Natural vegetation restoration of Liaodong oak (Quercus liaotungensis Koidz.) forests rapidly increased the content and ratio of inert carbon in soil macroaggregates Postprint

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Date: 2019-12-06T00:00:00+00:00

Abstract

The lack of clarity of how natural vegetation restoration influences soil organic carbon (SOC) content and SOC components in soil aggregate fractions limits the understanding of SOC sequestration and turnover in forest ecosystems. The aim of this study was to explore how natural vegetation restoration affects the SOC content and ratio of SOC components in soil macroaggregates (>250 μm), microaggregates (53-250 μm), and silt and clay (<53 μm) fractions in 30-, 60-, 90- and 120-year-old Liaodong oak (Quercus liaotungensis Koidz.) forests, Shaanxi, China in 2015. And the associated effects of biomasses of leaf litter and different sizes of roots (0–0.5, 0.5–1.0, 1.0–2.0 and >2.0 mm diameter) on SOC components were studied too. Results showed that the contents of high activated carbon (HAC), activated carbon (AC) and inert carbon (IC) in the macroaggregates, microaggregates and silt and clay fractions increased with restoration ages. Moreover, IC content in the microaggregates in topsoil (0–20 cm) rapidly increased; peaking in the 90-year-old restored forest, and was 5.74 times higher than AC content. In deep soil (20–80 cm), IC content was 3.58 times that of AC content. Biomasses of 0.5–1.0 mm diameter roots and leaf litter affected the content of aggregate fractions in topsoil, while the biomass of >2.0 mm diameter roots affected the content of aggregate fractions in deep soil. Across the soil profiles, macroaggregates had the highest capacity for HAC sequestration. The effects of restoration ages on soil aggregate fractions and SOC content were less in deep soil than in topsoil. In conclusion, natural vegetation restoration of Liaodong oak forests improved the contents of SOC, especially IC within topsoil and deep soil. The influence of IC on aggregate stability was greater than the other SOC components, and the aggregate stability was significantly affected by the biomasses of litter, 0.5–1.0 mm diameter roots in topsoil

and >2.0 mm diameter roots in deep soil. Natural vegetation restoration of Liaodong oak forests promoted SOC sequestration by soil macroaggregates.

Full Text

Preamble

Natural vegetation restoration of Liaodong oak (Quercus liaotungensis Koidz.) forests rapidly increased the content and ratio of inert carbon in soil macroaggregates

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Abstract

The lack of clarity regarding how natural vegetation restoration influences soil organic carbon (SOC) content and SOC components in soil aggregate fractions limits understanding of SOC sequestration and turnover in forest ecosystems. This study explored how natural vegetation restoration affects SOC content and the ratio of SOC components in soil macroaggregates (>250 µm), microaggregates (53-250 µm), and silt and clay (<53 µm) fractions in 30-, 60-, 90-, and 120-year-old Liaodong oak (Quercus liaotungensis Koidz.) forests in Shaanxi, China, in 2015. We also examined the associated effects of leaf litter biomass and different root size classes (0–0.5, 0.5–1.0, 1.0–2.0, and >2.0 mm diameter) on SOC components. Results showed that contents of high activated carbon (HAC), activated carbon (AC), and inert carbon (IC) in macroaggregates, microaggregates, and silt and clay fractions all increased with restoration age. Moreover, IC content in microaggregates in topsoil (0–20 cm) increased rapidly, peaking in the 90-year-old restored forest and reaching 5.74 times higher than AC content. In deep soil (20–80 cm), IC content was 3.58 times that of AC content. Biomasses of 0.5–1.0 mm diameter roots and leaf litter affected aggregate fraction contents in topsoil, while >2.0 mm diameter root biomass affected aggregate fraction contents in deep soil. Across soil profiles, macroaggregates had the highest capacity for HAC sequestration. The effects of restoration age on soil aggregate fractions and SOC content were less pronounced in deep soil than in topsoil. In conclusion, natural vegetation restoration of Liaodong oak forests improved SOC contents, particularly IC, in both topsoil and deep soil. The influence of IC on aggregate stability was greater than that of other SOC components, and aggregate stability was significantly affected by litter biomass, 0.5–1.0 mm diameter roots in topsoil, and >2.0 mm diameter roots in deep soil. Natural vegetation restoration of Liaodong oak forests promoted SOC sequestration through soil macroaggregates.

Keywords: activated carbon; leaf litter; soil organic carbon; soil aggregates; silt and clay; Shaanxi

Citation: SUN Lipeng, HE Lirong, WANG Guoliang, JING Hang, LIU Guobin. 2019. Natural vegetation restoration of Liaodong oak (Quercus liaotungensis Koidz.) forests rapidly increased the content and ratio of inert carbon in soil macroaggregates. Journal of Arid Land, 11(6): 928–938. https://doi.org/10.1007/s40333-019-0004-y

1 Introduction

Rising atmospheric CO concentrations that contribute to global warming represent a critical environmental issue. Natural vegetation restoration is a management approach that increases carbon sequestration rates in soil by enhancing vegetation cover and is perceived as the most effective technique for decreasing atmospheric CO concentrations [?, ?]. Natural vegetation restoration changes soil organic carbon (SOC) content in soil aggregate fractions. For example, natural vegetation restoration increased SOC content in macroaggregates [?, ?]. Moreover, the effects of natural vegetation restoration were variable [?, ?, ?] and were probably associated with variation in environmental factors such as soil type, vegetation type, and temperature [?, ?]. Recent research has shown that the turnover rate of active organic carbon (AOC) varied with soil aggregate fraction sizes [?, ?, ?]. Furthermore, contents of SOC and AOC decreased with vegetation succession, while organic matter (OM) content increased [?, ?]. Meanwhile, coarse intra-aggregate particulate organic matter-carbon (iPOM-C) tended to increase with vegetation succession, while fine iPOM-C concentrations tended to fluctuate [?, ?]. The physical and chemical protection of organic carbon by soil aggregate fractions may lead to inert carbon (IC) accumulation. For example, Wang et al. (2016) found that afforestation decreased the coarse particle organic carbon fraction but increased the recalcitrant mineral-associated SOC content. Natural vegetation restoration is known to increase SOC content in surface soil (0–20 cm) [?, ?], and forest restoration has been shown to increase SOC content in deep soil due to root turnover and/or transfer of SOC from surface soil to deep soil through soil pore space via rainfall percolation [?, ?].

However, accumulation and decomposition processes among SOC fractions in deep soil aggregate fractions may differ from those in surface soil [?, ?] due to variations in temperature, soil moisture, and microbial activities. The influence of vegetation on accumulation processes of SOC components in deep soil remains unknown.

SOC in soil aggregate fractions primarily originates from leaf and root litter and root secretions. The effects of leaf and root litter on SOC contents in soil aggregate fractions may differ and vary with soil layer [?, ?]. Soil aggregate fractions and SOC contents in surface soil have been shown to be mainly affected by leaf litter and fine roots [?, ?]. It is likely that the influences of leaf and root litter on

SOC content vary with soil layers because differences in chemical composition, anatomical structure, and turnover rates have been recorded among different fine root size classes [**?**, **?**].

This study aimed to explore how natural vegetation restoration affects the content and ratio of SOC components in soil aggregate fractions. We hypothesized that (1) natural vegetation restoration of Liaodong oak (Quercus liaotungensis Koidz.) forests increases SOC content regardless of aggregate size, but accumulation rates are more rapid in macroaggregates of surface soil than in microaggregates of deep soil; and (2) SOC content is mainly affected by leaf litter and root biomasses in surface soil aggregate fractions and by fine root biomass in deep soil aggregate fractions.

2.1 Study area and sampling

The study area is located in the Renjiatai Forest Farm, Shaanxi, China (36°05 N, 109°11 E; 920–1680 m a.s.l.), in a gully loess hilly-gully region with a mean gully density of 4.5 km/km². The annual average temperature is 9.0°C, and average annual precipitation is 576.7 mm, of which about 60%–70% falls from July to September. Surface soils are principally brown forest soils, forest canopy density is 70%, and coverage exceeds 90%. Natural vegetation in the study area is represented by Liaodong oak, pine, and birch forests, among which Liaodong oak forest becomes the local climax community and is dominated by Q. liaotungensis, Populus davidiana, and Betula platyphyllum, with understory comprising Spiraea salicifolia, Sophora viciifoli, and Ostryopsis davidiana shrub species, and Carex lanceolata and Artemisia gmelinii herbaceous flora [**?**, **?**].

The study was conducted from 15 to 28 September 2015 in 30-, 60-, 90-, and 120-year-old Liaodong oak forests. Grassland converted from farmland was considered as the control. Five plots in each of the five stand types with an area above 1 hm × 1 hm were positioned on a southeastern slope with gradients of 15°–30° (Table 1), and soil samples were taken from four 20 m × 20 m quadrats in each plot.

Table 1 Characteristics of the restored forests

Stand type	Age (a)	Elevation (m)	Slope gradient (°)	Slope direction (°)	Dominant species
Converted grassland	-	1077±21	132±5	155±8	Carex lanceolata
Young forest	30	1157±16	109±11	170±12	Quercus liaotungensis, Pyrus betulaefolia

Stand type	Age (a)	Elevation (m)	Slope gradient (°)	Slope direction (°)	Dominant species
Semi-mature forest	60	1138±13	168±6	-	Quercus liaotungensis, Pyrus betulaefolia, Acer spp.
Mature forest	90	1321±24	-	-	Quercus liaotungensis, Pyrus betulaefolia, Acer spp.
Veteran forest	120	1396±11	-	-	Quercus liaotungensis, Populus tremula

Note: CK, control; Slope direction ranges from north (0°) to east (90°). Mean±SD.

Within each plot, undisturbed soil cores at 100 cm depth were sampled within an area of 1.0 m × 0.5 m, and soil moisture and bulk density were measured. Roots manually collected at 20-cm intervals along the 100-cm profile were separated according to their diameters into finest (<0.5 mm), finer (0.5–1.0 mm), fine (1.0–2.0 mm), and thick (>2.0 mm) roots that were cleaned and dried at 70°C to a constant weight to determine biomass [**?**, **?**]. Leaf litter was collected from three quadrats with an area of 10 cm × 10 cm and then dried to a constant weight at 70°C to determine biomass.

2.2 Determination of soil fertility parameters

We divided soil samples into macroaggregates (>250 μm), microaggregates (53-250 μm), and silt and clay (<53 μm) fractions based on the wet screening method that uses automatic shock sieves (250 and 53 μm) [**?**, **?**].

SOC can be classified as high activated carbon (HAC), activated carbon (AC), and IC. SOC content was determined using the external heating potassium dichromate method. HAC and AC contents were determined using the potassium permanganate (KMnO) oxidation method. IC content was calculated as the difference between total organic carbon and AC [**?**, **?**].

2.3 Statistical analyses

Mean weight diameter (MWD; mm) was calculated as follows [**?**, **?**]:

$$\mathrm{MWD} = \sum_{i=1}^{n} x_i w_i$$

where x_i is the mean diameter of each class of aggregates (mm); w_i is the proportion of each class of aggregates (%); and n is the number of aggregates.

HAC and AC are obtained from experimental data. IC is the difference between SOC and HAC. Relationships between SOC components and biomasses of different root size classes and leaf litter in aggregate fractions were tested by variance analysis. Multiple comparisons were tested using Tukey HSD of R software (v3.3.2) at the $P<0.05$ level.

3.1 MWD and soil aggregate fractions

We found that MWD and the percentage of macroaggregates increased with restoration age, with the greatest values observed in topsoil of the 90-year-old forest (21.09% and 23.85% higher than those of control, respectively) and in deep soil of the 60-year-old forest (16.33% and 19.19% higher than those of control, respectively) (Fig. 1 [Figure 1: see original paper]). However, the lowest values of MWD and macroaggregates occurred in topsoil of the 90-year-old forest (51.36% and 53.55% lower than those of control, respectively) and in deep soil of the 60-year-old forest (35.76% and 19.97% lower than those of control, respectively).

Fig. 1 Percentages of macroaggregates (a), microaggregates (b) and silt and clay (c) and mean weight diameter (d) of Liaodong oak forests at different restoration ages and soil layers. Different lowercase letters indicate significant differences among different restoration ages of the same soil layer at $P<0.05$ level. Bars represent standard errors.

3.2 SOC contents and SOC components in different soil aggregate fractions

Contents of SOC, HAC, AC, and IC in aggregate fractions of topsoil increased with restoration age and were higher in the 60-year-old forest than in the control (Fig. 2 [Figure 2: see original paper]). Moreover, they were 62.32%, 77.41%, and 132.88% higher in macroaggregates, 136.71%, 169.09%, and 218.25% higher in microaggregates, and 73.66%, 85.76%, and 97.97% higher in silt and clay, respectively, compared to the control. IC content increased most rapidly among all soil aggregate fractions.

Fig. 2 Contents of SOC and SOC components of Liaodong oak forests at different restoration ages and soil layers. SOC, soil organic carbon; HAC, high activated carbon; AC, activated carbon; IC, inert carbon; Ma, macroaggregates; Mi, microaggregates; SC, silt and clay. * indicates significant differences among different restoration ages of the same SOC components at P<0.05 level. Bars represent standard errors.

3.3 Proportion of SOC components in soil aggregate fractions

IC content in macroaggregates of topsoil was greatest in the 90-year-old forest, with an IC:AC:HAC ratio of 5.74:1.87:1.00. Similarly, IC content in microaggregates was greatest in the 90-year-old forest, with an IC:AC:HAC ratio of 6.57:2.29:1.00. In contrast, IC content in silt and clay was greatest in the 120-year-old forest, with an IC:AC:HAC ratio of 4.29:1.84:1.00 (Table 2).

IC and AC contents in macroaggregates of deep soil were greatest in the 60-year-old forest, with an IC:AC:HAC ratio of 3.58:3.96:1.00. Similarly, IC and AC contents in microaggregates and silt and clay fractions were greatest in the 60-year-old forest, while the IC:AC:HAC ratios in microaggregates and silt and clay fractions were 3.35:3.17:1.00 and 2.65:4.50:1.00, respectively (Table 2).

Table 2 Effects of restoration age of Liaodong oak forests on proportion of SOC components in soil aggregate fractions

Note: MaAH, ratio of activated carbon to high activated carbon content in macroaggregates; MaIH, ratio of inert carbon to high activated carbon content in macroaggregates; MiAH, ratio of activated carbon to high activated carbon content in microaggregates; MiIH, ratio of inert carbon to high activated carbon content in microaggregates; SCAH, ratio of activated carbon to high activated carbon content in silt and clay; SCIH, ratio of inert carbon to high activated carbon content in silt and clay. The abbreviations are the same in Figure 3. Mean±SD. Different lowercase letters within a row indicate significant differences among different restoration ages of the same SOC components at P<0.05 level.

3.4 Relationship between soil aggregate fractions and SOC components

We found that IC and HAC contents in both topsoil and deep soil were positively associated with macroaggregates (Pearson' s correlation coefficients were 0.52 and 0.42, respectively), but showed little association with microaggregates and silt and clay fractions (Fig. 3 [Figure 3: see original paper]).

Fig. 3 Pearson' s correlation coefficients of SOC components in soil aggregate fractions and different soil layers. (a), 0–20 cm; (b), 20–80 cm. Ma, macroaggregates; Mi, microaggregates; SC, silt and clay.

3.5 Leaf and root biomasses

Biomasses of thick roots and leaves followed similar trends, peaking in the 60-year-old forest (20.09 t/hm^2) and in the 90-year-old forest (9.90 t/hm^2), respectively. Biomasses of finer and finest roots in topsoil progressively increased with forest restoration age, reaching 11.71 and 5.89 t/hm² in the 120-year-old forest, respectively, while biomass of finer roots in deep soil peaked in the 120-year-old forest (Tables 3 and 4).

Table 3 Biomasses of different root size classes in different soil layers and restoration ages

Soil layer (cm)	Age (a)	TR (>2.0 mm)	FR (1.0–2.0 mm)	FRer (0.5–1.0 mm)	FRest (<0.5 mm)
0–20	30	1.40±0.00b	1.13±0.13c	18.82±7.11a	9.09±0.74ab
	60	20.09±4.13a	7.85±2.08b	19.25±4.68a	14.56±0.93a
	90	18.82±6.16a	8.67±1.37b	47.48±6.32b	5.98±1.27a
	120	0.70±0.30b	1.09±0.30b	181.96±22.2a	4.61±0.72a
20–40	30	0.90±0.16b	0.90±0.09b	9.18±3.82b	4.39±1.49a
	60	27.99±9.16b	6.67±2.14a	44.61±10.56a	5.11±0.89a
	90	17.53±8.28ab	3.02±0.41ab	25.11±7.16ab	3.14±0.76ab
	120	0.41±0.02b	7.38±0.91a	8.96±0.42a	9.67±2.18a
40–60	30	0.41±0.03b	2.24±0.82a	1.81±0.26a	1.86±0.47a
	60	0.41±0.02b	7.38±0.91a	8.96±0.42a	9.67±2.18a
	90	0.19±0.04c	3.21±0.28ab	2.98±0.21b	3.62±0.36ab
	120	0.84±0.06a	1.00±0.34a	0.97±0.23a	1.41±0.51a
60–80	30	0.23±0.11b	0.42±0.11ab	0.53±0.17ab	1.09±0.33a
	60	0.19±0.04c	3.21±0.28ac	2.98±0.21b	3.62±0.36ac
	90	0.76±0.1ab	1.19±0.07a	1.09±0.33a	0.76±0.1ab
	120	0.19±0.04c	3.21±0.28ac	2.98±0.21b	8.67±1.68b

Note: TR, thick root; FR, fine root; FRer, finer root; FRest, finest root. Different lowercase letters within a column indicate significant differences among different forest restoration ages of the same soil layer at P<0.05 level.

Table 4 Litter biomass in different restoration ages

Age (a)	Litter biomass (t/hm²)
30	3.26±0.19b
60	7.67±0.75a
90	8.93±0.31a
120	9.90±0.79a

Note: Different lowercase letters within a column indicate significant differences among different restored forest ages at P<0.05 level.

3.6 Relationship between SOC components and biomasses of roots and leaf litter in different soil aggregate fractions

We found that the greatest indirect impact on macroaggregate content in topsoil came from finer root biomass (indirect path coefficient = 1.70), while the greatest direct impact came from thick root and leaf litter biomasses (direct path coefficient = 0.81) (Fig. 4 [Figure 4: see original paper]). Sequestration of HAC in the topsoil layer (0-20 cm) was greatest in macroaggregates (direct path coefficient = 3.27). There was a positive correlation between macroaggregates and IC content.

In the deep soil layer (20-80 cm), finer root biomass had the greatest indirect impact on macroaggregate content (indirect path coefficient = 0.17), while thick root and leaf litter biomasses had the greatest direct impact (direct path coefficient = 0.15). Sequestration of HAC was greatest in macroaggregates (direct path coefficient = 0.35), and there was a positive correlation between macroaggregates and AC content.

Fig. 4 Relationship between SOC components and biomasses of different root size classes and leaf litter in soil aggregate fractions and different soil layers. (a), 0-20 cm; (b), 20-80 cm. Litter, leaf litter; FRest, finest root; FRer, finer root; FR, fine root; TR, thick root; SCIC, inert carbon content in silt and clay; SCHAC, high activated carbon content in silt and clay; SCAC, activated carbon content in silt and clay; SC, silt and clay. Grey line indicates negative coefficient, while blue line indicates positive coefficient.

4.1 Effects of restoration ages on soil aggregate fractions and SOC components

We found that contents of SOC components among aggregate fractions of topsoil increased with forest restoration age, with IC in macroaggregates increasing most rapidly. The ratio of IC to HAC limited the content of water-stable aggregate fractions, supporting our hypothesis to some extent.

We observed an increase in macroaggregate content with vegetation restoration, while microaggregate and silt and clay fractions decreased. These results are consistent with a previous study [?, ?]. Restoration benefits aggregate fraction formation by providing suitable physical, chemical, and microbiological conditions in the rhizosphere (root, root secretions, and litter) for creation of soil particles [?, ?]. In addition, the development of plant rhizosphere microorganisms produces greater abundance of mycelia [?, ?]. We found that finer root (0.5-1.0 mm) biomass had the greatest impact on aggregate fractions in topsoil, whereas thick root (>2.0 mm) biomass had the greatest impact on aggregate fractions in deep soil. We suggest that microaggregates, silt and clay, and macroaggregate fractions were affected by the same carbon sources during vegetation restoration in revegetated forests.

Total contents of SOC, HAC, AC, and IC in all topsoil aggregate fractions generally increased with restoration age, supporting results from previous research [?, ?]. We comprehensively analyzed SOC component contents among aggregate fractions and found the strongest relationship between macroaggregate content and the ratio of IC to HAC. Natural vegetation restoration changes the ratio of SOC components in soil aggregate fractions [?, ?], wherein SOC in the structure of clay mineral laminates is encompassed by organic binding material within aggregate fractions [?, ?]. We analyzed HAC, AC, and IC and found they changed the overall structure of aggregate fractions, probably as a result of their physical and chemical properties that affected molecular forces, chemical bonds, and cohesive forces. Annual increases in plant leaf and root litter biomasses continuously provided carbon sources, thus increasing SOC content with restoration age. We also found that contents of HAC, AC, and IC changed; however, IC content was positively associated with a rise in aggregate fractions. Thus, natural vegetation restoration can be considered a driver of soil development, and carbon sequestration and release from soil aggregate fractions continuously changed the ratios of SOC components. Other studies confirmed that AC content in macroaggregates is greater than that in microaggregates [?, ?] because organic matter in macroaggregates was more readily decomposed, while that in microaggregates was more stable. Contents of HAC and IC in macroaggregates in this study were higher than those in other aggregate fractions, leading us to conclude that IC was the main source of carbon sequestration in macroaggregates. The addition of fresh biochar to soil rapidly converts to stable soil carbon [?, ?], and forest succession increases carbon storage, especially the ratio of stable organic carbon [?, ?]. Chemical properties of IC are stable and allied to soil humus that is the primary source (50%-65%) of soil organic matter. The primary types of IC are humic and fulvic acids with moderate bonding ability, capable of bonding silt and clay to form a granular structure [?, ?]. Organic matter containing humic and fulvic acids and inorganic substances such as amorphous iron, aluminum oxide, calcium carbonate, magnesium, and aluminum silicate were incorporated to form an organic and inorganic complex that constitutes the aggregate core [?, ?]. However, macroaggregate content and MWD did not increase with increasing IC ratio. This finding indicates that macroaggregates collapsed and microaggregates and organic matter were released at some point [?, ?]. We found that macroaggregate content decreased when the ratio of IC to HAC exceeded 5.74, and as plant residues in the soil rapidly increased, aggregate and MWD contents similarly increased. It is likely that the source of fresh carbon in macroaggregates was transformed into stable IC as a result of microorganism activity, and the IC was primarily incorporated by inorganic substances with chemical bonds (calcium, iron, and aluminum). Moreover, the increase in IC content may have resulted from weak molecular forces that prevent the formation of macromolecular compounds. Here, we imply that the increase in IC content restricted further formation of macroaggregates, since there were lower macroaggregate contents and MWD values.

4.2 Effects of biomasses of roots and leaf litter on aggregate fractions and SOC components

Sequestration of HAC was greatest in topsoil, and macroaggregate contents in topsoil were mostly affected by litter and finer root (0.5-1.0 mm) biomasses. Furthermore, there was an association between macroaggregates and IC content. Impacts of finer root biomass on microaggregate contents were greater than those of other root size classes. We also found that roots entered the soil and subsequently generated root litter and secretions as a result of continuous root system metabolism that forms rhizosphere aggregates around the root system during restoration. Theoretically, MWD increased with root diameter; therefore, it is likely that the micro-ecosystem structure of macroaggregates was stronger and composed of plant roots, soil microbes and fauna, metabolic secretions, and soil particles [**?**, **?**]. Turnover volume of thick root (>2 mm) biomass was greater than that of other root size classes, potentially producing the greatest amount of biomass in topsoil [**?**, **?**]. Thus, thick roots were a major source of SOC components in macroaggregates that could encapsulate, decompose, and fix larger-sized roots.

Effects of thick root biomass on macroaggregate content in deep soil were greater than those of other root size classes, wherein sequestration of HAC was greatest. There was a positive correlation between macroaggregate content and AC, and thick root biomass had the greatest impact on microaggregate and silt and clay fractions. Unlike in topsoil, there was a greater proportion of thick roots in deep soil, and these larger roots provide better support for plant growth [**?**, **?**]. It is also likely that these thick roots could increase access to moisture in deep soil during dry seasons to maintain normal metabolism.

4.3 Effects of restoration ages on proportion of SOC components in soil aggregate fractions

Changes in proportions of SOC components in deep soil lagged behind those in surface soil in restored forests, consistent with results from previous studies [**?**, **?**]. Finer root biomass and leaf litter had the greatest impacts on proportions of topsoil aggregate fractions, whereas thick root biomass had the greatest impact on proportions of deep soil aggregate fractions. These results indicated that aggregate formation in topsoil and deep soil was mainly influenced by differences in root sizes. Macroaggregate content peaked in the 90-year-old forest in topsoil and in the 120-year-old forest in deep soil, while SOC content peaked in the 60-year-old forest in topsoil and in the 120-year-old forest in deep soil. In topsoil, SOC was rich due to leaf and root litter, whereas SOC was limited in deep soil due to relatively less root litter and lower rates of organic matter decomposition.

5 Conclusions

This study showed that natural vegetation restoration of Liaodong oak forests increased macroaggregate content and SOC in both topsoil and deep soil, particularly IC. Moreover, IC had the greatest effect on the stability of aggregate fractions. Root biomasses (0.5–1.0 mm) and leaf litter in topsoil affected IC, while roots >2.0 mm in deep soil affected IC. Our study demonstrated that restoration of natural forests improved carbon sequestration capacity in macroaggregates.

Acknowledgements

This research was funded by the National Key Research and Development Program of China (2017YFC0504601), the Science and Technology Service Network Initiative of Chinese Academy of Sciences (KFJ-STS-ZDTP-036), and the National Natural Science Foundation of China (41671513).

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