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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 ($\times 10^6$ 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.