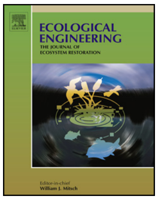
Ecological Engineering 82 (2015) 361–367

Contents lists available at ScienceDirect

Ecological Engineering

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



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

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ARTICLE INFO

Article history:
Received 16 December 2014
Received in revised form 6 April 2015
Accepted 23 May 2015
Available online 5 June 2015

Keywords:
Forest
Cropland
Plant root
Carbon management
Loess Plateau

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 ± 0.57 g kg^{-1}, respectively. In the deep soil layer (5–21 m), SOC storage was significantly higher ($P < 0.01$) under forest (47 ± 0.43 kg m^{-2}) than under cropland (38 ± 0.44 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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http://dx.doi.org/10.1016/j.ecoleng.2015.05.004
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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.