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Distribution of soil carbon and nitrogen in two typical forests in the semiarid region of the Loess Plateau, China

Bian-Lan Song [a,b,d], Mei-Jie Yan [a,b,*], Hao Hou [b], Jin-Hong Guan [a,b], Wei-Yu Shi [c], Guo-Qing Li [a,b], Sheng Du [a,b,*]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences, Yangling, Shaanxi 712100, China
[b] Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China
[c] State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, Shaanxi 710075, China
[d] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

Forest ecosystems on the Loess Plateau are receiving increasing attention for their special importance in carbon sequestration and in the conservation of soil and water in the region. To evaluate soil carbon and nitrogen accumulation in two typical forests in the region, we conducted plot surveys in three near-mature stands for each forest type. Soil samples within 0–200 cm were collected from different depths, and the soil organic carbon (SOC), inorganic carbon (SIC), and total nitrogen (STN) were measured. The results indicate that the oak (*Quercus liaotungensis*) forests had greater SOC and STN contents and lower soil buck density than the black locust (*Robinia pseudoacacia*) plantations within top soil layers. Both SOC and STN contents decreased with soil depth, and the differences between the forest types became insignificant in layers beneath 50 cm. The total accumulations of SOC and STN were larger in the oak forests than in the black locust plantations, particularly in the upper soil layers. The results suggest that the oak forest has advantages over the plantation forest regarding SOC and nitrogen accumulation in the upper soil layer, and both types of forest soils have acted as substantial carbon sinks. However, in the loess soil in this region, there were considerable amounts of SIC storage (4–5 times of SOC in deep layers), and the amounts of soil total carbon (STC) did not differ obviously between the two ecosystems. Relative to the conventional soil survey of 100-cm depth, the SOC, STN and STC stored in 100–200 cm deep soil account for 0.45, 0.49 and 0.91 times in the oak forests, respectively, compared to 0.65, 0.65 and 1.01 times in the black locust plantations for SOC, STN and STC, respectively. Thick loess soil coupled with dry climate may be attributable to the development of root system and consequent SOC and STN distribution into deeper layer. This suggests that deep soil layers contribute considerable amounts and should not be omitted in soil carbon estimates.

1. Introduction

It is widely documented that soil carbon (C) plays an important role in the earth's carbon cycling and is the largest terrestrial carbon pool (Dixon et al., 1994; Post and Kwon, 2000; Sedjo, 1993; Sombroek et al., 1993). Approximately 40%–90% of the inventory of the global soil carbon resides in forest ecosystems (Schlesinger, 1997; Whittaker and Likens, 1973). In addition, nitrogen (N) plays a crucial role through the interaction with carbon in the ecosystem productivity and carbon sequestration (Knops and Tilman, 2000; Reich et al., 2006; Vitousek and Howarth, 1991). Quantitative evaluations of the stock and changes of soil carbon and nitrogen in various region and forest types are thus considered of great importance by both researchers and government officials worldwide.

Arid and semi-arid regions have received increasing attention as potential areas of carbon sequestration (Ardo and Olsson, 2003; Grunzweig et al., 2003; Lal, 2002; Squires, 1998). The central Loess Plateau, which is located in a semiarid region, has very unique and deep loess. The soil may serve high productivity for agriculture and natural vegetation under appropriate climates. However, during its history, because of frequent and long-term anthropogenic activities, the local ecosystems have greatly worsened, namely, natural vegetation has been severely destroyed and soil erosion has become a serious issue (Peng et al., 1995; Shi and Shao, 2000). Since the 1950s, the government has been conducting large-scale reforestation, leading to the improvement of the ecosystems. The forest ecosystem was restored by both natural restoration and reforestation. Therefore, in the region, the forests are composed mostly of secondary natural forests and plantations of fast-growing species. The natural oak (*Quercus liaotungensis*) forest is one of the main warm temperate deciduous broad-leaved forests and is the climax of forest natural recovery in the sub-humid and semiarid region of the central Loess Plateau (Kang et al., 2007; Zhu, 1993).

* Coresponding authors at: Institute of Soil and Water Conservation, Northwest A&F University, 26 Xinong Rd, Yangling, Shaanxi 712100, China.
E-mail addresses: yanmj@ms.iswc.ac.cn (M.-J. Yan), shengdu@ms.iswc.ac.cn (S. Du).

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Currently, the forest area is approximately 9.0×10^5 ha in the Loess Plateau. Among plantations, the exotic black locust (*Robinia pseudoacacia*) ranks as the largest area, 2.7×10^5 ha in the region. It has been the main plantation forest since the 1960s in the Loess Plateau gully region (Zhang and Zhang, 2009). Although the natural forests and plantations both contributed to the controlling of soil erosion, comparative studies on these ecosystems from the viewpoint of long-term ecological benefit have been inadequate. Evaluating the accumulation of soil carbon and nitrogen in these forests would provide basic information regarding the multiple ecosystem services and nutrient cycling in addition to the traditional focus of soil conservation.

In addition, although the accumulation of soil organic carbon (SOC) is generally a process in the upper soil layer, the deep (>100 cm) may also store considerable amounts in the widespread deep soil areas (Sombroek et al., 1993). The Loess Plateau is famous for its thick loess deposition, up to tens or even hundreds of meters (Yan et al., 2014). There have been reports that trees in this region may develop their roots to deep soil layers (Cui et al., 2005; Zhao et al., 2000). Some trees' roots (e.g. the black locust roots) often reach to 160–190 cm, though the top 100-cm horizon is general considered as the space for root distribution (Cui et al., 2005; Shan and Liang, 2006; Wang et al., 2004). Globally, studies on soil carbon and nitrogen in various ecosystems are generally focused on depths of <100 cm, including those conduced in this region (Chang et al., 2012; Fu et al., 2010; Gao et al., 2014; Li et al., 2013; Liu et al., 2014; Tateno et al., 2007; Wang et al., 2010; Wang et al., 2012; Xing et al., 2013; Zhang et al., 2004; Zhang et al., 2014). Many studies are focused on the top soil layers, i.e. 0–20 cm or slightly more (e.g. those reviewed by Deng et al., 2014; Song et al., 2014). Investigations on carbon and nitrogen accumulations in soils below 100 cm are quite infrequent (Zhang et al., 2013).

The soil carbon reservoir consists of SOC and soil inorganic carbon (SIC). Soil inorganic carbon was also as one of the largest carbon pools and plays a significant role in carbon sequestration (Eswaran et al., 2000; Lal, 2008). In arid and semi-arid areas, which cover about one third of the earth's surface, SIC is even the dominant form of it in soil (Lal and Kimble, 2000; Mielnick et al., 2005). In such areas the SIC reservoirs approximate 2–10 times larger than that of SOC (Eswaran et al., 2000; Schlesinger, 1982). The Loess Plateau is one of the areas with the highest SIC contents in China (Wu et al., 2009), where some investigations showed a density for SIC at about 4 times of SOC (Chang et al., 2012). In addition, soil N pool is usually coupled with SOC. Forest N accumulation and cycling are affected by soil organic matter and vary with species and environmental conditions. In semi-arid ecosystems, soil organic matter and N pools tend to be small compared to the litter production. STN is an important index representing efficient nutrient cycling and ecosystem service of forests.

The objectives of the present study are (1) to comparatively evaluate the SOC, SIC and the soil total nitrogen (STN) stocks and their distribution along the vertical profiles of 0–200 cm in soils of two major forest ecosystems, and (2) to verify the hypothesis that there is abundant carbon and nitrogen in the deep soil layers (100–200 cm) under the forests in the region, which has been omitted in the estimates in the past.

2. Materials and methods

2.1. Study area

The investigated forest stand sites are located on Mt Gonglushan, near Yan'an city of Shaanxi province, China (36°25.40′ N, 109°31.53′ E; 1353 m a.s.l.). On the Loess Plateau, the amount of precipitation and the occurrence of forest gradually decrease northwestward, and the present study site is located in the forest-grassland transition zone (Yamanaka et al., 2014). The area is characterized by a semiarid climate. The 40-year averages (1971–2010) of the mean annual precipitation and air temperature are 504.7 mm and 10.1 °C, respectively (Shi et al., 2014).

According to previous reports based on historical surveys, the study area had been covered with oak forests before extensive deforestation at the early decades of 1900s (Du et al., 2007; Tateno et al., 2007). Because water erosion of the loess soil is serious, from time to time there would be abandonment of cultivation on the slope croplands. Secondary oak forests have developed in early-conserved places since 1940s. Black locust plantations were mainly planted after 1970s. These two kinds of forests are typical forest ecosystems in this region and are coming to their near-mature stages.

2.2. Field survey and soil sampling

We selected three stands of oak forests and three stands of black locust plantations that were located 0.5–1.5 km apart at the site. We assumed that these stands were representative to the two forest types in this area. The field surveys were conducted in August 2013 by identifying a plot of 20 m × 40 m in each stand. The tree amounts, heights and stem diameters at breast height (DBH; 1.3 m) for all trees with DBH ≥ 5 cm were recorded within each plot. In addition to the density, means of height and DBH of the recorded trees, the basal area (BA) was also calculated as the sum of tree area at breast height based on the horizontal area of each plot. The structures of the stands are presented in Table 1. Preliminary estimates showed that the stands of oak and black locust have biomass stocks of about 184 and 164 t ha^{-1}, respectively, and have annual litter production of about 4.2 and 3.7 t ha^{-1}, respectively (unpublished data and Tateno et al., 2007).

The soil type at the site is loess which has developed from the thick deposition of >50 m (Yamamoto and Endo, 2014; Yan et al., 2014). A previous investigation showed that root systems are mainly distributed within the 1-m soil layer (Shi et al., 2011; Tateno et al., 2007). They also revealed some differences in the soil structure and nutrient contents between the two forest types. Whereas both the semi-decomposed, fragmented organic matter layer (F horizon) and humus layer (H horizon) had developed in the oak forest, only the F horizon was observed in the black locust plantation. Furthermore, both the C and N contents in 0–20 cm soil were higher in the oak forest than in the black locust plantation. Basic information for soil properties are shown in Table 2. We can note that soils in this area are alkali, substantially different from the forest soils in many other regions. Relatively lower soil bulk density in oak forests should be consistent with their above-mentioned characteristics.

Table 1
Stand structure of the study plots.

Plot	Altitude (m)	Aspect	Slope	Density (DBH ≥ 5 cm trees ha^{-1})	DBH (cm) (Mean ± SD)	Height (m) (Mean ± SD)	BA (m^2 ha^{-1})	Max age (yr)
Oak (*Q. liaotungensis*)								
Q1	1353	N60°E	22°	1325	13.2 ± 5.3	6.6 ± 2.7	22.4	64
Q2	1302	S85°W	20°	1363	13.0 ± 5.7	8.6 ± 2.8	21.4	72
Q3	1380	N8°E	10°	1800	14.8 ± 8.5	9.5 ± 3.2	40.9	76
Black locust (*R. pseudoacacia*)								
R1	1327	S45°E	24.5°	2925	10.2 ± 3.0	8.5 ± 2.6	26	36
R2	1324	S46°E	13.5°	2325	11.3 ± 3.6	9.7 ± 3.0	25.5	36
R3	1302	S85°W	26°	1475	11.0 ± 3.5	8.9 ± 2.5	15.5	36