and explained 93.4% of the variation in SOC at 0–5 cm, 87.5% at 0–15 cm, 75.2% at 0–30 cm, and 68.2% at 0–50 cm soil depth (Table 5). Aspect and elevation together explained 97.9% of the overall variation in SOC stocks at 0–5 cm, 97.6% at 0–15 cm, 97.4% at 0–30 cm, and 97.5% at 0–50 cm soil depth (Table 5). In addition, the proportion of the variance explained by elevation increased, while the proportion explained by aspect decreased with soil depth (Table 5).

4. Discussion

4.1. Storage and distribution of SOC and TN

Until recently, soil storage of C and N in the Qilian Mountains was unknown due to limited soil survey and high spatial variability of soils in this region. In our study, we investigated the storage and spatial

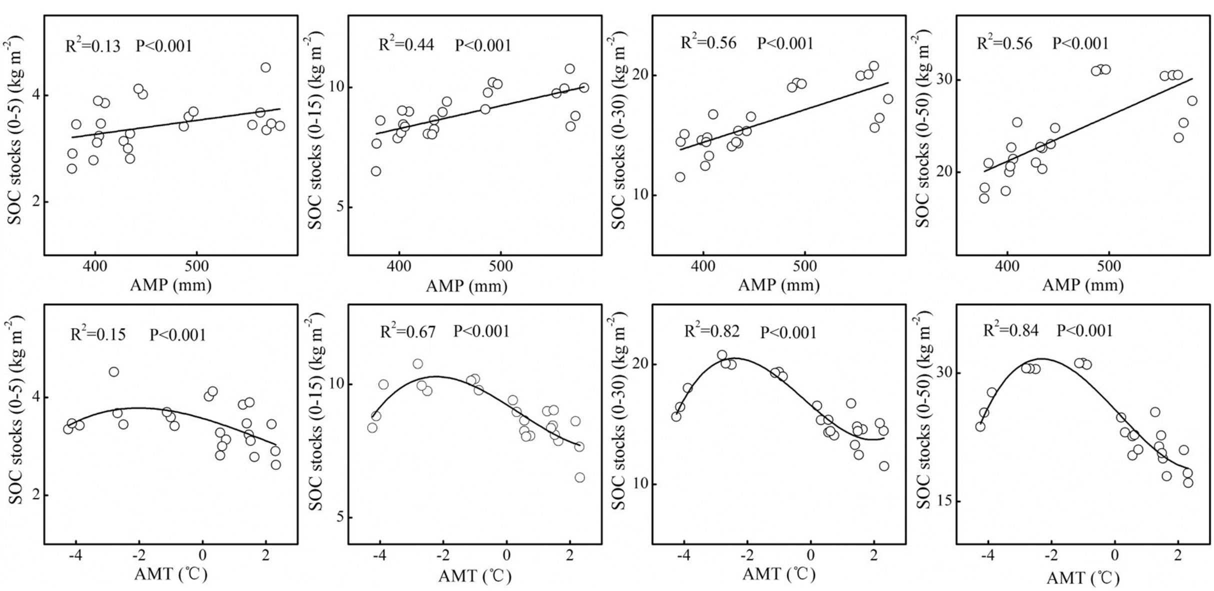

Fig. 3. Regression correlation of soil organic carbon (SOC) stocks with mean annual precipitation (MAP) and mean annual temperature (MAT) at different depths for shady slopes.

Table 4
Integrative effects of mean annual precipitation (MAP) and mean annual temperature (MAT) on soil organic carbon stocks at different soil depths on shady slopes.

Source	0–5 cm			0–15 cm			0–30 cm			0–50 cm		
	df	MS	SS%	df	MS	SS%	df	MS	SS%	df	MS	SS%
MAT	1	0.48	48.98	1	5.79	57.44***	1	45.86	58.67***	1	110.22	59.62***
MAP	1	0.33	33.67	1	3.91	38.79**	1	30.72	39.30***	1	68.34	36.97**
Residuals	21	0.17	17.35	21	0.38	3.77	21	1.58	2.02	21	6.3	3.41

Note: *P < 0.05; **P < 0.01; ***P < 0.001; df, degrees of freedom; MS, mean squares; SS%, proportion of the variance explained by the variable; the results were obtained from general linear model (GLM) analysis.

Table 5
Integrative effects of aspect and elevation on soil organic carbon stocks at different soil depths (0–5, 0–15, 0–30, and 0–50 cm) for the whole catchment.

Source	0–5 cm			0–15 cm			0–30 cm			0–50 cm		
	df	MS	SS%	df	MS	SS%	df	MS	SS%	df	MS	SS%
Aspect	1	12.90	93.41***	1	70.02	87.51***	1	224.83	75.21***	1	515.34	68.16***
Elevation	1	0.62	4.49	1	8.05	10.06*	1	66.18	22.14**	1	221.79	29.33**
Residuals	30	0.29	2.10	30	1.94	2.42	30	7.92	2.65	30	18.93	2.50

Note: *P < 0.05; **P < 0.01; ***P < 0.001; df, degrees of freedom; MS, mean squares; SS%, proportion of the variance explained by the variable; the results were obtained from general linear model (GLM) analysis.

distribution patterns of SOC and TN in different vegetation types in a typical catchment in the Qilian Mountains. Estimates of SOC storage at regional scales widely use vegetation-typing for referencing (Yimer et al., 2006; Zhang et al., 2008). We observed that both SOC and TN stocks varied significantly with vegetation types. In the catchment, grasslands on sunny slopes and the *P. crassifolia* forest were the most widely-distributed vegetation types, and SOC storage in the two ecosystems accounted for about 80% of the total SOC to 50 cm soil depth. The mean SOC stocks of *P. crassifolia* forest and grassland on sunny slopes were 23.68 and 10.11 kg m^{-2}, respectively, at soil depth of 0–50 cm. The estimate for *P. crassifolia* forest was higher than the global mean (12.50 kg m^{-2} at a soil depth of 0–30 cm) for boreal forest (Jobbágy and Jackson, 2000), and also exceeded the average SOC stocks (12.7–23.2 kg m^{-2} at a soil depth of 0–100 cm) for cold-temperate forests in China (Yang et al., 2007). The SOC stocks for grassland on sunny slopes were close to the global mean (11.7 kg m^{-2} at a soil depth of 0–100 cm) for temperate grasslands (Jobbágy and Jackson, 2000), and higher than that for temperate grasslands of Inner Mongolia (6.68 kg m^{-2} at a soil depth of 0–100 cm) (Ma, 2006) and for Tibetan grasslands (6.5 kg m^{-2} at a soil depth of 0–100 cm) (Yang et al., 2008) in China. In general, the SOC stocks of the forest and grassland in the Qilian Mountains were higher than their counterparts in other regions. Their relatively higher C density and large distribution area make them of special interest in regional carbon sequestration, indicating the potential for large CO_2 flux in response to changes in climate or local environment.

The C:N ratios in all sampled soil depths also differed significantly with vegetation types, but not between vegetation types with similar vegetation composition (Table 3). For example, relatively consistent soil C:N ratios were observed across grassland types, although SOC stocks in grassland on shady slopes were substantially higher than those on sunny slopes. The C:N ratios were also not statistically significantly different between alpine meadow and shrubland due to their similar vegetation composition (both of them had a combination of shrubs and herbs), and regardless of the marked difference in environmental conditions; the soil C:N ratios for alpine meadow and shrubland were significantly lower, however, than that of alpine shrubland, which contained only a few herb species under the shrub canopy. Our observations highlighted the stoichiometric controls of biotic factors on soil C:N ratios, reflecting the results of other studies. Another study showed that there were no significant differences in soil C:N ratios between alpine grasslands in the Tibetan Plateau and temperate grasslands in the Inner Mongolian Plateau (Yang et al., 2014). Based on the results of a synthesis of more than 100 studies from across the globe, Yang et al. (2011) noted that the C:N ratios of forest soils remained constant over long time spans.

4.2. The effects of environmental factors on SOC stocks

In montane ecosystems, topography is the most significant environmental factor influencing the microclimate and generating differences in ecological conditions (Yimer et al., 2006; Zhang et al., 2008; Bennie et al., 2008). Our study showed that SOC stocks varied significantly with topographic aspect and elevation in the Qilian Mountains. Of the studied environmental variables, aspect was the most important factor affecting the distribution of SOC, and SOC stocks on sunny slopes were significantly lower than those on shady and semi-shady slopes (Table 2). Solar radiation is the dominant component of the surface energy balance; differences in the amount of solar radiation received by surfaces with different topographic aspects would lead to differences in near-surface temperatures, evaporative demand, and soil moisture (Rorison et al., 1986; Barry, 1992; Bennie et al., 2008). For example, MAT difference between adjacent slopes in a British calcareous grassland was 2.5 to 3 °C (Rorison et al., 1986). In our study area, higher soil temperature and lower moisture content were detected on the sunny slope (data not shown); the large differences in microclimate induced by aspect had resulted in large variability in vegetation patterns, which in turn affected the patterns of SOC.

Elevation was another important controlling factor of SOC stocks in the Qilian Mountains (Table 5). In the region, marked differences in temperature and precipitation were observed along elevation, especially for shady slopes. The differences in microclimate, along with variation in vegetation patterns induced by climate gradients, regulated C inputs from litter production and C outputs through decomposition (Wang et al., 2001; Longbottom et al., 2014), influencing the distribution of SOC.

We also investigated the effects of environmental factors on SOC stocks on shady slopes. Our results showed that the variation in temperature and precipitation along the elevation gradient controlled the distribution of SOC on shady slopes. It has been widely observed in other studies that the spatial variation of SOC is closely related to climate variables such as temperature and precipitation (Jobbágy and Jackson, 2000; Callesen et al., 2003; Davidson and Janssens, 2006; Yang et al., 2008; Meier and Leuschner, 2010; Wiesmeier et al., 2013; Wang et al., 2014). In our study, SOC storage increased with precipitation (Fig. 3), which was consistent with global trends (Jobbágy and Jackson, 2000), and was also observed in numerous studies at regional scales (Callesen et al., 2003; Baritz et al., 2010; Meier and Leuschner, 2010; Wiesmeier et al., 2013). Decomposition of soil organic matter is temperature-dependent, and the amounts of soil organic matter stored in soils decrease with increasing temperature as a result of accelerated decomposition (Davidson and Janssens, 2006; Yang et al., 2008; Craine et al., 2010; Conant et al., 2011). Globally, a positive correlation was found between temperature and SOC stocks (Jobbágy and Jackson, 2000); however, a consensus at a regional scale is lacking. In the Tibetan grasslands, SOC increased with MAT (Yang et al., 2008). A positive correlation between SOC stocks and temperature was also observed in a Nordic well-drained forest (Callesen et al., 2003). However, a study on the Iberian Peninsula showed that SOC was not correlated with temperature (Rodríguez-Murillo, 2001). Our study indicated that SOC stocks on shady slopes increased with MAT at high elevations, but decreased with MAT at low-lying areas (Fig. 3). At our experimental site, temperature decreased while precipitation increased with elevation. At high elevations, temperature was a limiting factor for vegetation growth, and vegetation productivity can be expected to be stimulated by increasing temperature (He et al., 2013). The increasing C inputs may surpass accelerated decomposition resulting from higher temperatures, and thus SOC stocks increased. However, at low-lying areas, vegetation growth was less limited by temperature, and water deficit induced by rising temperature and lower precipitation may have restricted plant growth.

Furthermore, increased decomposition rate resulting from higher temperatures may have accelerated the decrease in SOC stocks. In addition, GLM analysis suggested that temperature was the most important environmental factor influencing the distribution of SOC for shady slopes in the Qilian Mountains.

5. Conclusions

In the Qilian Mountains, SOC and TN stocks varied significantly with vegetation types. SOC storage of grasslands on sunny slopes and the *P. crassifolia* forest together, due to their large distribution area, accounted for about 80% of the total SOC storage in our study catchment. In general, SOC stocks for grasslands on sunny slopes and the *P. crassifolia* forest were higher than their counterparts in other vegetation types, and were 23.68 and 10.11 kg m^{-2}, respectively, at soil depth of 0–50 cm. Soil C:N ratios also differed significantly with the studied vegetation types, however, no significant differences were observed between vegetation types with similar composition regardless of the marked differences in environmental conditions. Our results highlighted the stoichiometric controls of biotic factors on soil C:N ratios.

Soil OC stocks on shady slopes were mainly regulated by elevation-induced differences in temperature and precipitation, with temperature being the most important factor influencing the distribution of SOC. For the whole catchment, the distribution of SOC stocks was significantly affected by topographic aspect and elevation; aspect and elevation together explained 97.5% of the overall variation in SOC stocks at a soil depth of 0–50 cm, and aspect alone explained 68.2% of the overall variation. These results confirmed that topography was the most significant factor controlling the distribution of SOC in montane ecosystems. Therefore, acquiring topographic parameters in a precise manner is critical for an accurate estimation of SOC storage in montane ecosystems.

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