Science of the Total Environment 408 (2010) 1925–1931

Contents lists available at ScienceDirect

Science of the Total Environment

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

Profile storage of organic/inorganic carbon in soil: From forest to desert

Yugang Wang [a,b], Yan Li [a,b,*], Xuehua Ye [c], Yu Chu [c], Xinping Wang [d]

[a] Fukang Station of Desert Ecology, PR China
[b] Key Laboratory of Oasis Ecology and Desert Environment, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, 818 South Beijing Road, Urumqi, Xinjiang 830011, PR China
[c] Erdos Station of Grassland Ecology, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, PR China
[d] Shapotou Desert Research and Experiment Station, Cold and Arid regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 73000, PR China

ARTICLE INFO

Article history:
Received 9 August 2009
Received in revised form 12 December 2009
Accepted 11 January 2010
Available online 2 February 2010

Keywords:
Landscape type
Deep soil
Precipitation gradient
Root density

ABSTRACT

Understanding the distribution of organic/inorganic carbon storage in soil profile is crucial for assessing regional, continental and global soil C stores and predicting the consequences of global change. However, little is known about the organic/inorganic carbon storages in deep soil layers at various landscapes. This study was conducted to determine the soil organic/inorganic carbon storage in soil profile of 0–3 m at 5 sites of natural landscape from forest to desert. Landscapes are temperate forest, temperate grassland, temperate shrub–grassland, temperate shrub desert, and temperate desert. Root mass density and carbon contents at the profile were determined for each site. The results showed that considerable decrease in root biomass and soil organic carbon content at the soil profile of 0–3 m when landscape varied from forest to desert along a precipitation gradient, while soil inorganic carbon content increased significantly along the precipitation gradient. Namely, for density of soil organic carbon: forest > grassland > shrub–grassland > shrub desert > desert; for density of soil inorganic carbon: forest, grassland < shrub–grassland < shrub desert < desert ($P < 0.05$ in all cases). In landscapes other than forest, more than 50% soil carbon storage was found in 1–3 m depth. For grassland and shrub–grassland, the contribution from 1–3 m was mainly in the form of organic carbon, while for shrub desert and desert the contribution from this depth was mainly in the form of inorganic carbon. The comparison of soil C storage between top 0–1 m and 1–3 m showed that the using top 1 m of soil profile to estimate soil carbon storages would considerably underestimate soil carbon storage. This is especially true for organic soil carbon at grassland region, and for soil inorganic carbon at desert region.

1. Introduction

In recent decades, the importance of the soil organic and inorganic carbon pool in global C cycle is widely recognized (Post et al., 1982; Trumbore, 1997; Lal, 2004; Powlson, 2005). As the largest carbon pool in terrestrial ecosystems, soils interact strongly with microbial activity, climate, and landscapes (Schulze and Freibauer, 2005; Shrestha and Lal, 2006; Dawson and Smith, 2007). The abundance of organic and inorganic C in the soil affects and is affected by climate and vegetation cover, and organic carbon's role as a key factor of soil fertility and vegetation production has been documented in many studies (Tiessen et al., 1994; Houghton et al., 1999; Halvorson et al., 2002; Yoo et al., 2006). Human activity has adversely affected global C cycles, and contributed to climate change that will generate visible feedbacks to terrestrial ecosystems (He et al., 2008). A clear description of soil carbon distributions and the controlling factors for soil carbon loss and gain will facilitate us to predict the consequences of climate and land cover change (Jobbágy and Jackson, 2000). However, most of these studies have focused on the top meter of soil carbon storages (e.g. Feng et al., 2002; Singh et al., 2007) and frequently disregard the soil inorganic carbon pool (Gillabel et al., 2007). Thus, we are in urgent need of studies directly measuring and comparing C storages in deep soil layers across landscape types along a precipitation gradient, which will help in assessing current regional, continental and global soil C stores and predicting the consequences of global change.

Globally, the estimates of soil organic carbon storages range from 1200 to 1600 pg in the top 1 m soil depth. Soil inorganic carbon amounts to 695–930 pg down to the same depth (Schlesinger, 1982; Sombroek et al., 1993; Batjes, 1996), which is mostly stored in arid and semi-arid regions (Díaz-Hernández et al., 2003). Recent estimate of soil inorganic carbon gives values of 940 pg for the first meter (Eswaran et al., 2000). Soil C budget in China usually is based on the database of China's second national soil survey in 1980s, and more focused on agricultural soils at 1 m depth (Ni, 2001; Wang et al., 2001; Wu et al., 2003). So, soil carbon storage below 1 m depth profile of China is rarely estimated at the natural landscapes (Li et al., 2007). How much carbon is underestimated

---

* Corresponding author. Key Laboratory of Oasis Ecology and Desert Environment, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, 818 South Beijing Road, Urumqi, Xinjiang 830011, PR China. Fax: +86 991 7885320.
E-mail address: liyan@ms.xjb.ac.cn (Y. Li).

0048-9697/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.scitotenv.2010.01.015

in global budgets below the first meter is surely a bigger question mark. Batjes (1996) estimates a 60% increase in the global soil organic carbon (SOC) storage with depth extended to 2.0 m. A recent estimate of SOC storages has reported with a 56% increase at global level when the third meter of soil was also included (Jobbágy and Jackson, 2000). An increasing understanding of the importance of deep soil carbon is reflected in the mounting global estimates of soil carbon storages (Veldkamp et al., 2003). The biomes with the most SOC at 1–3 m depth were tropical evergreen forests and tropical grasslands/savannas (Jobbágy and Jackson, 2000). In China, most soils are well developed and most soil profiles are far beyond 1 m (Li et al., 2007; Mi et al., 2008). Soil C pool that remains poorly understood is its vertical distribution, especially the differences of this vertical distribution across landscape types from forest to desert.

Until now, SOC was the focus of most studies on this topic. Soil inorganic carbon (SIC) has been recognized as a large pool, mainly present in the form of soil carbonates in arid and semi-arid regions (Grossman et al., 1995; Schlesinger, 2002). But its dynamic and manageability has largely been neglected since its amount of SIC exchange with the atmosphere was estimated at only approximately 1.0–5.0 gC m^{-2} yr^{-1} in the desert soils (Schlesinger, 1997). However, most recent study suggested that carbon absorption by saline/alkaline soils could be as high as 62–622 gC m^{-2} yr^{-1} (Xie et al., 2009). Hence, on a global basis, SIC pool and its dynamics could be much more important (Nieder and Benbi, 2008) than we have recognized. 47% of the Chinese land is in arid and semi-arid area that is rich in SIC. Hence, SIC is also very important in estimating soil carbon pool of China.

With the above-mentioned consideration, the current study compares organic/inorganic carbon storage in natural soil profiles at deeper depths along a precipitation gradient across landscape types in northern China, with the objective of:

(1) quantifying both soil organic carbon and soil inorganic carbon storage along a precipitation gradient across landscape types at different soil depth;
(2) evaluating the relationship between SOC/SCI content and root distribution;
(3) exploring the importance of deep soil carbon storages at 1–3 m depth in natural soil profile from forest to desert.

2. Material and methods

2.1. Site description

The study was conducted along a precipitation gradient across natural landscape types in the Inner Mongolia Autonomous Region (IMAR) of northern China: temperate forest, temperate grassland; temperate shrub–grassland, temperate shrub desert, and desert. The temperate forest, dominated by *Larix gmelini*, *Populus davidiana*, and *Betula platyphylla*, distributed mainly in the rolling hills with altitude of 950–1300 m and annual precipitation of 408–484 mm. The temperate grassland, dominated by *Leymus chinensis*, *Stipa grandis*, *Agropyrum cristatrum*, and *Caragana microphylla*, distributed in tablelands with altitude less than 1300 m and annual precipitation of 318–389 mm. The temperate shrub–grassland is covered by scattered shrubs and herbaceous plant, and is dominated by *C. microphylla*, *Ulmus pumila*, *L. chinensis*, and *S. grandis*, with annual precipitation of 260–316 mm. The temperate shrub desert is dominated by *Tetraena mongolica*, *Salsola passerine* and *Reaumuria soongorica*, with annual precipitation of 161–209 mm. The temperate desert is low in species richness, and is dominated by *S. gobica*, *R. soongorica*, *N. sphaerocarpa* and *Potaninia mongolica*, with annual precipitation of 61–121 mm. Five sites were chosen to represent the distinctive five landscapes (Table 1) along this precipitation gradient (106°42′–120°08′ E, 39°29′–47°21′ N). According to the aridity index presented by Cheng and Zhang (1996), these sites are in semi-humid, semi-arid, arid regions of China. The topographies of the five sites are gently extent hills and tablelands, with elevation ranging from 1020 m in the west to 1258 m in the east. The mean annual precipitation (MAP) for these sites ranges from 102 to 448 mm, in which 70–80% occurs during the growing season (May–August) in synchrony with the peak temperature (Bai et al., 2008). Variation in latitude (and thus radiation and temperature) is within a small region among the sites (Table 1), thus precipitation can be considered as the major factor determining the vegetation change among the sites (Zhou et al., 2002). The soils of the study sites are chernozem soil in forest, chestnut soil in grassland and shrub–grassland, desert soil in shrub desert land and desert land.

Table 1
The basic characteristics of the five studied sites.

Site	MAP (mm)	MAT (°C)	MAI	Landscape type	Elevation (m)	Longitude	Latitude
Aershan	448	−3.2	1.22	Forest	1020	120°08′3.4″	47°21′50.1″
Erdos	350	5.3	2.17	Grassland	1258	110°11′57″	39°29′34″
Xilinhaote	295	6.4	2.74	Shrub–grassland	1230	115°37′23″	42°17′18″
Wuhai	170	9.0	4.05	Shrub desert	1150	106°49′54″	39°41′24″
Denkou	102	7.8	5.62	Desert	1065	106°42′53″	39°56′53″

Notes: Mean annual precipitation (MAP), mean annual temperature (MAT), and mean annual aridity index (MAI).

2.2. Soil and plant root sampling and analysis

For each of the selected site representing a landscape type, three sampling ditches were dug. The ditch is of 3.0 m (width) × 4.0 m (length) × 3.0 m (depth). Soil bulk density was determined using a soil corer (stainless steel cylinder of 100 cm^3 in volume) and soil samples were collected from 0.0 to 3.0 m depth (0.1 m, 0.2 m, or 0.5 m intervals; see Table 2) using steel cylinders (100 cm^3). A square soil column 0.8 by 0.8 m was excavated layer by layer: 0–0.1, 0.1–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, 0.8–1.0, 1.0–1.5, 1.5–2.0, 2.0–2.5, and 2.5–3.0 m. With a 2 mm sieved, roots were sieved from the soils from each depth, brought back to the laboratory, where the roots were washed and dried at 65°C to constant weight. In the laboratory, each soil sample was thoroughly sieved to 2 mm. The sieved sample was air-dried for the analysis of particle size constitution and chemical properties.

Soil organic carbon (SOC) was measured by the $K_2Cr_2O_7$–H_2SO_4 oxidation method of Walkey and Black (Nelson and Sommers, 1982). Soil inorganic carbon (SIC) was determined by a modified pressure transducer method described by Sherrod et al. (2002). For an individual profile with k layers, the equation of Batjes (1996) was used to calculate the amount of organic carbon in the whole soil profile:

$$\mathrm{SOC}_d = \sum_{i=1}^{k} \mathrm{SOC}_i = \sum_{i=1}^{k} \rho_i \times P_i \times D_i \times (1-S_i) \tag{1}$$

$$\mathrm{SOC}_i = \rho_i \times P_i \times D_i \times (1-S_i). \tag{2}$$

Where k is the number of horizons, SOC_i is soil organic carbon content (Mg m^{-2}), ρ_i is the bulk density (Mg m^{-3}), P_i is the proportion of organic carbon (gC g^{-1}) in layer i, D_i is the thickness of this layer (m), and S_i is the volume fraction of fragments >2 mm.

Similarly, soil inorganic carbon was calculated using Eq. (3) and (4):

$$\mathrm{SIC}_d = \sum_{i=1}^{k} \mathrm{SIC}_i = \sum_{i=1}^{k} \rho_i \times P_i \times D_i \times (1-S_i) \tag{3}$$

$$\mathrm{SIC}_i = \rho_i \times P_i \times D_i \times (1-S_i) \tag{4}$$

Where k is the number of horizons, SIC_i is soil inorganic carbon content (Mg m^{-2}), ρ_i is the bulk density (Mg m^{-3}), P_i is the

Table 2
Soil pH and bulk density of the five studied sites.

Depth (m)	Forest (448 mm MAP)	Grassland (350 mm MAP)	Shrub–grassland (295 mm MAP)	Shrub desert (170 mm MAP)	Desert (102 mm MAP)
pH(H_2O)					
0.0–0.1	5.7(0.1)a	7.7(0.5)b	8.5(0.1)c	8.5(0.3)c	8.7(0.2)c
0.1–0.2	6.1(0.1)a	7.8(0.4)b	8.9(0.1)c	8.9(0.1)c	8.9(0.1)c
0.2–0.4	5.9(0.1)a	7.4(0.2)b	8.8(0.3)c	8.7(0.2)c	8.9(0.2)c
0.4–0.6	6.3(0.1)a	7.7(0.4)b	8.8(0.2)c	8.9(0.1)c	9.1(0.1)c
0.6–0.8	5.8(0.1)a	7.6(0.3)b	8.8(0.2)c	9.3(0.1)d	9.1(0.2)cd
0.8–1.0	6.6(0.1)a	7.5(0.3)b	8.6(0.2)c	9.5(0.2)d	9.2(0.1)d
1.0–1.5	7.2(0.1)a	7.9(0.2)b	8.6(0.2)c	9.3(0.2)d	9.1(0.2)d
1.5–2.0	6.6(0.1)a	7.6(0.5)b	8.7(0.1)c	9.3(0.2)d	9.0(0.3)dc
2.0–2.5	6.9(0.2)a	7.5(0.1)b	8.4(0.2)c	8.9(0.1)d	8.9(0.2)d
2.5–3.0	7.4(0.1)a	7.7(0.2)b	8.5(0.1)c	8.8(0.1)d	9.4(0.1)e
0.0–3.0	6.5(0.6)a	7.6(0.2)b	8.7(0.2)c	9.0(0.3)d	9.0(0.2)d
Bulk density (Mg m^{-3})					
0.0–0.1	0.69(0.16)a	1.14(0.02)b	1.46(0.06)b	1.52(0.03)b	1.66(0.08)c
0.1–0.2	0.74(0.06)a	1.50(0.01)b	1.50(0.04)b	1.53(0.02)b	1.60(0.02)c
0.2–0.4	0.83(0.11)a	1.51(0.02)b	1.55(0.01)b	1.54(0.03)b	1.61(0.02)c
0.4–0.6	0.86(0.05)a	1.52(0.02)b	1.52(0.03)b	1.53(0.05)b	1.54(0.04)b
0.6–0.8	0.87(0.06)a	1.50(0.03)b	1.55(0.04)b	1.53(0.02)b	1.52(0.06)b
0.8–1.0	1.33(0.10)a	1.53(0.02)b	1.56(0.03)b	1.55(0.03)b	1.50(0.06)c
1.0–1.5	1.44(0.05) a	1.54(0.02)b	1.57(0.06)b	1.55(0.04)b	1.50(0.09) a
1.5–2.0	1.48(0.06)a	1.57(0.03)b	1.57(0.03)b	1.55(0.03)b	1.50(0.04)a
2.0–2.5	1.42(0.07)a	1.56(0.03)b	1.54(0.05)b	1.56(0.04)b	1.56(0.11)b
2.5–3.0	1.41(0.10)a	1.53(0.03)b	1.57(0.03)b	1.55(0.06)b	1.53(0.03)b
0.0–3.0	1.11(0.33)a	1.49(0.13)b	1.54(0.04)b	1.54(0.01)b	1.55(0.06)b

$N=3$ samples per site in each landscape type; SD in parentheses; and values with the same lower case letters within rows are not significantly different at $P<0.05$.

proportion of inorganic carbon (gC g^{-1}) in layer i, D_i is the thickness of this layer (m), and S_i is the volume fraction of fragments >2 mm.

2.3. Statistical analyses

All data were analyzed using SPSS software. Multiple comparisons and analyses of variance (ANOVA) were used to determine the significance of differences among sites (Sokal and Rohlf, 1995). We used linear regression to statistically quantify the relationship between soil carbon storage of each layer at each site and the MAP. The purpose of this linear regression analysis was not to find the best fit line since the number of samples is relatively low ($n=5$). Instead, we used linear regression to test whether increased MAP had a positive, negative, or neutral effect on soil carbon storages at each layer of the soil profile. In addition to the analyses of the root biomass already described, we used regressions to evaluate the relationships between soil carbon storage and root distribution in soil profile. The use of linear regression for these analyses meant to provide a common metric to compare among sites and depths.

3. Results

3.1. Soil chemical and physical properties

With the MAP decreased from forest to desert, the pH value of the soils increased significantly (Table 2). pH values of soils in shrub-grassland, shrub desert and desert were significantly higher than in forest and grassland ($P<0.05$). In soils of each landscape type, there was no clear relation between soil depth and pH (Table 2). In forest soil, the pH value ranged from 5.7 to 7.4, indicating that the soils were weakly acidic. In grassland soil it ranged from 7.4 to 7.9, weakly alkaline. In soils of, the shrub–grassland, shrub desert and desert, pH value was higher than 8.4, indicating strong alkalinity. There was no significant difference in the pH value among these three soils at depth above 0.6 m. Below 0.6 m, the differences were significant (Table 2, $P<0.05$).

The bulk density in natural soil is used as an indicator of soil strength and/or mechanical resistance to plant growth, and can thus affect distribution of soil carbon content (Gregorich et al., 1997; Drewry et al., 2008). The bulk density in forest soil was low, values ranged from 0.69 Mg m^{-3} at the surface layer to 1.48 Mg m^{-3} at 1.5–2.0 m depth and then decreased slightly after then. Vertical distribution of the bulk density below grassland, shrub–grassland and shrub desert followed similar trend, but the variation was much less. In desert soil, there is no clear trend in vertical variation. Overall, bulk density was lowest in forest, especially in the upper layer, increased with the decrease in precipitation till the highest in desert soil (Table 2; $P<0.05$).

3.2. Vertical distribution of soil carbon in the profiles

As can be seen in Fig. 1, the SOC content in the 0–3.0 m soil profile was significantly different among landscape types from forest to desert ($P<0.05$). On average, the order of decrease is in accordance with the MAP of each landscape: forest (15.04 g kg^{-1}) > grassland (1.33 g kg^{-1}) > shrub–grassland (0.92 g kg^{-1}) > shrub land desert (0.42 g kg^{-1}) > desert (0.25 g kg^{-1}). There are also significant differences in vertical distribution of SOC: with high concentration in upper layer for the forest, to the nearly even distribution in the profile of desert soil. Statistically speaking (Fig. 1, $P<0.05$), the SOC content of each individual layer was significant among forest, grassland (both grassland and shrub–grassland in the current classification of landscapes), and desert (both shrub desert and desert in the current classification of landscapes). Namely, the SOC differences among landscape types (and thus along precipitation gradient) not only presented in the whole profile (Fig. 1), but also presented significantly in profile distribution and even among each individual layer.

SIC content in the soil profiles of the five landscape types were shown in Fig. 2. It can be seen that the SIC content is also remarkably different along the precipitation gradient from forest to desert ($P<0.05$), but with a trend opposite to SOC: on average over the whole profile, forest (0.16 g kg^{-1}) < grassland (0.25 g kg^{-1}) < shrub–grassland (0.57 g kg^{-1}) < shrub desert (1.86 g kg^{-1}) < desert (2.89 g kg^{-1}). The profile distribution of SIC was much more diverse than that of SOC (Figs. 1 and 2): with the highest content appeared at the upper layer, middle of the profile, or both. SIC content in forest and grassland were smaller than 0.5 g kg^{-1} in the layer with highest content of the profile, but in shrub desert and desert, it was higher than 1 g kg^{-1} in the layer with lowest

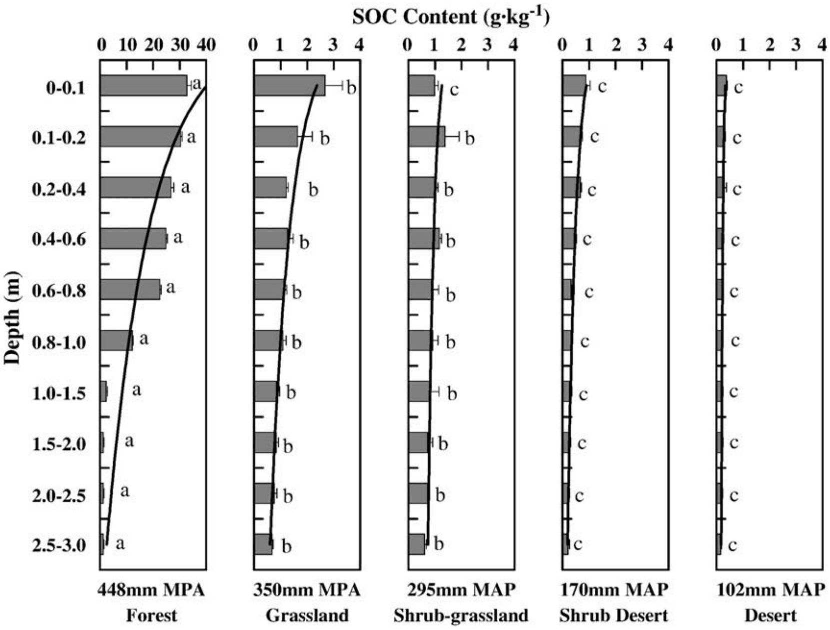

Fig. 1. The vertical distribution of SOC content in the soil profile of different landscapes (the different lower case letters within the same depth of different landscapes indicating significantly different at $P<0.05$).

content in the profile. Due to diversity of profile distribution of SIC, the significance of difference among landscapes was not the same for individual layer: above 1 m, forest and grassland were not statistically different, the others were; at 1–3 m depth, forest, grassland and shrub–grassland were not statistically different, the others were ($P<0.05$).

The relationship between soil organic/inorganic carbon contents at each layer and MAP was analyzed by linear regression to test whether increased MAP had a positive, negative, or neutral effect on soil carbon storages at each layer of soil profiles. SOC content at each layer of the soil profiles positively correlated with MAP, with R^2 increased remarkably with depth (Table 3). Generally speaking, for layers above 1 m, the correlation between SOC content and MAP was not significant at $P=0.05$, but for layers of 1–3 m, the correlation was significant. The relationship between SIC content and MAP was negative at each layer of soil profiles, and for most of the layers the correlation was significant at $P=0.05$, regardless the depth (Table 3). Namely, on layer basis SIC seems better correlated with MAP than SOC, which is surprising as common sense tells that SOC should be better correlated with MAP (via vegetation). Higher spatial variation and higher dynamics of SOC might be part of the reason.

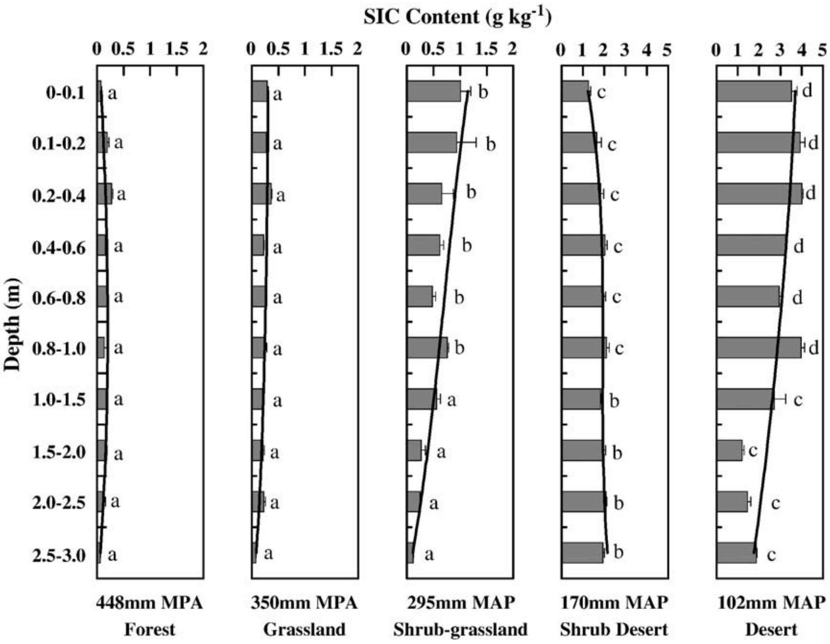

Fig. 2. The vertical distribution of SIC content in the soil profile of different landscapes (the different lower case letters within the same depth of different landscapes indicating significantly different at $P<0.05$).

Table 3
Relationships between SOC/SIC content at each layer and the MAP for the five sites.

	SOC			SIC		
Depth (m)	Regression line equations	R^2	*P*-value	Regression line equations	R^2	*P*-value
0.0–0.1	$Y_{SOC} = 0.0754\ (MAP) - 13.07$	0.549	0.152	$Y_{SIC} = -0.0087\ (MAP) + 3.62$	0.785	0.046
0.1–0.2	$Y_{SOC} = 0.0698\ (MAP) - 12.17$	0.541	0.157	$Y_{SIC} = -0.01\ (MAP) + 4.12$	0.813	0.036
0.2–0.4	$Y_{SOC} = 0.0608\ (MAP) - 10.63$	0.529	0.164	$Y_{SIC} = -0.0102\ (MAP) + 4.21$	0.808	0.038
0.4–0.6	$Y_{SOC} = 0.0571\ (MAP) - 9.98$	0.539	0.158	$Y_{SIC} = -0.0092\ (MAP) + 3.77$	0.894	0.015
0.6–0.8	$Y_{SOC} = 0.052\ (MAP) - 9.15$	0.537	0.159	$Y_{SIC} = -0.0083\ (MAP) + 3.44$	0.885	0.017
0.8–1.0	$Y_{SOC} = 0.028\ (MAP) - 4.73$	0.571	0.140	$Y_{SIC} = -0.0109\ (MAP) + 4.42$	0.871	0.021
1.0–1.5	$Y_{SOC} = 0.005\ (MAP) - 0.58$	0.812	0.037	$Y_{SIC} = -0.0077\ (MAP) + 3.21$	0.898	0.014
1.5–2.0	$Y_{SOC} = 0.003\ (MAP) - 0.09$	0.981	0.001	$Y_{SIC} = -0.0046\ (MAP) + 2.01$	0.658	0.096
2.0–2.5	$Y_{SOC} = 0.003\ (MAP) - 0.14$	0.973	0.002	$Y_{SIC} = -0.0055\ (MAP) + 2.31$	0.723	0.068
2.5–3.0	$Y_{SOC} = 0.003\ (MAP) - 0.20$	0.955	0.004	$Y_{SIC} = -0.0065\ (MAP) + 2.59$	0.819	0.034

3.3. The importance of carbon storage at 1–3 m depth

Fig. 3 shows soil organic and inorganic carbon storages under different landscape types in layers of 0–1 m and 1–3 m. It can be seen that (Fig. 3A) there was large and significant SOC storage below 1 m depth, especially for both grassland and shrub–grass land. There were also large and significant SIC storage at 1–3 m depth in general, especially for shrub desert and desert landscapes (Fig. 3B). To make the proportion at these two depths clear, Fig. 4 gives the percentage of carbon storage at 0–1 m and 1–3 m depths. In landscapes other than forest, overall carbon storage (SOC + SIC) at 1–3 m depth accounted for more than 50% of that for the 0–3 m soil profile (Fig. 4A). For both grassland and shrub–grassland, contribution from 1–3 m mainly in the form of SOC; for both shrub desert and desert, contribution from 1–3 m mainly in the form of SIC. Only for the landscape of forest, the contribution from 1–3 m layer is less than 50% (20% approximately), which is mainly in the form of SOC.

3.4. Root biomass density and its relationship with soil carbon content

Root biomass density at each layer was given in Table 4 for the five landscapes. There were large variations in root biomass density among landscapes (Table 4). For the same layer, the decrease from forest to desert could be two orders of magnitude (Table 4). Due to large spatial variation in root distribution and low replication in our sampling, standard deviation were high for most of the data (Table 4). As a result, statistical test often told that there was no significant difference among some landscapes, although the mean values were rather different (Table 4). The vertical distributions of root biomass were similar among landscapes, with more than 65% of root biomass stocked in 0–60 cm depth. For forest soil and shrub–grassland, this was more than 90%.

In Fig. 5, the root biomass density for each layer from each landscape was plotted against corresponding SOC and SIC of that layer. As expected, there was a strong, positive correlation between root biomass density and SOC (Fig. 5, $P < 0.001$). The relationship between root biomass density and SIC was exponentially negative (Fig. 5, $P < 0.001$), which means that across a precipitation gradient, high precipitation resulted in leaching out of SIC from soils.

4. Discussions

On a precipitation gradient combined with gradient variation in landscapes, SOC and SIC varied in an opposite trend, with the former increase with precipitation and the latter decrease with precipitation (Figs. 1 and 2). The gradient variation in SOC was mainly determined

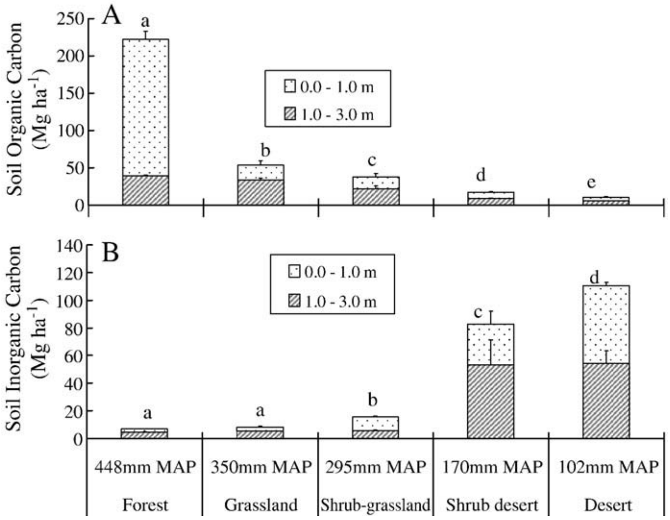

Fig. 3. Soil carbon (SOC/SIC) storage at different depths for the five landscapes.

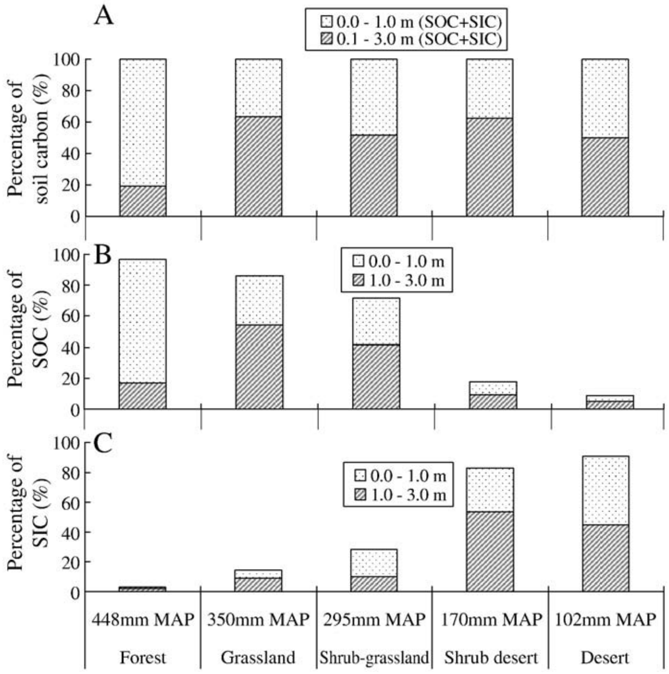

Fig. 4. Percentage of soil carbon at different depths for the five landscapes. Shown in A to C are percentages to SOC + SIC.

Table 4
Root biomass density (g m^{-3}) at different soil layers under different landscape types.

Depth (m)	Forest (448 mm MAP)	Grassland (350 mm MAP)	Shrub–grassland (295 mm MAP)	Shrub desert (170 mm MAP)	Desert (102 mm MAP)
0.0–0.1	2765(1366)a	260(109)b	333(263)b	127(34)b	20(5)b
0.1–0.2	2033(114)a	650(141)b	327(138)c	131(98)d	82(51)d
0.2–0.4	1164(750)a	186(62)b	355(267)b	72(36)b	31(7)b
0.4–0.6	527(63)a	65(19)b	460(152)a	86(14)b	52(43)b
0.6–0.8	327(196)a	43(22)b	408(11)a	34(23)b	25(13)b
0.8–1.0	335(191)a	36(11)b	409(152)a	20(15)b	18(7)b
1.0–2.0	56(21)a	14(5)a	382(253)b	0	2.5(2)a
2.0–3.0	5(2)a	0	0	0	0
0.0–3.0	2421(645)a	423(77)bc	1019(391)b	185(35)c	77(20)c

Values are means ± SD. Values with the same lower case letters within rows are not significantly different at $P<0.05$.

by the biological activities of vegetation, which concentrated at upper layer (Fig. 1, Charley and West 1977; Schlesinger and Adrienne, 1998); while SIC was determined by leaching, which created a complicated profile distribution (Fig. 2, Schlesinger and Adrienne, 1998; Nordt et al., 2000; Díaz-hernández and Fernández, 2008). The character of vertical distribution in SOC and SIC in the 0–3 m profile further proved this: SOC was always higher at upper layers (Fig. 1), and SIC was not necessarily following the same trend (See Fig. 2, shrub–grassland vs. shrub desert). Lack of data on soil C distribution in the profile at different landscapes has been identified as one of the major knowledge gaps in soil science (Lal et al., 1998). Our results partially filled this gap and should help to improve global predictions of soil carbon storage.

Most previous studies on soil carbon storage have been focused on upper layer, especially the top 1.0 m, although deeper profile was known to be important in soil carbon storage (Nepstad et al., 1994; Batjes, 1996; Jobbágy and Jackson, 2000; Veldkamp et al., 2003; Mi et al., 2008). Our study indicated that there is large soil carbon storage below 1.0 m, whether it is mainly SOC in grassland landscapes or mainly SIC in desert landscapes (Fig. 3). Namely, in landscapes other than forest, more than 50% soil carbon storage was in 1–3 m depth (Fig. 4). Jobbágy and Jackson (2000) estimated SOC storage at 1–3 m to full soil profile was about 39% in temperate grassland, 39% in scerophyllous shrub land, and 46% in desert. These values were smaller than the values we measured (Fig. 4, 63% in grassland, 52% in shrub–grassland, and 50% in desert). Li et al. (2007) gave 45% soil carbon storage at 1–3 m to full soil profile in Chernozems and 61% in desert soil, which were higher than our values (about 20% in forest Chernozems and about 50% in desert soil). The discrepancy of these data set suggested that further direct measurement like ours are desired. In addition, our data showed that SIC could be as important as SOC storage at continental scale, especially now when more and more evidence showed that SIC might be as dynamic as SOC (Jordan et al., 1999; Stone, 2008; Wohlfahrt et al., 2008; Xie et al., 2009).

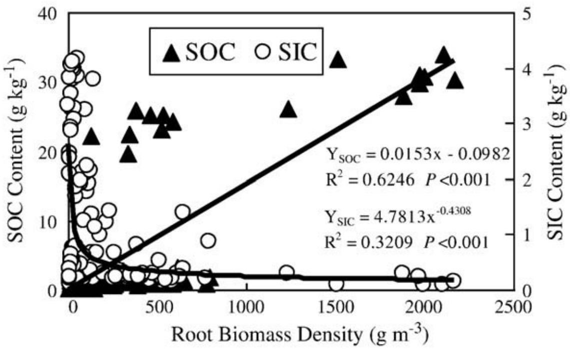

Fig. 5. Relationship between soil organic/inorganic carbon content and root biomass density.

The spatial variation of root biomass density was obvious across landscapes and depths (Table 4), and the linear relationship between root density and SOC was also significant (Fig. 5). However, Fig. 5 also shows that this linear relationship is not tight (namely, data are scattered). Looking further into Table 4, one can found that, in grassland and shrub–grassland, for instance, most of the roots were distributed in the upper 1.0 m (Table 4), but around half of the SOC has been stored at 1–3 m (Fig. 4). This may be easily explained by downward migrating of organic carbon in the soil profile by leaching (Dosskey and Bertsch, 1997) and microbial activities. Namely, profile distribution of SOC was not only determined by root distribution (Schenk and Jackson, 2002), which was in itself a character determined by vegetation/landscape type (Jackson et al., 2000; Jobbágy and Jackson, 2000), but also by precipitation, which was the driving force of leaching. Hence, the effect of precipitation on SOC is two folded: on one hand, precipitation shapes vegetation/landscape types that in turn determined the root distribution; on the other hand, it directly shapes the profile distribution of SOC by leaching. In fact, this two-fold effect was also true to SIC: Plant and microbial activity could significantly improve water infiltration that would in turn favor the SIC leaching and precipitation of secondary carbonate (Lal, 2004). Of course, very high precipitation combined with strong biological activity could lead to bicarbonate leaching out almost completely. These explain the exponentially negative relationship between root biomass density and SIC.

5. Concluding remarks

The direct comparison of soil C storage between top 0–1 m and 1–3 m showed that the using top 1 m soil profile to estimate soil carbon storages would considerably underestimate soil carbon storage. This is especially true for SOC at temperate grassland and shrub–grassland, for SIC of temperate shrub desert and desert. This kind of underestimation is the least in temperate forest. Namely, the depth distribution is landscape/vegetation specific. This kind of information is crucial when effort is made to assess current regional, continental and global soil C storage and to optimize strategies of mitigating the accumulation of CO_2 in the atmosphere.

Acknowledgements

We thank all staff at Fukang Station of Desert Ecology and Erdos Station of Grassland Ecology for help with site selection and laboratory assistance. This research was founded by one of the National Basic Research Programs of China (2009CB825102) and CAS Knowledge Innovation Project (KZCX2-YW-431).

References

Bai YF, Wu JG, Xing Q, Pan QM, Huang JH, Yang DL, Han XG. Primary production and rain use efficiency across a precipitation gradient on the Mongolia plateau. Ecology 2008;89:2140–53.

Batjes NH. Total carbon and nitrogen in the soils of the world. Eur J Soil Sci 1996;47: 151–63.

Charley JL, West NE. Micro-patterns of nitrogen mineralization activity in soils of some shrub-dominated semi-desert ecosystems of Utah. Soil Biol Biochem 1977;9:357–65.

Cheng JW, Zhang YX. Discussion on relation between humidity index and aridity degree. J Desert Res 1996;16:79–82.

Dawson JJC, Smith P. Carbon losses from soil and its consequences for land-use management. Sci Total Environ 2007;382:165–90.

Díaz-hernández JL, Fernández EB. The effect of petrocalcic horizons on the content and distribution of organic carbon in a Mediterranean semiarid landscape. Catena 2008;74: 80–6.

Díaz-hernández JL, Fernández EB, González JL. Organic and inorganic carbon in soils pf semiarid regions: a case study from the Guadix–Baza basin (southeast Spain). Geoderma 2003;114:65–80.

Dosskey MG, Bertsch PM. Transport of dissolved organic matter through a sandy forest soil. Soil Sci Soc Amer J 1997;61:920–7.

Drewry JJ, Cameron KC, Buchan GD. Pasture yield and soil physical property responses to soil compaction from treading and grazing — a review. Aust J Soil Res 2008;46: 237–56.

Eswaran H, Reich PF, Kimble JM, Beinroth FH, Padmanabhan E, Moncharoen P. Global carbon stocks. In: Lal R, Kimble JM, Eswaran H, Stewart BA, editors. Global climate change and pedogenic carbonates. Boca Raton, FL: Lewis; 2000. p. 15–25.

Feng Q, Endo KN, Cheng GD. Soil carbon in desertified land in relation to site characteristics. Geoderma 2002;106:21–43.

Gillabel J, Denef K, Brenner J, Merckx R, Paustian K. Carbon sequestration and soil aggregation in center-pivot irrigated and dryland cultivated farming systems. Soil Sci Soc Am J 2007;71:1020–8.

Gregorich DJ, Carter MR, Doran JW, Pankhurst CE, Dwyer LM. Biological attributes of soil quality. In: Gregorich EG, Carter MR, editors. Soil quality for crop production and ecosystem health. Developments in soil scienceNew York, NY: Elsevier; 1997. p. 81-144.

Grossman RB, Ahrens RJ, Gile LH, Montoya CE, Chadwick OA, (1995) Areal evaluation of carbonate carbon in a desert area of southern New Mexico. In: lal R, Kimble J, Levine E, Stewart BA, editors. Soils and global change. CRC/Lewis Publisher, Boca, FL: Lewis Publishers; 1995. p. 81-91.

Halvorson AD, Wienhold BJ, Black AL. Tillage, nitrogen, and cropping system effects on soil carbon sequestration. Soil Sci Soc Amer J 2002;66:906–12.

He NP, Yu Q, Wu L, Wang YS, Han XG. Carbon and nitrogen store and storage potential as affected by land-use in a *Leymus chinensis* grassland of northern China. Soil Biol Biochem 2008;40:2952–9.

Houghton RA, Hackler JL, Lawrence KT. The U.S. carbon budget: contributions from land-use change. Science 1999;285:574–8.

Jackson RB, Schenk HJ, Jobbágy EG, Canadell J, Colello D, Dickinson RE, Field CB, Friedlingstein P, HEIMANN M, Hibbard K, Kicklighter DW, Kleidon A, Neilson RP, Parton WJ, Sala OE, Sykes MT. Belowground consequences of vegetation change and their treatment in models. Ecol Appl 2000;10:470–83.

Jobbágy EG, Jackson RB. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol Appl 2000;10:423–36.

Jordan DN, Zitzer SF, Hendrey GR, Lewin KF, Nagy J, Nowak R, Smith SD, Coleman JS, Seemann JR. Biotic, abiotic and performance aspects of the Nevada Desert Free-Air CO_2 Enrichment (FACE) Facility. Glob Chang Biol 1999;5:659–68.

Lal R. Soil carbon sequestration impacts on global climate change and food security. Science 2004;304:1623–7.

Lal R, Kimble JM, Follett RF, Cole CV. The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. Chelsea, MI: Ann Arbor Press; 1998. p. 128.

Li ZP, Han FX, Su Y, Zhang TL, Sun B, Monts DL, Plodinec MJ. Assessment of soil organic and carbonate carbon storage in China. Geoderma 2007;138:119–26.

Mi N, Wang SQ, Liu JY, Yu GR, Zhang WJ, Jobbágy E. Soil inorganic carbon storage pattern in China. Global Change Biology 2008;14:2380–7.

Nelson DW, Sommers LE. Total carbon, organic carbon, and organic matter. In: Page AL, Miller RH, Keeney DR, editors. Methods of soil analysis, agronomy, part 2. 2nd edition. Madison, WI: ASA and SSSA; 1982. p. 539–77.

Nepstad DC, de Carvalho CR, Davidson EA, Jipp PH, Lefebvre PA, Negreiros GH, da Silva ED, Stone TA, Trumbore SE, Vieira S. The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. Nature 1994;372:666–9.

Ni J. Carbon storage in terrestrial ecosystems of China: estimate at different spatial resolutions and their response to climate change. Climate Change 2001;49:339–58.

Nieder R, Benbi DK. Carbon and nitrogen in the terrestrial environment. Springer Science+Business Media B.V; 2008. p. 137.

Nordt LC, Wilding LP, Drees LR. Pedogenic carbonate transformations in leaching soil system: implications for the global C cycle. In: Lal R, Kimble JM, Eswaran H, Stewart BA, editors. Global climate change and pedogenic carbonates. Boca Raton, USA: CRC Press; 2000. p. 43–64.

Post WF, Emanuel WR, Zinke PJ, Stangenberger AG. Soil carbon pools and world life zones. Nature 1982;298:156–9.

Powlson D. Will soil amplify climate change? Nature 2005;433:204–5.

Schenk HJ, Jackson RB. Rooting depths, lateral root spreads, and belowground/aboveground allometries of plants in water-limited environments. J Ecol 2002;90:480–94.

Schlesinger WH. Carbon storage in the Caliche of arid soils: a case study from Arizona. Soil Sci 1982;133:247–55.

Schlesinger WH. Biogeochemistry: an analysis of global change. San Diego, California, USA: Academic Press; 1997. p. 588.

Schlesinger WH. Inorganic carbon and the global carbon cycle. In: Lal R, editor. Encyclopedia of soil science. New York: Marcel Dekker; 2002. p. 706–8.

Schlesinger WH, Adrienne MP. Plant–soil interaction in deserts. Biogeochemistry 1998;42:169–87.

Schulze DE, Freibauer A. Carbon unlocked from soil. Nature 2005;437:205–6.

Sherrod LA, Dun G, Peterson GA, Kolberg RL. Inorganic carbon analysis by modified pressure-calcimeter method. Soil Sci Soc Amer J 2002;66:299–305.

Shrestha RK, Lal R. Ecosystem carbon budgeting and soil carbon sequestration in reclaimed mine soil. Environ Int 2006;32:781–96.

Singh SK, Singh AK, Sharma BK, Tarafdar JC. Carbon stock and organic carbon dynamics in soils of Rajasthan, India. J Arid Environ 2007;68:408–21.

Sokal RR, Rohlf FJ. Biometry: the principles and practice of statistics in biological research. 3rd edition. New York: W.H. Freeman; 1995.

Sombroek WG, Nachtergaeke FO, Hebel A. Amounts, dynamics and sequestrations of carbon in tropical and subtropical soils. AMBIO 1993;22:417–26.

Stone R. Have desert researchers discovered a hidden loop in the carbon cycle? Science 2008;320:1409–50.

Tiessen H, Cuevas E, Chacon P. The role of soil organic matter in sustaining soil fertility. Nature 1994;371:783–5.

Trumbore SE. Potential responses of soil organic carbon to global environmental change. Proc Natl Acad Sci 1997;94:8284–91.

Veldkamp E, Becker A, Schwendenmann L, Clark A, Schulte-Bisping H. Substantial labile carbon stocks and microbial activity in deeply weathered soils below a tropical wet forest. Global Change Biology 2003;9:1171–84.

Wang SQ, Zhou CH, Li KR, Zhou SL, Huang FH. Estimation of soil organic carbon reservoir in China. J Geogr Sci 2001;11:3-13.

Wohlfahrt G, Fenstermaker LF, Arnone JA. Large annual net ecosystem CO_2 uptake of a Mojave desert ecosystem. Global Change Biology 2008;14:1475–87.

Wu H, Guo Z, Peng C. Distribution and storage of soil organic carbon in China. Global Biogeochem Cycles 2003;17:1048.

Xie JX, Li Y, Zhai CX, Li CH, Lan ZD. CO_2 absorption by alkaline soils and its implication to the global carbon cycle. Environ Geol 2009;56:953–61.

Yoo K, Amundson R, Heimsath AM, Dietrich WE. Spatial patterns of soil organic carbon on hill slopes: integrating geomorphic processes and the biological C cycle. Geoderma 2006;130:47–65.

Zhou G, Wang Y, Wang S. Responses of grassland ecosystems to precipitation and land use along the northeast China transect. J Veg Sci 2002;13:361–8.