Catena 152 (2017) 94–102

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Soil organic carbon as functions of slope aspects and soil depths in a semiarid alpine region of Northwest China

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ARTICLE INFO

Article history:
Received 1 March 2016
Received in revised form 5 January 2017
Accepted 10 January 2017
Available online 14 January 2017

Keywords:
Semiarid alpine region
Soil organic carbon
Slope aspect
Soil depth
Profile pedotransfer function

ABSTRACT

Soils in alpine regions associated with complex topography are characterized by large variability in the spatial distribution of soil organic carbon (SOC). However, the patterns and topographic controls on SOC at the hill scale in semiarid alpine regions are not well understood. In this study, the effects of slope aspects and depths on SOC were quantified based on field investigations in a mainly undisturbed region of the Qilian Mountains in northwestern China. Soil samples were collected at 0–10, 10–20, 20–40 and 40–60 cm on south-, southwest-, west-, and north-facing slopes of three hills. Results showed that the SOC density at 0–60 cm varied from 9.73 to 35.21 kg m^{-2}, and increased from the south- to north-facing slopes. The average SOC density on the north-facing slopes was about 3.2, 2.9 and 1.9 times larger than on the south-, southwest- and west-facing slopes. Both the general linear model and mixed linear model suggested that, at the hill scale, the slope aspects and soil depths explained the main variations of SOC concentration in our study. The profile pedotransfer function method indicated that the SOC varied predictably with soil depths and aspects, and the prediction functions well predicted the SOC data from literature. Our results highlight the importance of slope aspect as an indicator of the SOC, and demonstrate that the transformed aspect is a good continuous variable in predicting the SOC in the semiarid alpine region.

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1. Introduction

The effect of complex topography on soil organic carbon (SOC) contributes large uncertainties to the accurate estimation of SOC storage in alpine regions (Arrouays et al., 1998; Gessler et al., 2000; Chaplot et al., 2001; Yimer et al., 2006; Li et al., 2007; Hancock et al., 2010; Lenka et al., 2013; Huang et al., 2015; Chen et al., 2016). Slope aspect, an important topographic variable, substantially modifies both the solar radiation intensity and the ecological processes on hillslopes, and create microclimates that differ significantly from the regional climatic conditions (Buffo et al., 1972; Flint and Childs, 1987; Nikolov and Zeller, 1992; McCune and Keon, 2002; Bennie et al., 2008; Zhang et al., 2015). Vegetation communities and species occurrence are also modified by these microclimatic conditions at different slope aspects (Holland and Steyn, 1975; Rorison et al., 1986; Sternberg and Shoshany, 2001; Amezaga and Onaindia, 2009; Bennie et al., 2006; Aström et al., 2007). The changing climatic, hydrological and ecological conditions result in high variability in SOC at smaller scales in the alpine region.

Slope aspect plays an important role in redistributing the solar radiation. According to the equations presented by McCune and Keon (2002), potential annual direct incident radiation is the maximum on the south-facing slopes and the minimum on the north-facing slopes over the mid-latitudes in the Northern Hemisphere. The heterogeneity of solar radiation on hillslopes results in the differences in temperature and soil water content. Rorison et al. (1986) found that there was a 2.5–3 °C annual mean temperature difference on adjacent slopes in a British calcareous landscape. The accumulation of SOC varies on hillslopes because of the differences in litter input and the decomposition rates of organic matter (Post et al., 1982; Alvarez and Lavado, 1998; Yimer et al., 2006). Huang et al. (2015) found that the SOC concentration on half-shaded and shaded aspects was significantly higher than the sunny aspects in the Chinese loess region. Similar results were also found by Lenka et al. (2013) in a degraded alfisol in the Indian subtropics, where SOC concentration was 11–12% higher on the north-facing aspect than the east-facing aspect. In another two studies performed near the equatorial region, the SOC concentration was higher on the southern aspects and the lower northern aspects because of higher precipitation and lower temperature on the southern aspect (Yimer et al., 2006; Sigua and Coleman, 2010). Slope aspects also affect the distribution of SOC by altering the precipitation at a larger scale. Pu et al. (2008)

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http://dx.doi.org/10.1016/j.catena.2017.01.011
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found that the SOC concentration was higher on the windward (east) compared to the leeward (west) slopes in the northern Hengduan Mountains region in southwest China, attributing this distribution pattern to the higher precipitation (1735 mm) on the windward slopes and lower on the leeward slopes (640 mm).

Soil depth is an important variable in modeling the vertical distribution pattern of SOC and investigating organic carbon storage at a regional scale. The vertical distribution pattern of SOC enables us to estimate the organic carbon storage in the subsoil from the topsoil data, and to quantify and map the SOC for different soil depths (Mestdagh et al., 2004; Yang et al., 2007). Generally, the relations between SOC and depths can be expressed by many mathematical functions (exponential, logarithmic, power and quadratic). Among these functions, the exponential function was most widely employed (Minasny et al., 2006).

In semiarid alpine regions, soil water availability is a main environmental control involved in shaping the ecosystem productivity because of the relatively low annual precipitation and strong potential transpiration. Topography, which exerts a significant influence on the spatial variability of soil water content (Li et al., 2015; Gao et al., 2015), may significantly affect the accumulation of organic carbon in semiarid alpine soils. However, the distribution pattern of SOC at the hillslope scale in semiarid alpine region is less understood, especially in high altitude regions. This is mainly because of their limited accessibility. Moreover, although the effect of slope aspects on SOC is widely recognized, few studies have been conducted to examine the quantitative relation of SOC with slope aspects and soil depths (Lenka et al., 2013; Huang et al., 2015; Chen et al., 2016). Therefore, the main goals of this study are (1) to investigate the distribution patterns of SOC along the aspect and depth gradients, (2) to determine the contributions of slope aspects and depths to the overall variation of SOC at the hill scale, and (3) to construct the SOC prediction functions with slope aspects and soil depths as independent variables.

2. Materials and methods

2.1. Study area

The study was carried out in the Xishui Forest Zone (100°03′–100°23′ E, 38°23′–38°48′ N) of the Qilian Mountains National Forest Reserve, which lies in the north edge of Qinghai–Tibet Plateau, Northwestern China. The Xishui Forest Zone covers an area of 7239.8 km^2 with elevation ranging from 2400 to 4000 m, and is characterized by a semiarid climate with an annual average temperature of 0.7 °C and annual average precipitation of 435 mm (Chang et al., 2013). The landscape in the study area is forest-steppe, which represents the main landscape type in the middle Qilian Mountains (Lu et al., 2001). Vegetation patterns are closely related to the slope aspect, and represent a mosaic of grasslands and forests (Chen et al., 2016). At our sampling sites, grasslands occupy mainly south-, southwest-, and west-facing slopes with the dominant species including *Agropyron cristatum*, *Carex crebra*, *Stipa capillata* Linn, and *Kobresia humilis*. Forests, dominated by Qinghai spruce (*Picea crassifolia*), are mainly distributed on northwest- and north-facing slopes (Table 1). The soils, according to the taxonomic classification system, are mainly argic-ustic semi-luvisols on north-facing slopes and calcaric-ustic pedocal on other aspects. In the *Picea crassifolia* forest, there was a clear gravel composition, mainly of calcareous rock, below 60 cm.

2.2. Experimental design

In this study, we selected three sites in total (Hills A, B, and C) as the replicates with similar landscape type (forest-steppe), elevation (about 2950 m), and slope (33°) in the middle Qilian Mountains (Fig. 1, Table 1). The relative elevations of the three hills were <100 m, which enabled us to control the effect of elevations on the SOC and to focus on the variation of SOC along the aspect gradients. On each hill, we examined transects from the south- (SFS, azimuth angle of 180°), southwest- (SWFS, 225°), west- (WFS, 270°) to north-facing slope (NFS, 360°). Along each transect, three sampling positions (1 to 3) were selected from the shoulderslope to footslope position (Fig. 1c). Each sampling position contained three plots, and the size of each plot was (5×5) m^2 on SFS, SWFS, and WFS (mainly occupied by grasslands), and 10×10 m^2 on NFS (forests). Within each plot, three soil profiles were excavated (after removing the surface litter layer), and soil samples of 5.00 cm in diameter and 5.05 cm in length were collected by the core ring method (100 cm^3 core volume) at 5, 15, 30, and 50 cm, and were oven dried at 105 °C for 24 h to obtain the dry weight for calculating the bulk density (Blake and Hartge, 1986). Soil samples for chemical analyses were collected next to each soil profile using a soil auger (3.5 cm in diameter) at 0–10, 10–20, 20–40, and 40–60 cm. Soil samples (three replicates) from each plot were pooled to give a composite sample from each of the four depth intervals. In total, 324 soil profiles were excavated and 432 composite soil samples were collected for SOC concentration analysis in this study.

2.3. Soil analyses

In the laboratory, soil samples were air-dried and passed through a 2 mm sieve to remove the gravel and roots. SOC concentration was determined by wet oxidation with dichromate according to the Walkley–Black method (Nelson and Sommers, 1982).

Table 1
Geographical and vegetative characteristics of the sampled transects on the three hills.

Hill	Transect	Length (m)	Slope (°)	Elevation of sampling position (m)			Vegetation types	Cover (%)	Dominant species
				1	2	3			
A	SFS	50	30	2912	2905	2897	grassland	30	*Agropyron cristatum, Kobresia capillifolia*
	SWFS	72	33	2903	2890	2874	grassland	45	*Agropyron cristatum, Carex crebra*
	WFS	125	37	2902	2881	2849	grassland	65	*Kobresia humilis, Carex crebra*
	NFS	93	31	2901	2885	2864	forest	70	*Picea crassifolia*
B	SFS	91	28	3012	2983	2964	grassland	40	*Agropyron cristatum, Potentilla bifurca* L.
	SWFS	138	34	3007	2979	2950	grassland	60	*Carex crebra, Potentilla bifurca* L.
	WFS	157	36	2996	2950	2938	grassland	70	*Kobresia humilis, Potentilla bifurca* L.
	NFS	78	33	3007	2990	2974	forest	75	*Picea crassifolia*
C	SFS	118	30	2962	2940	2928	grassland	35	*Agropyron cristatum, Stipa przewalskyi* Roshev.
	SWFS	161	33	2958	2922	2886	grassland	50	*Carex crebra, Agropyron cristatum*
	WFS	179	35	2950	2899	2866	grassland	60	*Kobresia humilis, Poa annua* L.
	NFS	77	33	2964	2948	2939	forest	75	*Picea crassifolia*

Note: SFS, SWFS, WFS, and NFS are south-, southwest-, west-, and north-facing slopes, respectively.

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