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Effect of different vegetation cover on the vertical distribution of soil organic and inorganic carbon in the Zhifanggou Watershed on the loess plateau

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ABSTRACT

Understanding the carbon cycle of the terrestrial ecosystem and estimating the potential of carbon sequestration in soils requires adequate information on the relationship between soil organic carbon (SOC) and inorganic carbon (SIC). The vertical distribution and transformation of SOC and SIC under different types of vegetation and slope aspects in the Zhifanggou Watershed on the Loess Plateau were investigated. The distribution of SOC with soil depth in the 0–200 cm soil can be described by the exponential model. The theoretical initial accumulation of organic carbon at the litter/soil contact increased with the decrease in the C/N ratio of the litter from the vegetation and followed the order shrub > forest > grass. Compared to the shady slope, the low theoretical initial accumulation of organic carbon at the litter/soil contact resulted from the relatively small quantity of SOC formation by the decomposition of litter on the sunny slope. The variation tendency of SIC in the 0–50 cm is opposite to that of SOC. The transfer of the soil carbonate slowed down with the decrease in the soil water content (SWC), which was reflected by the significant negative correlation between SIC content and SWC ($r = -0.400$, $p < 0.001$). Among the three different types of vegetation, shrub was most helpful for inorganic carbon sink because (1) more $CaCO_3$ can be formed by precipitating with more Ca released from the decomposed shrub litter and (2) the dissolution and precipitation of the pedogenic carbonate is comparatively slow due to the relatively low SWC under shrub cover.

1. Introduction

The soil carbon (C) pool is considered to be by far the largest terrestrial C pool, storing more than double the quantity of C in vegetation or the atmosphere (Batjes, 1996). A potential increase in the carbon storage capacity of soil is an ideal option for alleviating the buildup of atmospheric CO_2 in the future (Watson et al., 2000). The soil C pool consists of soil organic carbon (SOC) and soil inorganic carbon (SIC). SOC is mainly derived from the litter or residues (including root litter) produced by plants. When plant residues are returned to the soil, various organic compounds undergo decomposition. Decomposition includes physical breakdown and biochemical transformation of complex organic molecules of dead material into simpler organic molecules, CO_2, water, and mineral nutrients (Kavvadias et al., 2001). The decomposition rate of litter is mainly controlled by environmental conditions (moisture and temperature, etc.), composition and activities of soil (micro)organisms and chemical characteristics of the litter (for example, a ratio of carbon to nitrogen) (Berger and Berger, 2012). SIC exists primarily as carbonates of calcium (calcite, $CaCO_3$) and calcium plus magnesium (dolomite, $CaMg(CO_3)_2$) (Ming, 2005). SIC pools exchange C with the atmosphere through a series of physical and chemical processes, such as C sequestration by carbonate formation or CO_2 release by acidification and leaching (Lal and Kimble, 2000). SIC originates from dissolution and precipitation of carbonate material (calcite and dolomite) and weathering of Ca/Mg-bearing silicates. With the first process no net carbon storage occurs, while the second leads to the sequestration of atmospheric CO_2 on land (Tamir et al., 2012). The atmospheric CO_2 consumed in the above reactions originates mainly from soil respiration. Soil respiration includes autotrophic root respiration and heterotrophic microbial respiration. Microbial respiration is predominantly driven by microbial activities and environmental factors, while root respiration is additionally affected by above-ground photosynthesis (Hogberg et al., 2001) and plant physiological processes (Tang, 2003).

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In arid and semiarid regions covering as much as one-third of Earth surface, the SIC pool is approximately two to ten times larger than the SOC pool (Eswaran et al., 2000) and the rate of SIC accumulation is generally higher than that of SOC (Landi et al., 2003). China has an extensive terrestrial surface with strong spatial variability in climate and topography. Approximately 40% of the total land surface is arid and/or semiarid in north and northwest China (National Soil Survey Office, 1998) where soils contain significant amounts of SIC. Feng et al. (2001) reported that the SIC stock and SOC stock in the desert region of northern China are 14.91 and 7.84 Pg C, respectively, i.e., here SIC stock is 1.8 times the SOC stock. SIC stock of the grassland on the Tibetan Plateau was found to be 15.2 Pg C, which is 2.1 times higher than the corresponding SOC stock (Yang et al., 2010) and the SIC stock of Chinese Loess Plateau is 10.20 Pg C, which is 2.1 times more than SOC stock in this region (Tan et al., 2014). Most studies regarding SOC and SIC stocks of the arid and semiarid inland regions provide, however, little or no information on the variance and transformation of SOC and SIC with soil depth, while this knowledge is important to accurately predict soil carbon dynamics and soil carbon storage.

Another aspect is that carbon sequestration efficiency is affected by the type of vegetation types (Feng et al., 2013; Jobbagy and Jackson, 2000). It has been shown that SOC accumulation was affected by (i) the quality of vegetation litter and the soil microbial biomass (Berg and McClaugherty, 2003), (ii) the root distribution of the vegetation, which influences the soil respiration and soil water content (Carbone and Trumbore, 2007; Osman and Barakbah, 2006) and (iii) the difference in sun exposure of the soil, which has an impact on SOC accumulation and soil respiration (Singh and Gupta, 1977).

The Loess Plateau in China (CLP; 620,000 km^2), which is situated in both an arid and semiarid area, has deep loess soils (Shi and Shao, 2000) that have a large carbon sequestration potential. Studies of the carbon sequestration of the CLP are therefore important and should consider not only the total SIC and SOC but also their variation with vegetation type and soil depth. Consequently, the objective of this study was to examine the variance and the transformation of SOC and SIC with soil depth under different vegetation types (grass, shrub, forest) and vegetation habitats (shady slope and sunny slope) in a watershed, with the aim to get better insight into the potential of the Loess Plateau for carbon sequestration.

2. Materials and methods

2.1. Site description and soil sampling

The study was conducted in the Zhifanggou catchment in Ansai County, Shaanxi Province, NW China (36°42′42″-36°46′28″N, 109°13′46″–109°16′03″E, 1010–1431 m altitude, 8.27 km^2), which is a representative watershed in the hilly gullied loess landscape (Qiu et al., 2012; Zhu et al., 2010). Slope gradients vary between 0° and 65°. The area is under a temperate and semi-arid climate. Mean annual temperature is 8.8 °C (min. −23.6 °C and max. 36.8 °C) and the average frost-free period is 157 days. Mean annual precipitation is 505 mm (1970–2006), of which about 70% falls between July and September (McVicar et al., 2007).

The zonal soil in this region is Orthic Entisol according to Chinese Soil Taxonomy (Cooperative Research Group on Chinese Soil Taxonomy, 2001) or Calcaric Cambisol according to FAO-UNESCO Soil Map of the World (FAO and ISRIC, 1988), which developed directly from the parent wind-deposited yellow material. In general, the type of soil is homogeneous yellowish (Munsell color of 10YR in standard soil color charts (Oyama, 1995)), looseness, macroporousness and wetness-induced collapsibility (Zhu et al., 2010). The average clay, silt, and sand contents in the soil are 17%, 69%, and 14%, respectively (Qiu et al., 2012); the dry bulk density of the 0–20 cm topsoil is 1.10–1.30 g/cm^3; CEC is 5–7 meq per 100 g, $CaCO_3$ content 10–16%, organic matter content 0.5–1.5% and the average soil pH (H_2O) is from 8.4 to 8.6 (Messing et al., 2003).

The watershed is located in the ecotone of forest and grass. The vegetation types in this watershed are typical for the western part of the Chinese Loess Plateau. The woods are dominated by *Robinia pseudoacacia*. The steppe vegetation mainly comprises *Artemisia gmelinii*, *Artemisia giraldii*, *Lespedeza davurica*, and *Stipa bungeana*. The shrub land is dominated by *Caragana korshinskii*, *Hippophae rhamnoides*, and *Sophora viciifolia* (Fu et al., 2006).

For the investigation, 68 soil profiles were chosen under different vegetation covers: 30 soil profiles under forest (*R. pseudoacacia*), 13 soil profiles under shrub (*C. korshinskii*), and 25 soil profiles under grass (*S. bungeana*, *B. ischaemum* (*L.*) *Keng*, and *Carex lanceolata*). The slope aspects include shady slope (soil slope gradient is 29.6 ± 10.9, 26.0 ± 4.6, and 32.4 ± 11.2 for forest, shrub, and grass, respectively) and sunny slope (soil slope gradient is 29.2 ± 8.8, 34.0 ± 12.5, and 38.5 ± 8.1 for forest, shrub, and grass, respectively) (Fig. 1). Soil samples were collected in July 2011 from the profiles by using a 5-cm diameter soil auger at 10 cm intervals from 0 to 60 cm and at 20 cm intervals from 60 to 200 cm after removing the litter.

2.2. Contents of total C and N in the plant residues

The residues of each plant species (forest, shrub, and grass) were sampled at three different sites for the shady slope and the sunny slope, respectively. The foliar was taken from forest and shrub, and the above-ground was taken for grass. The residue samples were washed, air-dried, and then dried at 60 °C. The resulting samples were crushed and sieved into 0.5–1.0 mm for further analysis. The total organic carbon (TOC) content and the total nitrogen content of the residues were assayed by dichromate oxidation (Kalembasa and Jenkinson, 1973) and the Kjeldahl method (Bremner, 1996), respectively. Ca contents were determined using ICP (Varian, U.S.A.), with a sample pre-digestion step using nitric acid in a closed Teflon vessel in a microwave oven (Brun et al., 2010). All above measurements were performed in triplicate and averaged.

2.3. Soil physicochemical properties

Fresh soil samples were collected in July 2011; the soil water content (SWC) of each sample was determined by weighting a portion after collection and drying in an oven at 105 °C for 12 h. The samples were air dried, crushed and passed through a 2 mm sieve for carbonate content

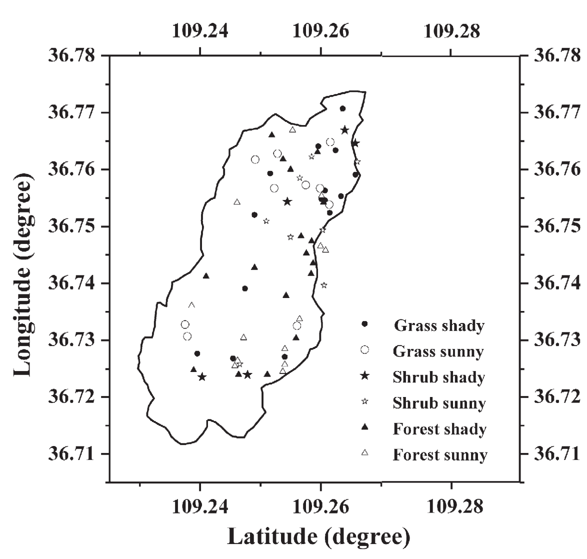

Fig. 1. Sample sites in the Zhifanggou Watershed. The symbols circle, pentagram and triangle represent the soils under grass, shrub, and forest cover, respectively.

Table 1
Chemical component properties of the plant residues.

	Main vegetation	Slope direction	Ca (g/kg)	TOC (g/kg)	Total N (g/kg)	C/N ratio
Shrub	*Caragana korshinskii Kom*	Shady slope	19.7 ± 1.6	490.8 ± 1.2 [a]	32.2 ± 1.5	15.2 ± 0.5
		Sunny slope	18.8 ± 1.3	461.3 ± 1.8	30.1 ± 1.3	15.3 ± 0.5
Forest	*Robinia pseudoacacia*	Shady slope	16.9 ± 1.1	434.2 ± 1.4	16.1 ± 1.1	27.0 ± 0.6
		Sunny slope	16.1 ± 1.5	403.7 ± 1.7	14.7 ± 1.5	27.5 ± 0.6
Grass	*Stipa bungeana*	Shady slope	10.5 ± 1.8	485.6 ± 1.8	10.9 ± 1.3	44.6 ± 0.6
		Sunny slope	9.6 ± 1.2	463.4 ± 1.4	8.5 ± 1.1	54.5 ± 0.6
	Bothriochloa ischaemum (L.) Keng	Shady slope	9.2 ± 1.0	425.3 ± 2.3	7.9 ± 1.4	53.8 ± 0.7
		Sunny slope	8.3 ± 1.3	402.5 ± 1.8	6.4 ± 1.0	62.9 ± 0.7
	Carex lanceolata	Shady slope	10.9 ± 1.5	510.1 ± 2.1	13.6 ± 1.5	37.5 ± 0.6
		Sunny slope	10.2 ± 1.7	486.4 ± 1.6	11.3 ± 1.3	43.0 ± 0.6
Coef. of variation (%)			33.4	8.3	59.1	43.5

[a] Mean ± standard error.

determination and through a 0.25 mm sieve for organic matter content measurement.

Soil inorganic carbon (SIC) was determined by the HCl method using the Chittick apparatus (Dreimanis, 1962). The resulting SIC refers to the sum of $CaCO_3$, $MgCO_3$ and other carbonate minerals in soils. In this region, $CaCO_3$ is dominant (84.4–94.5%) and dolomite and $MgCO_3$ (5.5–15.6%) are minor components of the carbonate (Jeong et al., 2011), to simplify, all SIC examined was considered to originate from $CaCO_3$. The resulting SIC content includes the contents of lithogenic inorganic carbon (LIC) and pedogenic inorganic carbon (PIC). For LIC in soil depth, it could be neglected for simplification in the present study. That is because LIC in soil depth accounts for less than 25% soil inorganic carbon based on many literatures. For example, Geng and Wen (1988) found that the SIC in 0–60 m soil depth in Luochuan on the Loess Plateau region is composed of approximately 80–98% pedogenic carbonate. Chen et al. (1997) employing Sr isotopic composition to assess the SIC in 0–10 m soil depth in Luochuan, found that the content of pedogenic carbonate is close to the results from Geng and Wen (1988). In addition, Li et al. (2013a) estimated that the SIC in 0–18 m soil depth in Xifeng on the Loess Plateau region is composed of approximately 75–100% pedogenic carbonate based on the Mn/Ca and Mg/Ca ratios of bulk carbonate.

Soil organic carbon (SOC) was determined by the $K_2Cr_2O_7$ titration method after digestion (Nelson and Sommers, 1982). The vertical distributions of SOC in the 0–200 cm soil were fitted to the exponential model modified from Arrouays and Pelissier (1994).

Results of SIC and SOC from the same vegetation cover, the same slope aspect and the same soil depth were averaged and the averages were reported. Significance tests were examined at a significance level of 0.05 or 0.1 and performed using SPSS 13.0 software (SPSS, Chicago, Illinois, USA).

3. Results

3.1. Chemical compositions of residues for different plant species

The contents of Ca, total organic C and total N in the plant residues are presented in Table 1. The Ca, C and N contents of residues on the shady slope are generally higher than those on the sunny slope. The coefficient of variation (CV) of the Ca content in the plant residues was 33.4%, *C. korshinskii Kom* (shrub) had the highest total Ca content (shady slope 19.7 ± 1.6 g/kg, sunny slope 18.8 ± 1.3 g/kg), *B. ischaemum* (*L.*) *Keng* (grass) the lowest (shady slope 9.2 ± 1.0 g/kg, sunny slope 8.3 ± 1.3 g/kg). The CV of the total N content in the plant residues was as high as 59.1%, and *C. korshinskii Kom* had the highest total N content (shady slope 32.2 ± 1.5 g/kg, sunny slope 30.1 ± 1.3 g/kg), *B. ischaemum* (*L.*) *Keng* the lowest (shady slope 7.9 ± 1.4 g/kg, sunny slope 6.4 ± 1.0 g/kg). Comparing the variation in N (Table 1), the variation of organic C in the plant residues was relatively low (CV = 8.3%). The total organic C (TOC) content in *Carex lanceolata* (grass) was the highest (shady slope 510.1 ± 2.1 g/kg, sunny slope 486.4 ± 1.6 g/kg), and *B. ischaemum* (*L.*) *Keng* (grass) was the lowest (shady slope 425.3 ± 2.3 g/kg, sunny slope 402.5 ± 1.8 g/kg). The much stronger variation in total N content than in TOC resulted in a high variation of the C/N ratio of the plant residues (CV = 43.5%). The C/N ratio in *B. ischaemum* (*L.*) *Keng* was the highest (C/N shady slope = 53.8 ± 0.7, C/N sunny slope = 62.9 ± 0.7), and *Caragana korshinskii Kom* was the lowest (C/N shady slope = 15.2 ± 0.5, C/N sunny slope = 15.3 ± 0.5).

3.2. Content of soil organic carbon

SOC contents in the samples as a function of profile depth are depicted in Fig. 2. In general, SOC of the samples on the shady slope (2.1–6.2, 1.8–8.6, 2.1–5.3 g/kg for grass, shrub, and forest, respectively) was higher than that on the sunny slope (2.1–4.2, 1.9–6.7, 1.9–4.1 g/kg for grass, shrub, and forest, respectively). The SOC under different vegetation covers decreased sharply along soil depth in the top 0–50 cm of the soil layer, and kept stable values around 2 g/kg over the 50–200 cm depth. For different types of vegetation, the SOC in the 0–50 cm top layer decreased in the order of shrub ≥ grass > forest for the shady slope and shrub > grass ≥ forest for the sunny slope. In the layer 50–200 cm, the SOC had no significant difference under the three vegetation covers for both the shady slope and the sunny slope (*t* test). In addition, the SOC in the 0–40 cm top soil under the grass cover at the shady slope showed a highly significant difference with the sunny slope (*t* test, $p < 0.01$), while in the layer 40–200 cm, no significant difference in SOC of the shady and sunny slope could be found (*t* test). Under the shrub a similar behavior was found. The SOC in the 0–10 cm top soil under the forest cover had a highly significant difference between the shady and sunny slope (*t* test, $p < 0.01$) but in the layer 20–200 cm, the SOC did not differ (*t* test).

According to Arrouays and Pelissier (1994), the organic C content with soil depth can be fitted by an exponential equation (Eq. (1)):

$$C_x = C_2 + (C_1 - C_2)\left[\left(e^{-bx} - e^{-bx_2}\right)/\left(e^{-bx_1} - e^{-bx_2}\right)\right] \tag{1}$$

where x is the depth (cm) along the profile and C_x is the corresponding organic carbon content (g/kg), x_1 and C_1 and x_2 and C_2 are the same parameters but now relating to the surface layer, and the deepest layer. The coefficient b (cm^{-1}) represents the curvature of the profile.

In this study, the parameters x_1 and x_2 have been fixed to 0 cm and 200 cm, and C_1 and C_2 therefore represent respectively the theoretical organic C content at the litter/soil contact and to 200 cm depth. In this way, Eq. (1) can be written as Eq. (2). The vertical distributions of SOC in the 0–200 cm soil are well fitted to Eq. (2), and the obtained parameters are listed in Table 2:

$$C_x = C_2 + (C_1 - C_2)\left[\left(e^{-bx} - e^{-200b}\right)/\left(1 - e^{-200b}\right)\right]. \tag{2}$$

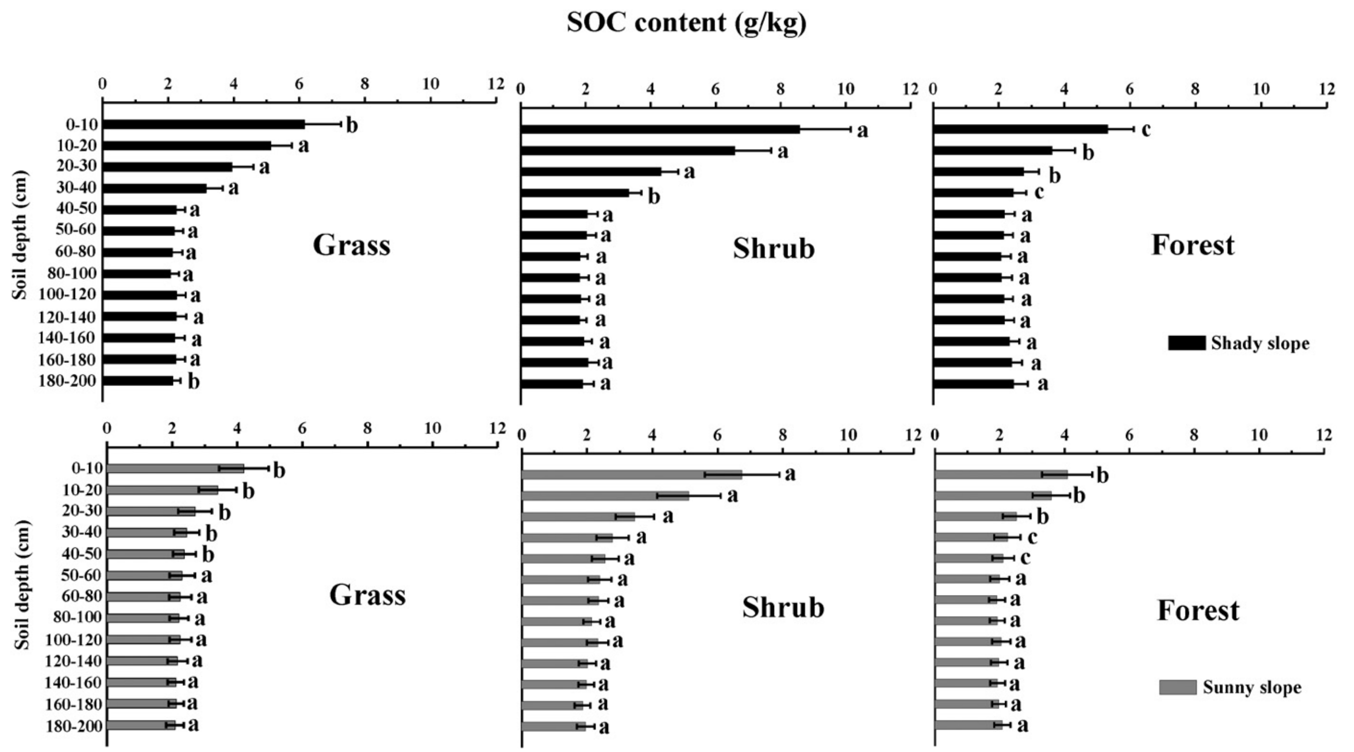

Fig. 2. Profiles of soil organic carbon (SOC) distributions under different vegetation cover (mean + standard error). Black bars and gray bars indicate the distribution of SOC content in the 0–200 cm soil depth for the shady slope and the sunny slope, respectively. These values were obtained by averaging the actual content values of individual soils. Letters indicate significant differences among vegetation types at each depth interval (t test, $p < 0.05$).

C_1 reflects the theoretical initial accumulation of organic C content at the litter/soil contact and C_2 reflects the stabilized organic C content, C_1-C_2 thus reflects the unstabilized organic C content. Orders of C_1 values are shrub > forest > grass for both the shady slope and the sunny slope. Orders of C_2 values are forest > grass > shrub for the shady slope and grass > shrub > forest for the sunny slope, respectively. The unstabilized organic C content (C_1-C_2) on the shady slope is higher than that on the sunny slope. And ratios of the unstabilized organic C content (C_1-C_2) to the initial accumulation of organic C content (C_1) are shrub > forest > grass for both the shady slope and the sunny slope.

3.3. Content of soil inorganic carbon

SIC values as a function of profile depth are displayed in Fig. 3. Compared to SOC, SIC showed the opposite trend: SIC on the shady slope (12.9–14.3, 14.0–15.4, 13.7–14.8 g/kg for grass, shrub, and forest, respectively) was lower than that on the sunny slope (14.8–15.3, 15.4–16.5, 14.2–15.1 g/kg for grass, shrub, and forest, respectively).

Under different vegetation covers SIC increased in the top 0–50 cm of soil, and kept a stable value in the 50–200 cm layer. For the entire profile the order of the SIC was for the sunny slope shrub > grass > forest and for the shady slope shrub ≥ forest > grass. Under the same type of vegetation cover, the SIC in the entire profile of the shady slope was highly significant different (t test, $p < 0.01$) from the sunny slope.

3.4. Soil water content

The vertical distribution of soil water content (SWC) for the different soil profiles is shown in Fig. 4. For most of the soil profiles, the SWC decreased sharply along with soil depth in the top 0–50 cm of soil, and changed a little in the 50 to 200 cm horizon.

In the top layer (0–30 cm) the water content is higher for the shady slope than that for the sunny slope, and the order of the SWC was grass > shrub ≥ forest for both the shady slope and the sunny slope. In the deeper horizon (30–200 cm), the order of the SWC was grass > forest > shrub for both the shady slope and the sunny slope.

4. Discussion

4.1. Vertical distribution of SWC with soil depth

The distribution of roots in the soil profile accounts for the soil water distribution. Considering water consumption by root system, the order of the SWC (grass > shrub ≥ forest) in the 0–30 cm soil layer results

Table 2
Model parameters for the exponential distribution of SOC in the vertical direction[a].

Vegetation	Slope direction	C_1 (g/kg)	C_2 (g/kg)	b (cm^{-1})	R^2	$(C_1 - C_2)/C_1 * 100$ (%)
Shrub	Shady slope	14.31	1.79	−5.55	0.99	87.5
	Sunny slope	10.37	2.05	−5.52	0.99	80.2
Forest	Shady slope	9.58	2.21	−8.54	0.99	76.9
	Sunny slope	5.97	1.95	−5.77	0.98	67.3
Grass	Shady slope	9.06	2.10	−4.83	0.98	76.8
	Sunny slope	5.92	2.16	−5.98	0.99	63.5

[a] C_1 and C_2 represent respectively the theoretical organic C content at the litter/soil contact and to 200 cm depth, b is a coefficient which reflects the curvature of the profile, and R^2-value is a measure of goodness-of-fit of the regression. The regression was carried out on averages of values for a 0–200 cm soil depth in the profiles of one class of soil.

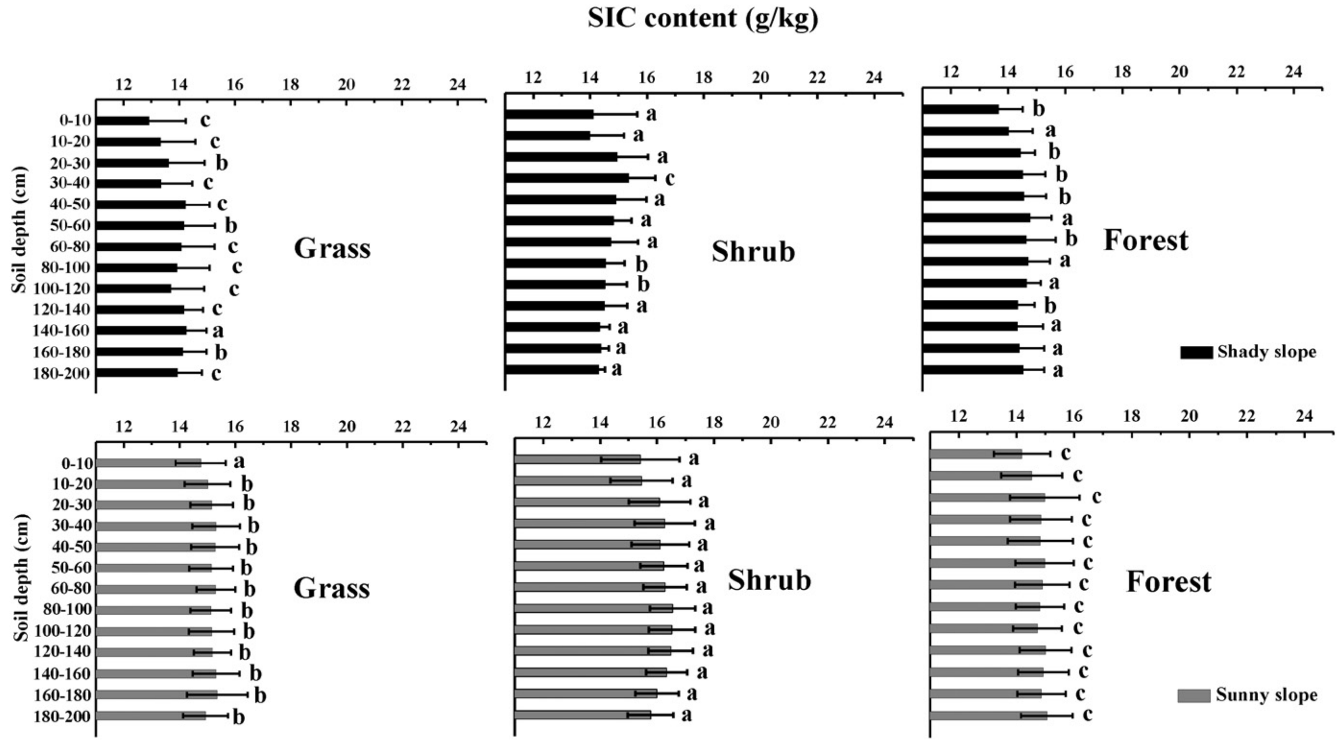

Fig. 3. Profiles of soil inorganic carbon (SIC) distributions under different vegetation cover (mean + standard error). Black bars and gray bars indicate the distribution of SIC content in the 0–200 cm soil depth for the shady slope and the sunny slope, respectively. These values were obtained by averaging the actual content values of individual soils. Letters indicate significant differences among vegetation types at each depth interval (t test, $p < 0.05$).

from the order of the root densities of the different vegetations under temperate climate: shrub ≥ forest > grass (Jackson et al., 1996). In the 30–200 cm soil depth, the order of the SWC (grass > forest ≥ shrub) results from the order of the root length of the different types of vegetation covers under temperate climate: shrub ≥ forest > grass (Jackson et al., 1996).

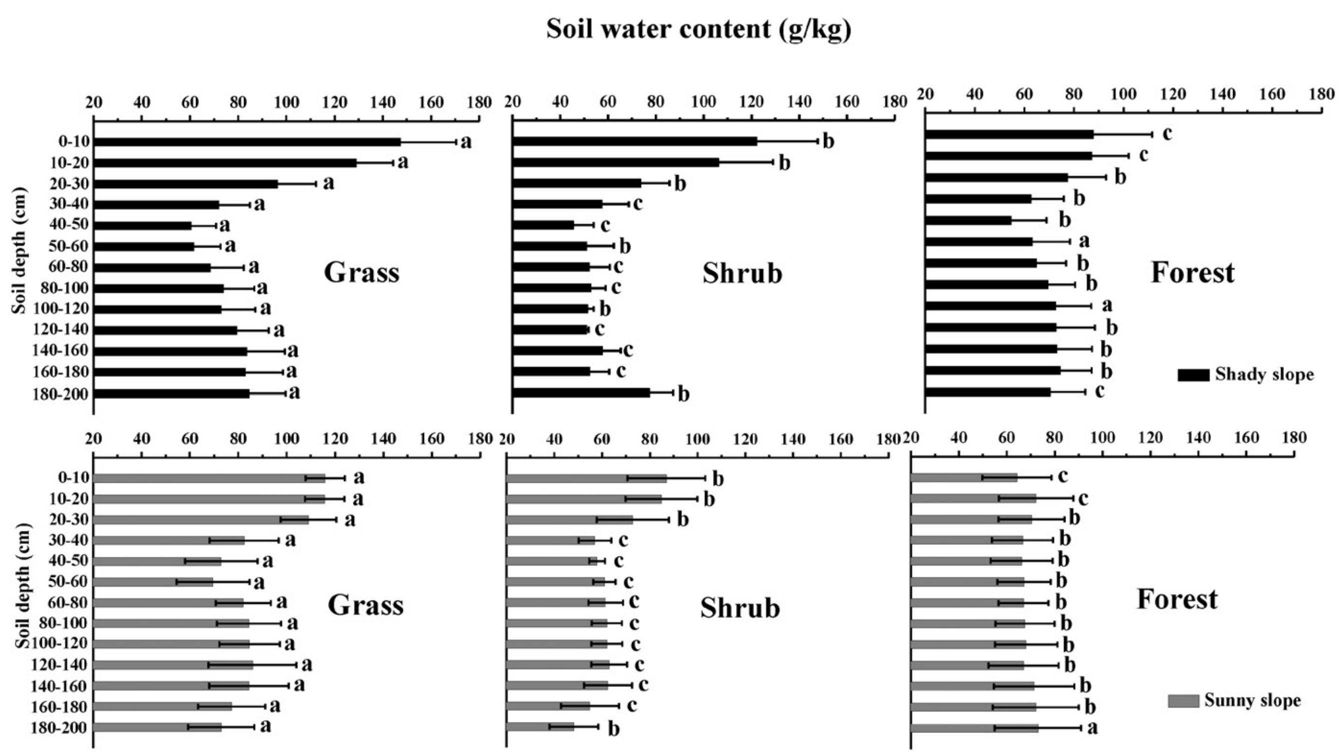

Fig. 4. Profiles of soil water content (SWC) distributions under different vegetation cover (mean + standard error). Black bars and gray bars indicate the distribution of SWC in the 0–200 cm soil depth for the shady slope and the sunny slope, respectively. These values were obtained by averaging the actual content values of individual soils. Letters indicate significant differences among vegetation types at each depth interval (t test, $p < 0.05$).

4.2. Vertical distribution of SOC with soil depth

The theoretical initial accumulation of organic C content at the litter/soil contact (C_1) is opposite to the order of the average C/N ratios of the plant litter (Table 1 and Table 2). This indicates that a low C/N ratio of plant litter is favorable to the formation of SOC, which is consistent with findings of Berg (2000). As shown in Table 1, the low CV value of TOC and the high CV value of total N contents in the litter from the three different types of vegetation suggest that the plant litter with the lower C/N ratio has higher nitrogen content. The higher nitrogen content can stimulate microbial prosperity and more microbial activity will faster decompose litter into soil organic matter (Berg, 2000). Therefore, decomposition of 'fresh' litter increases in the order of shrub > forest > grass with the decrease in the C/N ratio, which explains that the average C_1 value for shrub is relatively large and that for grass is relatively small. Under the same kind of vegetation type cover, the C_1 values for the sunny slope are less than that for the shady slope. It is possible that compared with the shady slope, the greater solar radiation on the sunny slope leads to the lower litter water content, which inhibits the microbial activity. The relatively low microbial activity results in the relatively low SOC formation on the sunny slope. Protecting soil from solar radiation by the coverage of the litter is also important. Fig. 2 shows a closer vertical SOC distribution in the 0–50 cm soil profile under the forest cover between the sunny and the shady slope than those under the shrub and grass covers. That is likely that with increasing coverage of litter (forest (71%) > shrub (52%) > grass (50%), Zhang and Liu, 2010), the difference in the soil environment between the sunny and the shady slope decreases for the soils under the same vegetation cover.

4.3. Vertical distribution of SIC with soil depth

In the first 50 cm, more SOC (Fig. 2) and soil microbial biomass (Ekelund et al., 2001) correlate with less SIC (Fig. 3). It appears that an increase in microbial activity (thus more CO_2 production) leads to a decrease of SIC in soil. But, in fact, large quantities of soil microbial biomass and SOC will promote the formation or the process of dissolution of SIC and precipitation of SIC. On the one hand, more soil microbial biomass can mineralize the unstabilized organic C to produce more CO_2. The produced CO_2 will be dissolved in the soil solution and transform into CO_3^{2-} (Eq. (3)). The resulting CO_3^{2-} can form $CaCO_3$ by precipitation with the Ca that is released from the decomposed litter (Eq. (4)).

$$H_2O + CO_2 \leftrightarrow CO_3^{2-} + 2H^+ \tag{3}$$

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3. \tag{4}$$

In this case, one mole of pedogenic carbonate formed can sequester one mole of CO_2, which may be one of the origins of the inorganic carbon sink.

On the other hand, more soil microbial biomass indicates more CO_2 generated by soil respiration since the microbial respiration is about half of the soil respiration (Hanson et al., 2000). An increase in partial pressure of CO_2 in soils leads to some dissolution of the pedogenic carbonate in the top soil (Eq. (5)). Dissolved pedogenic carbonate transfers to the deep soil and then re-crystallizes under a relatively low soil water content (Eq. (6)), which results in a significant negative correlation between SIC content and SWC in the soil profile ($r = -0.400$, $p < 0.001$) (Fig. 5). In this case, the carbon exchange has no net generation or consumption of CO_2.

$$CaCO_3 + CO_2 + H_2O \leftrightarrow Ca^{2+} + 2HCO_3^- \tag{5}$$

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_2\uparrow + H_2O. \tag{6}$$

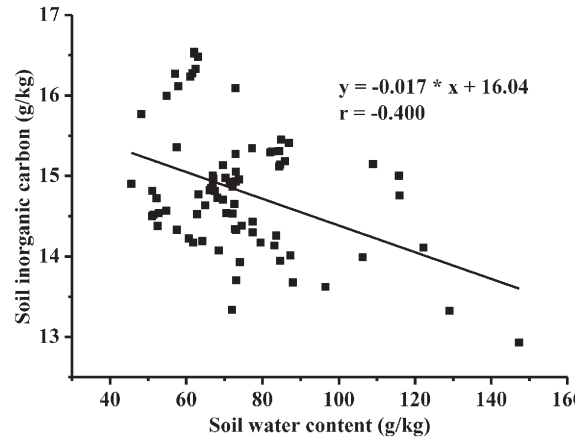

Fig. 5. Relation between soil inorganic carbon and soil water content for all soil profiles.

Based on the discussion above, the largest quantity of the pedogenic carbonate is produced by precipitating most Ca released from litter under the shrub cover. This is because for the soils under shrub cover on the shady slope, there are the greatest quantities of Ca in the litter (Table 1) and the unstabilized organic C (Table 2). Meanwhile, soil microbial carbon in 0–20 cm soil horizon for the shrub was larger (265.0 mg/kg) than that for the forest (224.4 mg/kg) and for the grass (129.8 mg/kg) (Li et al., 2013b). In addition, the transfer of the pedogenic carbonate is relatively slow due to the relatively low SWC under shrub cover. Accordingly, SIC in the soils under shrub cover is relatively high at the same soil depth compared with that in the soils under forest and grass covers. This indicates that shrub is most helpful for inorganic carbon sink. Compared to the shady slope, the SIC content on the sunny slope is relatively high. This may be caused by the lower SWC on the sunny slope, which decreases the transfer of the pedogenic carbonate.

4.4. Relationship between SOC and SIC in the soil profiles

To investigate the relationship between SOC and SIC in detail, the correlation analysis between the SIC and SOC in the 0–50 cm soil depth is shown in Fig. 6. There are negative correlations between the SOC and SIC in the 0–50 cm soil under the different vegetation covers ($n = 5$, $p < 0.10$). For the shady slope, the absolute values of the slopes of the linear regression patterns between SOC and SIC are obviously different for the different vegetation covers: forest > grass > shrub (Fig. 6a). This indicates that under the forest cover the increment in SIC is largest per unit decrement in SOC. This is caused by the soil microbial biomass (Li et al., 2013b), the unstabilized organic C content (Table 2), and the Ca content (Table 1) in the litter, which are similar under forest and shrub cover and this leads to similar amounts of pedogenic carbonate. In addition, the relatively low SWC under forest cover slows down the transfer of the pedogenic carbonate compared with that of soils under shrub cover. Consequently, for the soil profiles under the forest cover, more carbonate is accumulated with the same decrement of SOC.

For the sunny slope ($n = 5$, $p < 0.05$, Fig. 6b), the order of the absolute values of the slopes of the linear regression patterns between the SOC and SIC in the 0–50 cm soil depth is also forest > grass > shrub. However, the absolute values of the slopes are somewhat larger than the values for the shady slope. This suggests that the increment in SIC per unit decrement in SOC is on the sunny slope larger than on the shady slope. This can be attributed to the lower SWC on the sunny slope, which causes a slower transfer of the pedogenic carbonate in the soils (Katou and Akiyama, 1990).

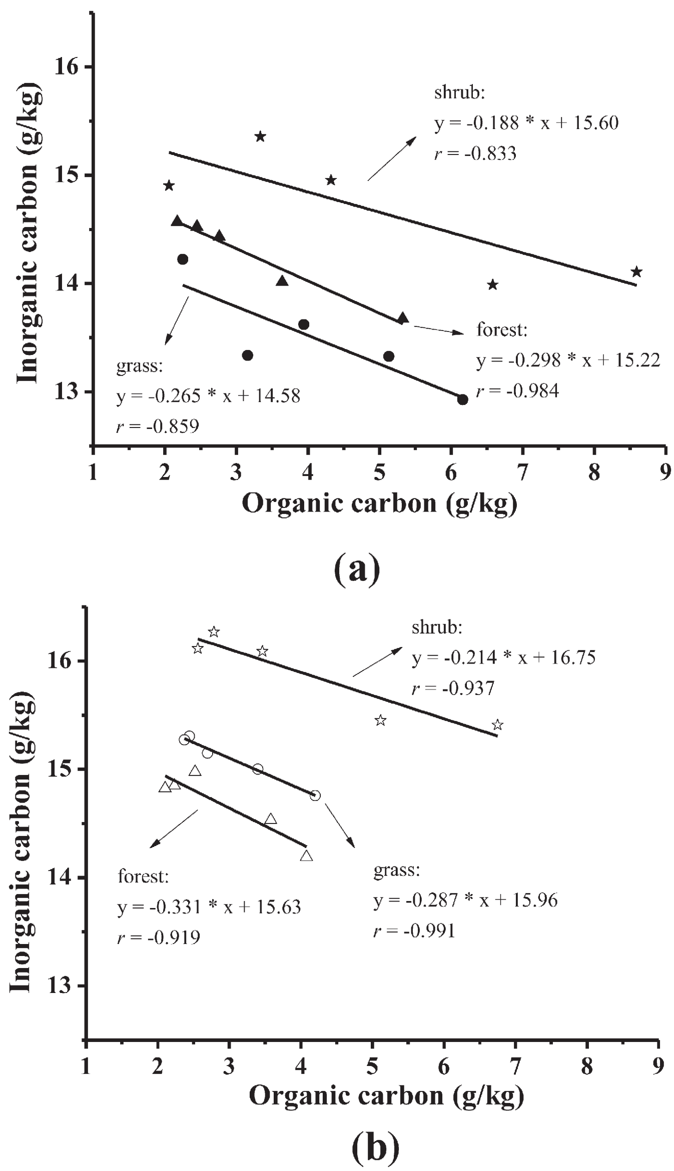

Fig. 6. Linear correlations between SOC and SIC in the 0–50 cm soil depth under different vegetation cover in different slope aspects: (a) shady slope; (b) sunny slope.

5. Conclusions

Vegetation cover and soil environments affect the accumulation and distribution of SOC and SIC in soil depth.

The distribution of SOC with soil depth in the 0–200 cm soil was in accordance with the exponential model of Arrouays and Pelissier (1994). The theoretical initial accumulation of organic carbon at the litter/soil contact increased with the decrease in C/N ratio of the litter from the vegetation and followed the order shrub > forest > grass. The low water content on the sunny slope caused the relatively small quantity of organic carbon formation by the decomposition of litter as compared to the wetter shady slope.

The variation tendency of SIC in the first 50 cm is just opposite to that of SOC. Among the three different vegetations, shrub was most advantageous for fixation of inorganic carbon. SIC was significantly negative correlated with the soil water content under the three different vegetation covers and in the two slope apsects, indicating that the dissolution and precipitation of the pedogenic carbonate decreased with the decrease in the SWC in the soil profiles.

The results of the current study can improve the predictions of soil carbon dynamics and soil carbon storage.

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