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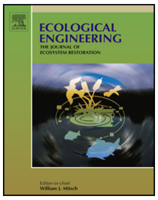

Soil organic carbon in deep profiles under Chinese continental monsoon climate and its relations with land uses

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ABSTRACT

We collected soil samples from depths between 0 and 12–21 m at 33 sites across the Chinese Loess Plateau in order to determine the vertical distributions and storage of soil organic carbon (SOC), as well as to test the hypothesis that SOC in deep soils (below 5 m) is greater under forest than under permanent cropland. The overall distributions of SOC within a profile were divided into three sub-layers: 0–2, 2–14, and 14–21 m, with significantly different ($P < 0.01$) mean SOC values of 3.28 ± 2.39, 2.07 ± 0.79, and $1.56 \pm 0.57\ \mathrm{g\,kg^{-1}}$, respectively. In the deep soil layer (5–21 m), SOC storage was significantly higher ($P < 0.01$) under forest ($47 \pm 0.43\ \mathrm{kg\,m^{-2}}$) than under cropland ($38 \pm 0.44\ \mathrm{kg\,m^{-2}}$). Within the rooting zone, the factors affecting SOC variation were root length, pH and clay content; below the rooting zone, the factors were soil water content, pH and clay content. Land use and rooting characteristics significantly affected the magnitude and vertical distribution of SOC within both shallow and deep layers. Therefore, changes in land use can alter SOC storage in deep soils, which can have important consequences for global climate change.

1. Introduction

Soil organic carbon (SOC) stored in deep soil layers plays an important role in the global carbon (C) cycle by altering biogeochemical processes via plant root systems. Many studies have examined the magnitude and/or distribution of SOC for a variety of ecosystem types at local (Huo et al., 2013; Jimenez et al., 2008), regional (Liu et al., 2011, 2014a), and global scales (Lal, 2004; Van Minnen et al., 2009). However, most of these inventory studies have generally limited the measurements of SOC to the upper 1-m soil layer, either in whole or in part. For a given study area or land use type, the magnitude of SOC storage greatly depends on the depth sampled (Harrison et al., 2011; Jobbágy and Jackson, 2000).

Some research, related to paleoenvironmental reconstruction, has been carried out on the vertical distribution of SOC (Gocke et al., 2011; Liu et al., 2007). However, only a few studies focused on SOC storage and C cycling below a soil depth of 1 m. For example, Sommer et al. (2000) investigated the distribution of SOC to depths of 6 m, Davidson et al. (2011) to depths of 11 m, and Harper and Tibbett (2013) to depths of 38 m. Jobbágy and Jackson (2000) reported that the global SOC budget, based on the 0–1 m soil layer, increased by 33% and by a further 23% when the 1–2 m and 2–3 m soil layers, respectively, were taken into consideration. These studies provided important information on the distributions of deep SOC that is defined in this paper as those within soil profiles deeper than 5 m. Therefore, SOC storage may have been greatly underestimated because most previous investigations did not actually measure SOC in deep soil layers (Díaz-Hernández, 2010; Jobbágy and Jackson, 2000; Sommer et al., 2000). Moreover, the factors that contribute to differences in SOC in deeper soil layers are not well understood.

Land use is one of the important factors influencing the vertical distribution of SOC (Rumpel and Kögel-Knabner, 2011; Sommer et al., 2000), and is associated with contrasting plant functional types that are related to root systems (Jackson et al., 1996; Lu et al., 2012; Wang et al., 2014). Where plants with deep roots are present, organic C can

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be added to the soil within the deep vadose zone via the C in the roots, root exudates, and their associated biota (Díaz-Hernández, 2010; Dou et al., 2013; Harper and Tibbett, 2013). Therefore, the relatively deeper root systems of certain plants may lead to soil C profiles that extend to greater depths than those under plants with shallower root systems (Jobbágy and Jackson, 2000). Hence, Kell (2012) proposed breeding plants that would develop rooting systems to greater depths and have more desirable belowground C sequestration traits that would increase soil C storage.

Certain regions around the world are covered by deep soils (i.e., >5 m), e.g., the Chinese Loess Plateau (CLP), Brazilian Amazonia, and the Mississippi floodplains. In these soils, deep roots likely play an important role in determining the magnitude and vertical distribution of SOC. Rasse et al. (2005) showed that the incorporation of C into the soil was much greater due to plant roots than due to aboveground litter. Davidson et al. (2011) reported that, although root inputs of organic C to deep soils (0–11 m) were small with respect to the C dynamics of the aboveground vegetation (forest), the deep rooting behavior clearly affected the soil C profiles. Therefore, the contribution of root inputs to organic C can greatly influence both the total amount and vertical distribution of SOC over a long timescale (Oelbermann and Voroney, 2007; Rumpel and Kögel-Knabner, 2011). To our knowledge, information on the vertical distribution of SOC to a depth of about 21 m, to which the roots of some perennial plants can extend, is generally scarce for both the CLP and other regions around the world that have deep soils.

In this study, we used field measurements to examine the magnitude and vertical distribution of SOC as well as the factors that affect them on the CLP. The specific objectives of this study were: (1) to investigate the vertical distributions of SOC and its storage to a depth of 21 m; (2) to test our hypothesis that the amount of deep SOC under forest is greater than under permanent cropland; and (3) to determine the main factors affecting SOC within the 0–21 m soil profile and to then discuss the management of deep SOC.

2. Materials and methods

The study was conducted on the CLP that is mostly covered by loess–paleosol sequences ranging from 30 to 80 m in thickness. The CLP has a continental monsoon climate and its main geomorphic landforms are large flat surfaces with little or no erosion, ridges, hills, and extensive steep gullies that are severely eroded (Wang et al., 2013b). More details of the study area were described in Chen et al. (2007) and Liu et al. (2011). We selected 33 representative sites for soil sample collection from typical land uses including cropland, grassland and forest across the CLP. Table 1 presents the plant species, climate, and topography of the sites on the CLP.

At each site, soil samples were collected from the 0–21 m profile at multiple depth intervals using a soil auger (10 cm in diameter), which was extended by adding 1.5-m inter-locking sections as the sampling depth was increased. The combined length of all of the connected sections was 23 m, which facilitated the collection of

Table 1
Site description of the 33 sampling sites across the Chinese Loess Plateau.

Location	No.	Land use	Vegetation type	Slope position	Plant age (yr)	Elevation (m)	RD (m)	SD (m)	*T* (°C)	*P* (mm)	Sampling date
Shenmu	1	Grassland	*Stipa bungeana*	Slope top	>20	1260	1	21	8.4	437	2011-5-31
	2	Forest	*Chinese pine*	Slope top	>30	1245	0.8	14	8.4	437	2011-6-2
	3	Grassland	*Medicago sativa*	Slope top	>25	1229	8	21	8.4	437	2011-6-3
	4	Cropland	*Glycine max*	Slope top	>20	1220	0.8	21	8.4	437	2011-6-7
	5	Forest	*Prunus armeniaca*	Shady slope	>15	1227	2.8	12	8.4	437	2011-6-10
	6	Forest	*Caragana korshinskii*	Slope top	>30	1205	7	21	8.4	437	2011-6-12
	7	Forest	*Prunus armeniaca*	Sunny slope	>15	1231	3.8	12	8.4	437	2011-6-14
	8	Forest	*C. korshinskii*	Slope top	>30	1257	13	21	8.4	437	2009-7-17
Ansai	9	Forest	*Robinia pseudoacacia*	Shady slope	>6	1357	2.8	18	8.8	549	2011-6-29
	10	Forest	*R. pseudoacacia*	Slope top	>6	1376	3.8	18	8.8	549	2011-6-30
	11	Forest	*R. pseudoacacia*	Sunny slope	>6	1375	17.5	18	8.8	549	2011-7-1
	12	Forest	*R. pseudoacacia*	Sunny slope	>6	1348	8	18	8.8	549	2011-7-6
	13	Forest	*R. pseudoacacia*	Shady slope	>6	1357	5	18	8.8	549	2011-7-7
	14	Forest	*C. korshinskii*	Sunny slope	>30	1310	18	18	8.8	549	2011-7-8
	15	Forest	*C. korshinskii*	Shady slope	>30	1303	16	18	8.8	549	2011-7-9
	16	Cropland	*Zea mays*	Slope top	>30	1361	2.8	18	8.8	549	2011-7-11
	17	Cropland	*Zea mays*	Slope top	>30	1352	1.4	18	8.8	549	2011-7-11
Changwu	18	Cropland	*Triticum* spp	Slope top	>30	1225	1.6	18	9.1	560	2011-8-9
	19	Forest	*Malus domestica*	Slope top	>5	1226	5.8	18	9.1	560	2011-8-10
	20	Forest	*Malus domestica*	Slope top	>9	1224	8.5	18	9.1	560	2011-8-11
	21	Forest	*Malus domestica*	Slope top	>17	1228	15.5	18	9.1	560	2011-8-17
	22	Forest	*Malus domestica*	Slope top	>22	1219	17	18	9.1	560	2011-8-15
	23	Forest	*Malus domestica*	Slope top	>26	1256	18	18	9.1	560	2011-8-13
	24	Forest	*Malus domestica*	Slope top	>25	1225	18	21	9.1	560	2009-12-1
Guyuan	25	Cropland	*Fagopyrum esculentum*	Upslope	>30	1652	1.2	18	6.5	433	2011-8-27
	26	Grassland	*Stipa bungeana*	Topslope	>30	2127	2.2	18	6.5	433	2011-8-26
	27	Forest	*C. korshinskii*	Topslope	>30	1660	18	18	6.5	433	2011-8-23
	28	Forest	*C. korshinskii, S. bungeana*	Upslope	>30	1874	5.6	18	6.5	433	2011-8-24
	29	Forest	*C. korshinskii, M. sativa*	Upslope	>20	1622	15.5	18	6.5	433	2011-8-21
	30	Forest	*C. korshinskii*, Apricot	Upslope	>20	1695	6	18	6.5	433	2011-8-22
	31	Cropland	*Fagopyrum esculentum*	Upslope	>30	1656	1	18	6.5	433	2011-8-28
Wuqi	32	Forest	*R. pseudoacacia*	Slope top	>9	1519	14	21	7.8	483	2009-7-25
Suide	33	Cropland	Soybean	Slope top	>30	1051	1.5	21	8.7	486	2009-7-13

Note: RD, root depth (m); SD, sampling depth (m); *T*, annual mean temperature; *P*, annual mean rainfall.

samples to a depth of 21 m. Soil samples, at each site, were collected at 0.1 m, 0.2 m, and 0.5 m intervals for the 0–0.2–m, 0.2–6 m, and 6–21 m layers, respectively. The maximum depth to which fresh roots of plants extended was recorded during the collection of the soil samples; this depth was deemed to represent the root zone. Root samples were also collected from the same depths as the soil samples within the root zone. In total, 1839 soil samples and 691 plant root samples were collected.

Gravimetric soil water content (SWC) was determined from the loss in mass of a soil sample during oven drying at 105 °C to constant mass. Soil texture was measured by laser diffraction using a Mastersizer2000 (Malvern Instruments, Malvern, England). Soil pH (1:5 H_2O) was measured by a pH meter with a glass electrode. The SOC was determined using dichromate oxidation. Fresh root mass was determined by weighing. The roots were scanned on an Epson flatbed scanner, and root length, root surface area density, and mean diameter were determined by the WinRHIZO 2009® system (Regent Instruments Inc., Montreal, Canada).

Mass fractions of SOC, which were determined for the individual soil samples, were then converted into total amounts that would be contained in a soil column of unit area by using the soil layer thickness and bulk density (BD) data, which was calculated from a pedotransfer function (PTF) (Wang et al., 2013b). We used the measured datasets at two sites with sampling depths of 5.2 and 5.1 m, respectively, to evaluate the accuracy of the PTF. The coefficient of determination (R^2), the root mean square error (RMSE), and the mean residual (MR) were 0.5940, 0.1455, and −0.1062, respectively, indicating that the PTF, to some extent, was acceptable for BD prediction for deep soils. Actually, to the best of our knowledge, there is no established equation that can be used to predict the BD in the deep soil layers on the CLP. Furthermore, equations developed for areas outside of the CLP exhibited poorer performances than the PTF used in this study.

3. Results

The vertical SOC distribution varied among the 33 soil profiles (Fig. 1a). The mean SOC within the entire 21-m depth was $2.23 \pm 0.94\,\mathrm{g\,kg^{-1}}$ ($n = 1839$) with a coefficient of variation of 76%. Three sub-layers exhibiting distinct characteristics were identified. In the first sub-layer (0–2 m), the mean SOC values decreased rapidly with increasing soil depth, from $6.21 \pm 4.72\,\mathrm{g\,kg^{-1}}$ in the surface layer (0–10 cm) to $1.99 \pm 0.27\,\mathrm{g\,kg^{-1}}$ at 2 m. The SOC value at 2 m and the mean value of the 0–2 m sub-layer ($3.28 \pm 2.39\,\mathrm{g\,kg^{-1}}$) were 32% and 53%, respectively, of the SOC value of the 0–1 m layer. In the second sub-layer (2–14 m), SOC values that were generally stable with only slight fluctuations around a mean value for the sub-layer of $2.07 \pm 0.79\,\mathrm{g\,kg^{-1}}$. In the third sub-layer (14–21 m), a slight decline in SOC values was clearly observed and these varied around the mean value for the sub-layer ($1.56 \pm 0.57\,\mathrm{g\,kg^{-1}}$) that was only slightly lower than that of the second sub-layer. An ANOVA indicated that the mean SOC values differed significantly among the three sub-layers ($P < 0.01$).

Cropland and forest had similar SOC distribution patterns (Fig. 1b), but the SOC values differed between these two land uses (we did not consider grassland here because of the limited number

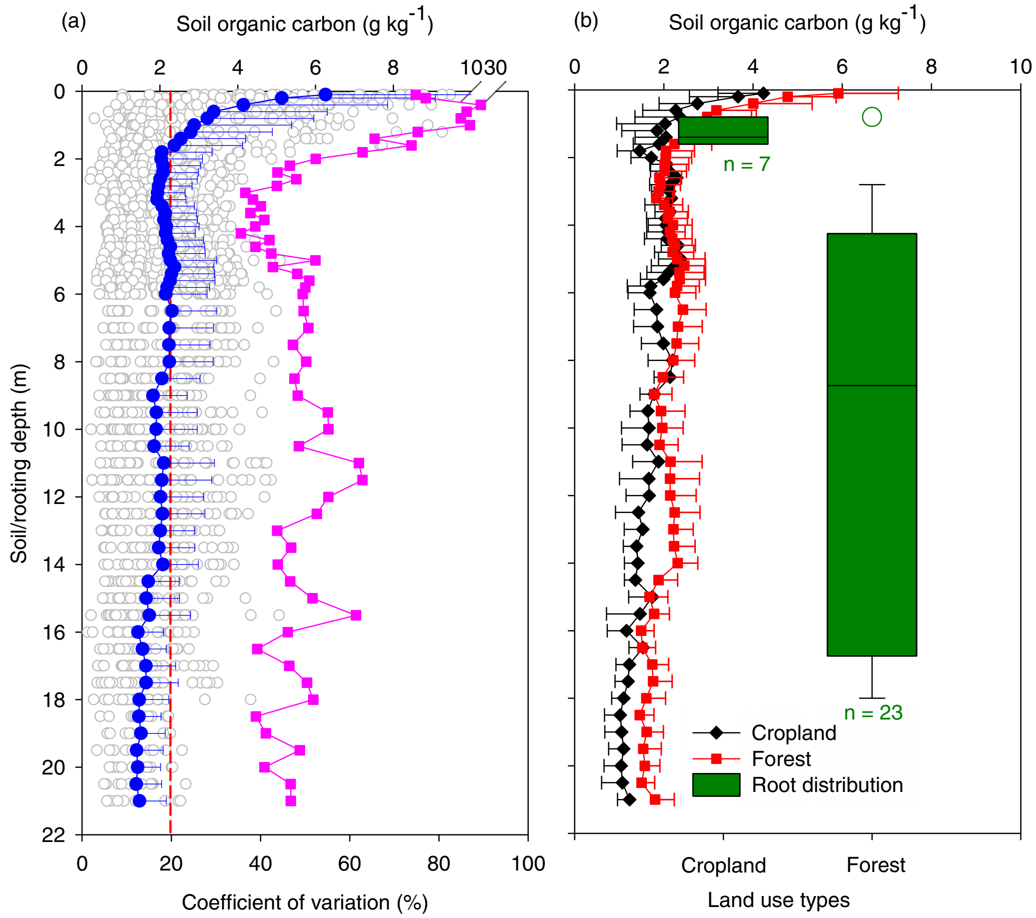

Fig. 1. Vertical distributions of (a) soil organic carbon (SOC) content data (open gray circles) and means (closed blue circles), and the coefficient of variation for SOC (magenta squares); (b) mean values of SOC content under cropland (black diamonds; $N = 7$) and forest (red squares; $N = 23$) and the rooting depth (green box plots) for different land use types in 33 soil profiles on the Loess Plateau. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of sampling sites, $n = 3$). Within the 0–2 m sub-layer, the SOC value was much greater under forest ($3.19 \pm 1.73\ \mathrm{g\,kg^{-1}}$, $n = 253$) than under cropland ($2.39 \pm 2.45\ \mathrm{g\,kg^{-1}}$, $n = 77$). The differences between the SOC values in the 2–14 m and 14–21 m sub-layers were smaller than that for the 0–2 m sub-layer; however, within both sub-layers SOC values were significantly ($P < 0.01$) greater under forest than under cropland (Fig. 1b).

To determine the contribution of plant roots to SOC, we analyzed the mean SOC values within and below the rooting zones. Within the rooting zone, the mean SOC value was higher under cropland ($2.99 \pm 1.23\ \mathrm{g\,kg^{-1}}$, $n = 43$) than under forest ($2.67 \pm 0.98\ \mathrm{g\,kg^{-1}}$, $n = 604$); while, below the rooting zone, the mean SOC values under both land use types were about $1.86 \pm 0.70\ \mathrm{g\,kg^{-1}}$ and were not significantly different.

Correlation analysis (Table 2) showed that, within the rooting zone, SOC was significantly correlated with SWC, soil texture, pH, and the root indices for forest and for mixed land uses. For cropland, correlations between SOC and either SWC or plant indices were not significant. Below the rooting zone, correlations between SOC and either SWC, soil texture, or pH were still significant under all of the land use types, with the exception of the correlation between SOC and pH under cropland. The correlations between SOC and either SWC or soil texture were generally stronger below the rooting zone than within it, while that between SOC and pH was weaker.

Stepwise multiple linear regression analysis further indicated that the factors influencing SOC differed between cropland and forest. Within the rooting zone, total root length, pH, and clay content had a major influence; while below the rooting zone, SWC, pH and clay were the more important factors.

The profile distribution of SOC storage (Fig. 2a) was similar to the pattern of SOC content (Fig. 1a). The greatest SOC storage ($5.34 \pm 2.13\ \mathrm{kg\,m^{-2}}$) occurred in the upper 1-m soil layer, while the layer (1–2 m) immediately underlying it stored only about 62% ($3.29 \pm 0.40\ \mathrm{kg\,m^{-2}}$) of that amount. Within the two soil sub-layers (2–14 m and 14–21 m), the mean SOC storage in a 1-m thick soil layer was $3.12 \pm 0.44\ \mathrm{kg\,m^{-2}}$ and $2.33 \pm 0.39\ \mathrm{kg\,m^{-2}}$, which was equivalent to about 58% and 44% of the C stored in the upper 1-m layer, respectively.

Although the upper 1-m soil layer stored the greatest amount of SOC per unit depth, this amount only accounted for a small proportion (9%) of the total C in the entire profile. The contribution of other sub-layers ranged from 3% to 5% (Fig. 2b). In the deep soil layers (5–21 m), SOC storage under forest ($47 \pm 0.43\ \mathrm{kg\,m^{-2}}$) was significantly ($P < 0.01$) greater than under cropland ($38 \pm 0.47\ \mathrm{kg\,m^{-2}}$), which confirmed our hypothesis that the deep SOC stored under forest would be greater than that under cropland.

4. Discussion

The SOC exhibited high variability within the 0–21 m profile, which may be related to differences in vegetation types, root distributions and land management practices (Davidson et al., 2011; Sommer et al., 2000). The pattern of variation pattern could be affected by water, soil and air availability in the soil (Gao et al., 2014; Wang et al., 2013a; Zhang et al., 2015). Rumpel and Kögel-Knabner (2011) identified three main processes involved in SOC incorporation into deep soil layers that were probably responsible for heterogeneous SOC distributions: (1) preferential flow of dissolved organic C down the soil profile; (2) plant rooting behavior such as root exudations and root overprint; and (3) SOC transport by bioturbation.

Sequence of loess–paleosol layers located in the profile might also have contributed to depth-dependent variations in SOC. Gocke et al., (2014) reported that plants can extend roots to as deep as 9 m in European loess–paleosol sequences; they showed that there was an association of roots with the paleosols and deduced that this was because the plants can use plant available nutrients and pre-existing pore systems that were more abundant in these layers than in the loess layers. Thus, the combined effects of paleosol distributions and root growth played important roles in determining the magnitudes and variations of the SOC content.

The SOC profile in the soils examined in our study may also be affected by increases in the proportion of more stable SOC fractions in deeper soil layers. This is more pertinent to the CLP where buried soils or paleosols occur (Zhao et al., 2012) that may contain ancient and relatively more stable forms of SOC. Moreover, deeper soil layers may impede the translocation of organic C since their porosity is often lower due to higher bulk densities resulting from compaction by overlying layers and possibly increased clay contents due to eluviation (Wu et al., 2011).

Stronger correlations between SOC and either SWC or soil texture for depths below the rooting zone than within the rooting zone implied that the contribution of soil texture and water availability to variations in SOC increased with increasing soil depth. The corresponding weaker correlation between SOC and pH may be explained by the absence of roots and associated micro-organisms as well as by other factors that affect soil pH such as $CaCO_3$ contents. Jobbágy and Jackson (2000) reported that the relative distribution of SOC in deep soils was most significantly affected by vegetation, which was also identified as a one of the main factors affecting SOC in deeper layers for podzols (Grand and Lavkulich, 2011), and this was partially verified by our results.

Table 2
Pearson correlations between soil organic carbon (SOC) and soil or root properties for different sub-layers on the Loess Plateau.

Variables	Cropland ($N = 7$)		Grassland ($N = 3$)		Forest ($N = 23$)		Mixed ($N = 33$)[a]	
	RZ ($n = 43$)	BTR ($n = 293$)	RZ ($n = 44$)	BTR ($n = 133$)	RZ ($n = 604$)	BTR ($n = 472$)	RZ ($n = 691$)	BTR ($n = 898$)
SWC	0.067	0.649[c]	0.622[c]	0.429[c]	0.425[c]	0.629[c]	0.317[c]	0.569[c]
Clay	0.459[c]	0.613[c]	−0.012	0.011	0.454[c]	0.622[c]	0.193[c]	0.494[c]
Silt	0.061	0.469[c]	0.476[c]	0.694[c]	−0.002	0.459[c]	0.137[c]	0.512[c]
Sand	−0.398[c]	−0.564[c]	−0.398[c]	−0.598[c]	−0.379[c]	−0.569[c]	−0.212[c]	−0.558[c]
pH	−0.519[c]	0.087	−0.703[c]	−0.449[c]	−0.528[c]	−0.131[c]	−0.528[c]	−0.074[b]
RM	0.005		0.751[c]		0.118[c]		0.232[c]	
RL	0.123		0.906[c]		0.305[c]		0.492[c]	
RA	0.08		0.896[c]		0.247[c]		0.450[c]	
RD	−0.06		0.061		0.084[b]		0.017	

Note: *N*, the number of sampling sites; *n*, the number of soil samples collected; RZ, root zone; BTR, below the root zone; SWC, soil water content; RM, root mass; RL, root length; RA, root surface area density; RD, mean root diameter.

[a] Mixed refers to the three land use types combined.

[b] Correlation is significant at the 0.05 level (2-tailed).

[c] Correlation is significant at the 0.01 level (2-tailed).

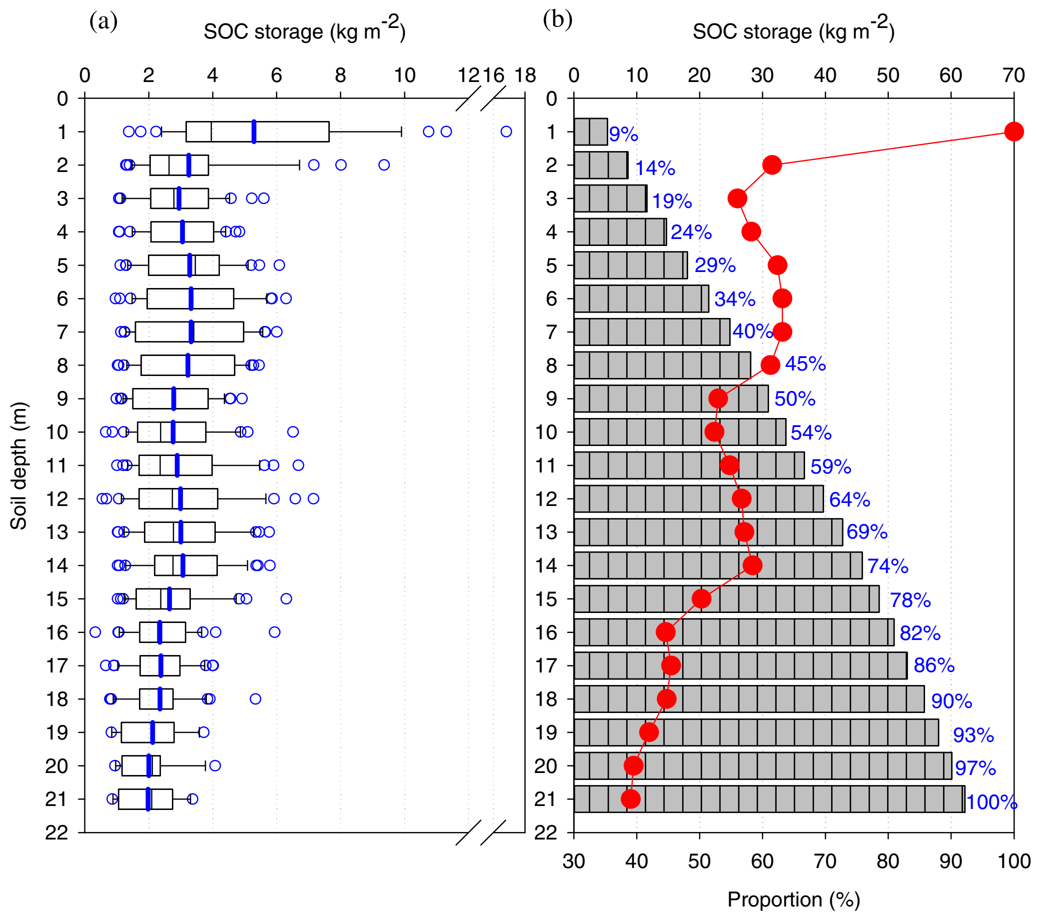

Fig. 2. Mean soil organic carbon (SOC) storage in 1-m thick soil layers (a) and the cumulative SOC storage (b) with depth at various soil depths in 33 soil profiles on the Loess Plateau. Blue and black lines within the box plots are the mean and median values, respectively. Red circles represent the SOC contributions as: (SOC storage in each sub-layer)/SOC storage in the 0-1 m layer) × 100%. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In general, the historical source of the SOC in deep soil layers on the CLP could occur in three ways. (1) These layers were presumably topsoils at some time because of the way loess is deposited (Pye, 1995). (2) Potentially, during historic periods when rainfall was considerably greater, some dissolved organic C could be leached to these layers (Clark et al., 2005). (3) Presumably the age of these layers might be linked to times when forests grew in the various areas, which would be affected greatly by human activities that subsequently changed land use (Rumpel and Kögel-Knabner, 2011).

Furthermore, deep SOC may take part in soil biogeochemical processes because: (1) it is the product of deep-root systems which deliver organic C to the soil through root exudation, mycorrhizal associations, and death/turnover (Davidson et al., 2011); in turn, the organic C inputs can be altered by microbially-related decomposition processes that are ‘primed’ by the easily degradable substrates (Zhu and Cheng, 2010); (2) it can influence microbial activities that affect and are affected by substrate availability, depolymerization and enzyme production, as well as by envrion-mental conditions (Kirschbaum, 1993); and (3) it possibly responds to human-induced changes involving soil redistribution that can occur, for example, during the construction of road or railway cuts and the digging of foundations for various structures, which may result in the decomposition of deep SOC, or in an acceleration of that decomposition, due to exposure to oxidation (Chappell et al., 2012; Doetterl et al., 2012).

The SOC levels differed significantly between cropland and forest within each of the three identified sub-layers. The variations in SOC in the upper sub-layer (0–2 m) was consistent with the findings of other studies undertaken on the CLP (Chen et al., 2006) and elsewhere in the world (e.g., Wiesmeier et al., (2012)). In both the 2–14 m and 14–21 m sub-layers, the significantly greater SOC values under forest than under cropland could be attributed to the difference in rooting depth between these two land use types (Fig. 1b). In the current study, the maximum rooting depth for the forest was 18 m, and for 11 of the 23 forest sites the rooting depth was greater than 13 m. The presence of roots in deeper layers could contribute significant amounts of organic C to the deep soil (Davidson et al., 2011), and could gradually raise the level of SOC over time (Brantley, 2008; Yang et al., 2012).

Our results showed that the SOC values for each of the three sub-layers within the 21-m profiles were significantly greater under forest than under cropland. This finding confirmed the hypothesis that, for soils deeper than 5 m, forest soils would contain more C than cropland soils due to contributions from the deeper roots of the trees. Therefore, changes in land use from cropland to forest, such as those undertaken within the framework of the Grain-for-Green project that aims to improve the natural environment at a regional scale, have a greater potential to sequester more C in deeper soils than in shallow soils. For example, Lu et al., (2012) reported that the C sequestered in the 0–20 cm soil layer alone increased by about 3.30 Tg after cropland was converted to forest over an area of 8.69×10^5 ha. The Grain-for-Green program played an important role in the evaluation of C cycling by virtue of changing land use patterns and, potentially, local climate conditions (Liu et al., 2014b; Xiao, 2014). The quantitative evaluation of such potential needs further study since our survey was limited to only 33 sites.

Moreover, our findings of large quantities of soil C in deep soil layers also raises important issues for regional/global C budgets and for C sequestration strategies and this requires further attention. The vertical SOC profiles showed that considerable amounts of organic C were stored at depths below the 1-m soil layer. Therefore, past reports of SOC storage on the CLP, based on measurements of SOC in the upper 1-m layer alone, considerably underestimated the actual SOC storage. This result supports the suggestions of others (Díaz-Hernández, 2010; Harper and Tibbett, 2013; Jobbágy and Jackson, 2000; Sommer et al., 2000) that SOC in deeper soil layers must be taken into account when estimating the true soil C pool at various spatial scales. Our results suggest that it is probable that SOC storage in other areas in the world where deep soils occur has also been underestimated, especially when the land use includes plants with deep rooting systems. Furthermore, the information provided by this study about the vertical distribution of SOC and the identification of causal factors contributing to variations in SOC will be important when evaluating the effect of vegetation/land use on the stored SOC. The SOC profile patterns presented might also be considered as input parameters for more refined ecosystem biogeochemical models, especially for those that include multiple soil layers.

5. Conclusions

The overall distribution of SOC within 0–21 m soil profiles could be divided into three sub-layers with significantly different mean values of SOC. In the rooting zone, the variables that best explained the differences in SOC were root length, pH and clay content; while below the rooting zone, these were soil water content, pH and clay content. The SOC storage in the upper 1-m soil layer only accounted for a small proportion of the total C in the entire 21-m soil profile. More attention should be paid to the C in deep soil layers in order to accurately estimate regional and/or global C budgets. In the deep soil layer (5–21 m), SOC storage was greater under forest ($47 \pm 0.43\,\mathrm{kg\,m^{-2}}$) than under permanent cropland ($38 \pm 0.47\,\mathrm{kg\,m^{-2}}$). Land use has significant effects on the magnitude and vertical patterns of SOC within both shallow and deep soils. Our findings have important implications for land use management and climate policy making.

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