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Soil organic carbon sequestration potential of artificial and natural vegetation in the hilly regions of Loess Plateau

Zhiqi Wang[a], Shengli Guo[a,b,c,*], Qiqi Sun[b], Nana Li[a], Jishao Jiang[b], Rui Wang[c], Yanjun Zhang[a], Qingfang Liu[c], Defeng Wu[c], Rujian Li[a], Lanlan Du[a], Man Zhao[c]

[a] *Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China*
[b] *Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resource,, Yangling 712100, China*
[c] *College of Resources and Environment, Northwest A&F University, Yangling 712100, China*

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ABSTRACT

The objectives of this study were (i) to determine the stock and distribution of soil organic carbon (SOC) and the quantity and quality of fine root; and (ii) the correlation between SOC stock and fine root quantity and quality in soils of artificial and natural vegetation in the Loess Plateau. Three vegetation types (grassland, shrubland and woodland) and two restoration approaches (artificially and naturally restored from cropland) were investigated in the Yangou watershed of the Loess Plateau. SOC stock, fine root biomass and root C/N ratio at the 0–20, 20–40, 40–60, 60–80, and 80–100 cm depths were determined. The mean SOC stock of natural vegetation at the 0–100 cm depth was significantly greater than that of artificial vegetation, with an increase of 100% for woodland, 15% for shrubland, and 23% for grassland. Natural vegetation restoration led to a significantly greater SOC stock up to a depth of 100 cm for woodland, 40 cm for shrubland, and 40 cm for grassland. The fine root biomass of natural vegetation at the 0–100 cm depth was also significantly greater than that of artificial vegetation, with an increase of 170% for woodland, 140% for shrubland, and 20% for grassland. Natural vegetation restoration led to a significantly greater fine root biomass up to a depth of 100 cm for woodland, 60 cm for shrubland, and only 20 cm for grassland. There was a significant linear correlation between SOC stock and fine root biomass. Thus, natural vegetation restoration could lead to a significantly greater SOC stock, fine root biomass, and fine root C/N ratio than the artificial vegetation restoration. Fine root was an important factor influencing the differences in the SOC stock between artificial and natural vegetation.

1. Introduction

Soil organic carbon (SOC) is a major component of the terrestrial carbon (C) pool that contains twice as much C as the atmosphere (Schlesinger, 1997; Post, 2000), and changes in the SOC pool can have a considerable effect on the atmospheric CO_2 concentration (Marin-Spiotta et al., 2009; Dou et al., 2013). Vegetation restoration from cropland into woodland, shrubland, and grassland has been recognized as an effective strategy for SOC stock and distribution (Bárcena et al., 2014; Deng et al., 2014; Zhu et al., 2014; Wang et al., 2014). However, natural vegetation restoration is distinctly different from the artificial approach in terms of management (Del Galdo et al., 2003; Six et al., 2000), microclimate (temperature and moisture) (Laganière et al., 2010), species composition (Shi et al., 2013), soil properties (Xu et al., 2014), and fine root quantity and quality (Solly et al., 2014), thus resulting in significantly different SOC stock and distribution (Jin et al., 2014). This highlights the need for a better understanding of the effects of artificial and natural vegetation restoration on the SOC stock and distribution, which is helpful for the selection of appropriate restoration measures.

The Loess Plateau that covers an area of approximately 58×10^4 km^2 in China is known for its long agricultural history and serious soil erosion. It is a long-term and arduous task to control soil erosion and establish a healthy ecosystem. Since the establishment of China, great importance has been attached to the restoration of vegetation in this region (Zhou et al., 2012), and artificial vegetation restoration, such as afforestation and plantation of grasses and shrubs (Yang et al., 2014), and natural vegetation restoration (Li and Shao, 2006; Zhu et al., 2010) have been conducted in this region. Although it is generally agreed that both approaches contribute to SOC accumulation in this region,

* Corresponding author at: Institute of Soil and Water Conservation, Xinong Road 26, Yangling, Shaanxi 712100, China. Tel.: +86 29 87012411; fax: +86 29 87012210.
E-mail address: slguo@ms.iswc.ac.cn (S. Guo).

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considerable controversy remains regarding their relative efficiency. Guo and Gifford (2002) showed that the conversion of cropland to native and artificial woodland resulted in an increase of SOC by 53% and 18% about 50 years, respectively. In addition, natural vegetation had a greater litter productivity all the year round and better SOC sequestration than artificial vegetation (Jin et al., 2014; Wei et al., 2012). However, some others argued that artificial vegetation had a greater C sequestration capacity due to superior growth rate and stand structure (Gong et al., 2006; Jia et al., 2012). Vesterdal et al. (2002) found the redistribution of SOC along the soil profile rather than an obvious increase after 30 years of forestation. However, factors contributing to these conflicting results are largely understudied, and thus further investigations on the effect of artificial and native vegetation on SOC sequestration are warranted.

Fine root quantity and quality have a profound and lasting effect on the dynamics and distribution of SOC stock (Liao et al., 2014; Sucre and Fox, 2009; Wang et al., 2013; Jessy et al., 2013; Zhang et al., 2015). However, it differs significantly among vegetation types. For instance, Beech (*Fagus sylvatica* L.) has a higher fine root biomass than spruce (*Picea abies* L. Karst.) and Scotspine (*Pinus sylvestris* L.) in Norway (Finér et al., 2007); deciduous tree has a higher fine root biomass than conifer tree in the temperate zone (Jackson et al., 1996; Vogt et al., 1986); and tree fine root biomass is higher in the temperate than in the boreal zone (Vogt et al., 1986, 1995; Christoph and Hertel, 2003). Naturally restored grassland

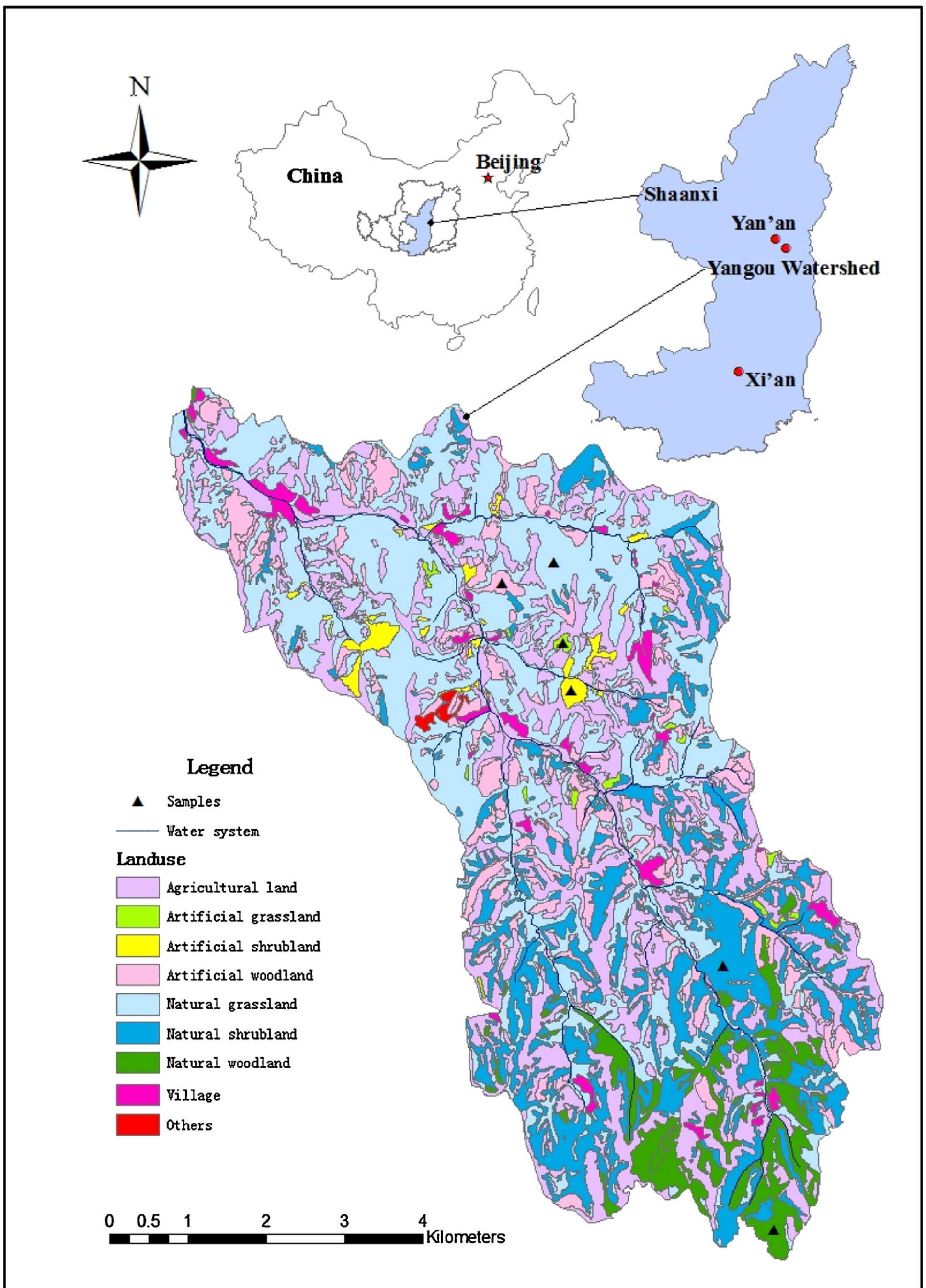

Fig. 1. Soil sampling sites and land-use map of the study watershed.

was more effective than forest plantation for SOC sequestration due to its higher carbon input from roots (Jin et al., 2014; Wei et al., 2012). However, the differences in SOC and fine root quantity and quality between artificial and natural vegetation as well as their relationships remain largely unknown.

The objectives of the present study were to determine (1) the stock and distribution of C in the 0–100 cm soil profile under artificial and natural vegetation; (2) the differences in fine root quantity and quality between artificial and natural vegetation; and (3) the relationship between SOC stock and fine root biomass in the Loess Plateau, China.

2. Materials and methods

2.1. Study area

The study area is located in the Yangou watershed (36° 27′ N–36° 32′ N, 109° 20′ E–109° 35′ E; 990–1410 m above sea level), a hilly region covering a total area of 48.0 km^2 in Baota district, Yan'an city, Shaanxi province, China (Fig. 1). There were 14 administrative villages in this region with a total population of 3133. The watershed is featured by Liang-Mao hilly-gully geomorphology, and has a main gully of 8.6 km with a gully density of 2.74 $km \times km^{-2}$. It has a semi-arid temperate climate, with an annual mean temperature of 9.8 °C and precipitation of 558 mm. The soil is the Loessi–Orthic Primosols (USDA Soil Taxonomy) and Cambisols (WRB) with a pH of 8.2 and $CaCO_3$ content of 12.6%, and is weakly resistant to erosion. The soil erosion modulus is as high as 2860 $t\,km^{-2}\,a^{-1}$ in this region (Zhu et al., 2014).

2.2. Background of vegetation in the study area

The vegetation at the study site was significantly altered by the two civil wars. In 1866, natural vegetation was recovered from abandoned cropland with the emigration of local inhabitants because of the Taiping Rebellion. During the Chinese Civil War (Kuomintang vs. Communist), a large area of natural vegetation was deforested by the army of the Communist Party for the reclamation of cropland, and one-year cropping system was implemented, with the main crops being corn, rice and millet in 1941. At present, most of the existing natural vegetation is the natural secondary forest formed from reclamation cropland and aged about 50–60 years (Shi et al., 2014).

The Loess Plateau in China has suffered from serious soil erosion and ecosystem degradation (Zhang et al., 2013a,b). Controlling soil erosion and establishing a healthy ecosystem on the Loess Plateau is a long-term and arduous task. Since the 1950s, considerable efforts have been made by Chinese government in soil erosion control and ecological rehabilitation in the Loess Plateau (Chen et al., 2006). Large-scale artificial vegetation restoration began in the late 1970s, including the Grain-to-Green Program implemented in 1999 (Zhou et al., 2012). The natural and artificial grassland communities have never been grazed, which can improve the ecological environment and the living standard for local residents because they can receive subsidies from the government and the artificial grassland was mowed 2–3 times a year providing feed for stockbreeding. The establishment of orchards on the river terrace also significantly increases the income of local farmers. Therefore, the age of artificial vegetation is 30–50 years and has a stable and balanced structure. Thus, the study area has stable natural and artificial restoration sequences (Guo et al., 2009), and the sampling sites were chosen with age about 50–60 years for natural vegetation and 40–50 years for artificial vegetation.

2.3. Experimental design

For assessment of the benefits of different vegetation restoration patterns on soil SOC, three vegetation types (grassland, shrubland and woodland) and two restoration approaches (artificial and natural) were investigated in this study. In mid-May 2007, the grassland, shrubland and woodland artificially or naturally restored from cropland with similar age, topography and geomorphic unit were selected and located by GPS on the hillslopes in the Loess Plateau. Vegetation community types were determined by the typical sampling method for terrestrial communities, with 3 quadrats at each sampling site. Quadrats of 1 m × 1 m were established for grassland to determine herb coverage, height, species and aboveground litter; and quadrats of 10 m × 10 m were established for shrubland and woodland to determine species, aboveground litter, canopy height and density, diameter at breast height (DBH), density and growing conditions. The characteristics of vegetation are described in Table 1.

2.4. Sampling and analysis

Soils in the 0–20, 20–40, 40–60, 60–80, and 80–100 cm soil profiles were sampled using a soil auger with a diameter of 3 cm (3 replicates per plot). Surface litter was brushed side down to the mineral layer before sampling. Soil bulk density was determined by the clod method using steel rings with a total volume of 100 cm^3 (50.46 mm in diameter and 50 mm in height) (Da Silva et al., 1997). The soil samples were mixed evenly, air dried, and then crushed to pass through a 0.15 mm sieve (Zhang et al., 2015). SOC was determined using the K_2CrO_7-H_2SO_4 oxidation method (Sparks et al., 1996). Soil samples were oven-dried to a constant weight at

Table 1
Structural characteristics of artificial and natural vegetation types in the Yangou watershed.

Vegetation type	Restoration approach	Longitude Latitude	Age	Prior land use	Mean canopy height (m)	Mean plant height (m)	Mean DBH (cm)	Canopy cover (%)	Litter production (Mg ha^{-1})	Dominant plant species
Woodland	Artificial	E109°31′42.0″ N36°31′25.0″	40–50	Cropland	5	3.8	15	45	15	*Robinia pseudoacacia* L.
	Natural	E109°32′55.8″ N36°27′12.7″	50–60	Cropland	6	4.2	18	60	30	*Queccus liaotungensis, Betula platyphylla* var, *Rhamnus davurica* Pall
Shrubland	Artificial	E109°32′55.0″ N36°27′11.0″	40–50	Cropland	2	1.5	7	45	1.3	*Caragana korshinski, Hippophae rhamnoides* L.
	Natural	E109°32′55.0″ N36°27′15.4″	50–60	Cropland	2	1.5	9	85	15.8	*Rosaxanthina, Ostryopsis davidiana* Dcne, *Cotoneaster acutifolius*Turcz
Grassland	Artificial	E109°31′34.6″ N36°27′45.4″	40–50	Cropland	–	0.2		48	0.2	*Medicago sativa* L.
	Natural	E109°32′57.3″ N36°27′15.3″	50–60	Cropland	–	0.15		50	6.1	*Artemisia gmelinii, Bothriochloa ischaemum, Setaria viridis* L.

105 ± 2 °C for 8–10 h, and then weighed to obtain the gravimetric soil water content (%).

Root samples in the 0–20, 20–40, 40–60, 60–80, and 80–100 cm soil profiles were gathered into plastic bags using a root auger with a diameter of 9 cm after removal of litter (3 replicates per plot), and then brought back to the laboratory for analysis. Fine roots with a diameter of <2 mm were separated from soil cores under running water (Ward, 1978), dried at 60 °C for 48 h to a constant weight, and weighed. The fine roots obtained from each sample site were mixed, ground to pass a 100 mesh sieve, and put into the plastic bags for the measurements of (1) C by K_2CrO_7-H_2SO_4 oxidation method (Sparks et al., 1996); and (2) N by the Kjeldahl method (Bremner, 1996).

2.5. Data analysis

Statistical analysis was performed by the two-way analysis of variance (ANOVA) followed by the Least Significant Difference (LSD) test using the SAS software (SAS 6.12). A $P < 0.05$ was considered statistically significant.

SOC stock was calculated using the following equations (Wang et al., 2011; Zhang et al., 2013a,b,c):

$$\mathrm{SOCS} = \sum_{i=1}^{n} \mathrm{SOCS}_i \quad (1)$$

$$\mathrm{SOCS}_i = \frac{\mathrm{BD}_i \times \mathrm{SOC}_i \times \mathrm{H}_i}{10} \quad (2)$$

where SOCS is the stock of organic C per unit land area to a depth of 1 m ($\mathrm{Mg\,ha^{-1}}$), BD is the bulk density ($\mathrm{g\,cm^{-3}}$), SOC is the mass-concentration of C in the bulk soil ($\mathrm{g\,C\,kg^{-1}}$ soil), H is the thickness of the soil layer sampled (cm), and the subscript i is number of soil layer.

Fine root biomass was calculated using the following equation:

$$R_j = 100 \times \sum_{i=1}^{j} \mathrm{r}_i \mathrm{d}_i \quad (3)$$

where R is the amount of fine root biomass ($\mathrm{Mg\,ha^{-1}}$), r is the density per unit soil bulk volume of fine root biomass (g root DW $\mathrm{cm^{-3}}$ bulk soil), and d is the thickness (cm), and the subscript i is number of soil layer, respectively.

3. Results

3.1. Vegetation restoration approaches influence SOC stock and distribution

The two-way ANOVA analysis indicated that the restoration approaches and soil depth exhibited a significant effect on SOC stock and distribution ($P < 0.001$) (Table 2). The average SOC stock of natural vegetation at the 0–100 cm depth was significantly higher than that of artificial vegetation ($P < 0.05$) (Table 3), by 100% for woodland, 15% for shrubland, and 23% for grassland. More specifically, the naturally restored woodland had a significantly higher SOC stock than the artificially restored one up to a depth of 100 cm, with the greatest difference and relative increase (+225%) observed in the 0–20 cm soil profile. The naturally restored shrubland had a significantly higher SOC stock than the artificially restored one up to a depth of only 40 cm, with the greatest difference and relative increase (+97%) observed in the 0–20 cm soil profile. The naturally restored grassland had a significantly higher SOC stock than the artificially restored one up to a depth of 40 cm, with the greatest difference and relative increase (+74%) observed also in the 0–20 cm soil profile. In addition, the distribution of SOC stock (%) in different soil layers differed significantly between artificial and natural vegetation restoration (Fig. 4). The SOC stock in the 0–20 cm soil profile accounted for 24.2–50.2% of the total SOC stock in the 0–100 cm soil profile.

Table 2
Results of two-way ANONA for the effect of restoration approaches and soil depth on soil organic carbon and fine root biomass distribution ($n = 30$).

		DF	SOC		Fine root biomass	
			F	P	F	P
Woodland	Restoration approaches	1	845.07	<0.0001	846.22	<0.0001
	Soil depth	4	710.24	<0.0001	1538.63	<0.0001
Shrubland	Restoration approaches	1	0.80	<0.0001	549.07	<0.0001
	Soil depth	4	226.49	<0.0001	1576.46	<0.0001
Grassland	Restoration approaches	1	108.79	<0.0001	41.79	<0.0001
	Soil depth	4	367.06	<0.0001	1811.18	<0.0001

3.2. Fine root biomass distribution in the soil profile of artificial and natural vegetation

Restoration approaches and soil depth showed a significant effect on fine root biomass ($P < 0.001$) (Table 2). The total fine root biomass of natural vegetation at the 0–100 cm depth was significantly greater than that of artificial vegetation ($P < 0.05$) (Table 4), with an increase of 170% for woodland (17.54 vs. 6.42 $\mathrm{Mg\,ha^{-1}}$), 140% for shrubland (8.54 vs. 3.54 $\mathrm{Mg\,ha^{-1}}$), and 20% for grassland (4.04 vs. 3.30 $\mathrm{Mg\,ha^{-1}}$), respectively. However, the differences in the fine root biomass between natural and artificial vegetation varied significantly among soil depths ($P < 0.05$), with the largest difference observed in the 0–20 soil profile (Table 4). More specifically, the naturally restored woodland had a significantly higher fine root biomass than the artificially restored one up to a depth of 100 cm, with the greatest difference (6.88 $\mathrm{Mg\,ha^{-1}}$) observed in the 0–20 cm soil profile and the greatest relative increase (+248%) observed in the 40–60 soil profile. The naturally restored shrubland had a significantly higher fine root biomass than the artificially restored one up to a depth of 60 cm, with the greatest difference (4.02 $\mathrm{Mg\,ha^{-1}}$) and relative increase (+157%) observed in the 0–20 cm soil profile. The naturally restored grassland had a significantly higher fine root biomass than the artificially restored one up to a depth of only 20 cm, with the greatest difference (1.2 $\mathrm{Mg\,ha^{-1}}$) observed in the 0–20 cm soil profile and the greatest relative increase (+142%) observed in the 80–100 cm soil profile. In addition, the distribution of fine root biomass (%) in different soil layers differed significantly between artificial and natural vegetation restoration (Fig. 5). The fine root biomass in the 0–20 cm soil profile accounted for 62.0–80.7% of the total fine root biomass in the 0–100 cm soil profile.

3.3. Relationship between SOC stock and fine root biomass

There was a significant linear correlation between SOC stock and fine root biomass ($P < 0.01$) (Fig. 2), and the correlation coefficient was higher for the natural vegetation ($R^2 = 0.96$) than that for the artificial vegetation ($R^2 = 0.57$), indicating that SOC stock was greatly affected by fine root biomass after vegetation restoration. The slope of the equation for the natural vegetation was 2.2 times that for the artificial vegetation (2.82 vs. 1.29), thus the changes of fine root biomass per unit area were more pronounced for the natural vegetation.

There was a significant linear correlation between the difference in SOC stock and fine root biomass, with a coefficient of 0.92 (Fig. 3), indicating that the difference in fine root biomass might be

Table 3
SOC storage (Mg ha^{-1}) and profile distribution under artificial and natural vegetation restoration.

Depth(cm)	Woodland			Shrubland			Grassland		
	Artificial	Natural	Difference	Artificial	Natural	Difference	Artificial	Natural	Difference
0–20	11.77 ± 1.58Ba	38.21 ± 9.83Aa	26.44	11.12 ± 0.82Ba	21.96 ± 1.98Aa	10.84	10.48 ± 0.71Ba	18.23 ± 2.11Aa	7.75
20–40	8.07 ± 0.40Bb	13.49 ± 0.77Ab	5.42	10.62 ± 0.61Ba	12.57 ± 0.49Ab	1.95	6.58 ± 0.36Bb	8.43 ± 0.48Ab	1.85
40–60	6.62 ± 0.32Bbc	9.58 ± 0.43Ac	2.96	8.38 ± 0.48Ab	6.67 ± 0.31Ac	−1.71	6.20 ± 0.71Ab	6.28 ± 0.36Ac	0.08
60–80	6.20 ± 0.30Abc	7.63 ± 0.38Ac	1.43	8.00 ± 0.46Ab	5.64 ± 0.26Ac	−2.36	6.87 ± 0.14Ab	6.50 ± 0.37Ac	−0.37
80–100	5.45 ± 0.31Ac	7.15 ± 0.35Ac	1.70	7.90 ± 0.45Ab	6.07 ± 0.28Ac	−1.83	6.51 ± 0.27Ab	5.71 ± 0.33Ac	−0.8
Sum	38.11 ± 1.50B	76.06 ± 4.90A	37.95	46.02 ± 0.8B	52.91 ± 2.5A	6.89	36.64 ± 0.9B	45.15 ± 1.70A	8.51

Sum is the total soil organic carbon at the 0–100 cm depth; Values followed by capital letters within rows and lowercase letters within columns are significantly different at $P < 0.05$.

Table 4
Fine root biomass (Mg ha^{-1}) distribution under artificial and natural vegetation restoration.

Depth(cm)	Woodland			Shrubland			Grassland		
	Artificial	Natural	Difference	Artificial	Natural	Difference	Artificial	Natural	Difference
0–20	4.30 ± 0.93Ba	11.18 ± 2.83Aa	6.88	2.56 ± 0.59Ba	6.58 ± 1.96Aa	4.02	2.05 ± 0.62Ba	3.26 ± 1.53Aa	1.21
20–40	0.82 ± 0.17Bb	2.72 ± 0.72Ab	1.90	0.42 ± 0.13Bb	1.06 ± 0.31Ab	0.64	0.76 ± 0.16Ab	0.34 ± 0.1Bb	−0.42
40–60	0.42 ± 0.12Bc	1.46 ± 0.79Ac	1.04	0.28 ± 0.06Ac	0.54 ± 0.13Ac	0.26	0.33 ± 0.04Ac	0.14 ± 0.03Ac	−0.19
60–80	0.40 ± 0.09Bc	1.36 ± 0.37Ac	0.96	0.14 ± 0.02Ad	0.20 ± 0.06Ad	0.06	0.13 ± 0.02Ad	0.22 ± 0.05Ac	0.09
80–100	0.48 ± 0.19Ac	0.82 ± 0.18Ac	0.34	0.14 ± 0.03Ad	0.16 ± 0.04Ad	0.02	0.03 ± 0.02Ae	0.08 ± 0.03Ad	0.05
Sum	6.42 ± 1.50B	17.54 ± 4.90A	11.12	3.54 ± 0.80B	8.54 ± 2.50A	5.00	3.30 ± 0.90B	4.04 ± 1.70A	0.74

Sum is the total fine root biomass at the 0–100 cm depth; values followed by capital letters within rows and lowercase letters within columns are significantly different at $P < 0.05$.

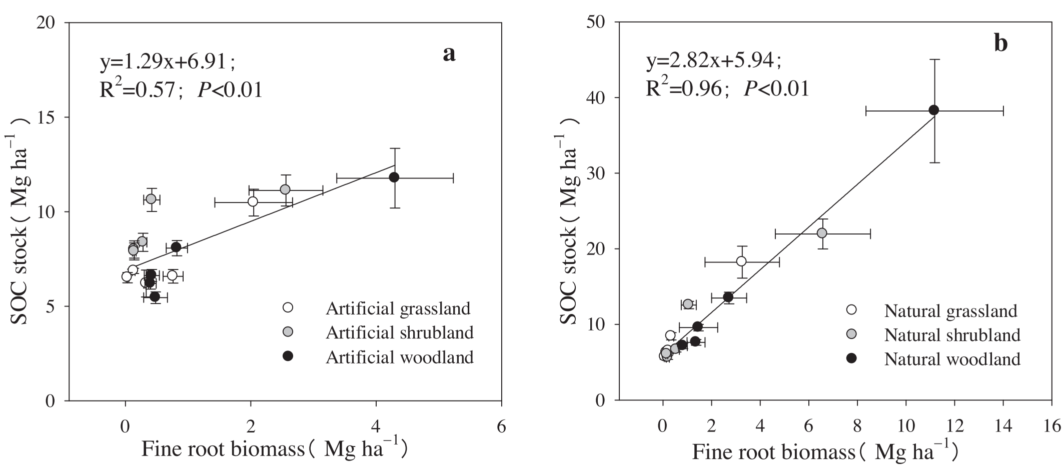

Fig. 2. Relationship between SOC stock (Mg ha^{-1}) and fine root biomass (Mg ha^{-1}) at the 0–100 cm depth under artificial and natural vegetation restoration.

the dominant factor influencing SOC stock variation after the artificial and natural vegetation restoration.

3.4. Root C/N ratio under artificial and natural vegetation

The fine root C/N ratio ranged from 46.3 to 59.8 for natural vegetation, which was significantly greater than that of artificial vegetation (22.2–42.0; $P < 0.05$) (Table 5), with an increase of 109% for woodland, 42% for shrubland, and 123% for grassland, respectively.

4. Discussion

4.1. Vegetation restoration approaches influenced the SOC stock and distribution

The SOC stock of all vegetation types at the 0–100 cm depth was significantly lower than the mean SOC stock across China (115.9 Mg ha^{-1}) for woodland (Xie et al., 2004), 72.5 Mg ha^{-1} for shrubland (Xie et al., 2004), and 53.3 Mg ha^{-1} for grassland (Yang et al., 2010), respectively. This probable be related to the low plant growth and organic matter inputs in the degraded Loess Plateau where soil erosion is severe and rainfall is rare (Guo et al., 2011; Wu et al., 2003; Zhang et al., 2013a,b,c).

The SOC stock of natural vegetation was significantly greater than that of artificial vegetation ($P < 0.05$) (Table 3), probably due to less anthropogenic disturbances, richer species diversity, and higher carbon input from roots and litter in the natural vegetation (Table 1). Zhou et al. (2013) also reported similar results that the SOC stock of natural woodland (61 Mg ha^{-1}) was significantly higher than that of artificial woodland (16 Mg ha^{-1}) at the 0–20 cm depth in the Caijiachuan watershed of the Loess Plateau. The SOC stock of shrubland at the 0–20 cm depth in this study was higher than 11.60 Mg ha^{-1} for natural shrubland (*Prunus armniaca* and *Hippophae rhamnoide*) in the Yangjuangou watershed of the Loess Plateau (Wang et al., 2011) and 5.90 Mg ha^{-1} for artificial shrubland

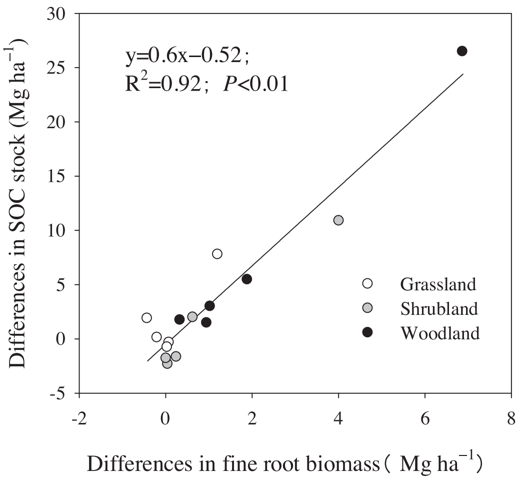

Fig. 3. Relationship between the differences in SOC stock (Mg ha^{-1}) and fine root biomass (Mg ha^{-1}) under artificial and natural vegetation restoration.

(*Korshinsk Peashrub*) in the Liudaogou watershed of the Loess Plateau (Fu et al., 2010). The SOC stock at 0–100 cm depth under natural and artificial grassland (45.15 and 36.64 Mg ha^{-1}, respectively) in this study was lower than that of natural grassland (*Arundinella hirta*, *Agropyron cristatum*, and *Artemisia argyi*) in the Dongzhuanggou Watershed (52.50 Mg ha^{-1}) (Jin et al., 2014), but higher than that of artificial grassland (*Medicago sativa*) in the Liudaogou watershed (14.70 Mg ha^{-1}) of the Loess Plateau (Fu et al., 2010).

The effect of restoration approaches on SOC distribution differed significantly among the soil depths (Fig. 4). The SOC stock of natural vegetation in the 0–20 cm soil layer was significantly greater than that of artificial vegetation (40.4–50.2% vs. 24.2–30.9%; $P < 0.05$) (Table 3). Han et al. (2010) showed that SOC stock decreased in the order of cropland > grassland > woodland > shrubland in the 0–10 cm soil layer, and grassland > cropland > shrubland > woodland in the 10–20 cm soil layer under artificial restoration. In comparison with the surface soil, SOC in deep soil (below 60 cm) varied little between artificial and natural vegetation, which was consistent with previous studies (Zhang et al., 2013a,b,c). Li et al. (2013) indicated that the SOC stock of woodland (artificial), shrubland (artificial), grassland (natural and artificial) varied greatly above the 60 cm soil layer, but little below the 60 cm soil layer. Zhang et al. (2013a,b,c) reported that the SOC concentration below 100 cm showed no significant difference for woodland (artificial), shrubland (artificial), grassland (natural and artificial), cropland, orchard, and abandoned cropland, which may be related to the distribution of vegetation roots.

4.2. Fine roots influenced SOC stock and distribution

The fine root biomass of natural vegetation was significantly greater than that of artificial vegetation ($P < 0.05$) (Table 4), which was in agreement with previous studies (Akburak and Makineci, 2012; Zhang, 2012). Akburak and Makineci (2012) indicated that the mean fine root biomass of natural forests (8.83 Mg ha^{-1}) at the 0–35 cm depth was significantly higher than that of plantation (3.68 Mg ha^{-1}) in the Belgrad Forest of Turkey. Zhang (2012) also reported that the fine root biomass of natural grass (6.29 Mg ha^{-1}) at the 0–10 cm depth was significantly higher than that of artificial grass (3.67 Mg ha^{-1}) in Hulunbeier of China. In addition, fine root biomass was considerably higher under natural restoration than under artificial restoration. This can be attributed to the fact that after long-term succession, natural vegetation communities tend to have abundant species, complete stand structures and less anthropogenic disturbances (Hertel et al., 2009), while the opposite is expected for artificial vegetation communities (Table 1), thus resulting in a significantly higher fine root biomass than that of artificial ones (Table 4).

Fine root biomass also affected the distribution of SOC stock in different depths (Fig. 5) (Chang et al., 2012; Li et al., 2013). In this study, the SOC stock of natural vegetation was greater than that of artificial vegetation in each layer for all vegetation types except grassland, with a relative increase of 14.2–247.6% (Table 3). Chang et al. (2012) found that 55% of fine root biomass was distributed in the 20 cm surface soil under woodland vegetation, with a good correspondence with the SOC stock. Natural vegetation had more fine root biomass and SOC stock in deep soils compared with those of the artificial vegetation (Tables 3 and 4) (Zhou et al., 2013), indicating that fine roots densely distributed in the deep soils may contribute to the accumulation of SOC.

There was a positive relationship between SOC and fine root biomass, but the slope of the regression line for the natural

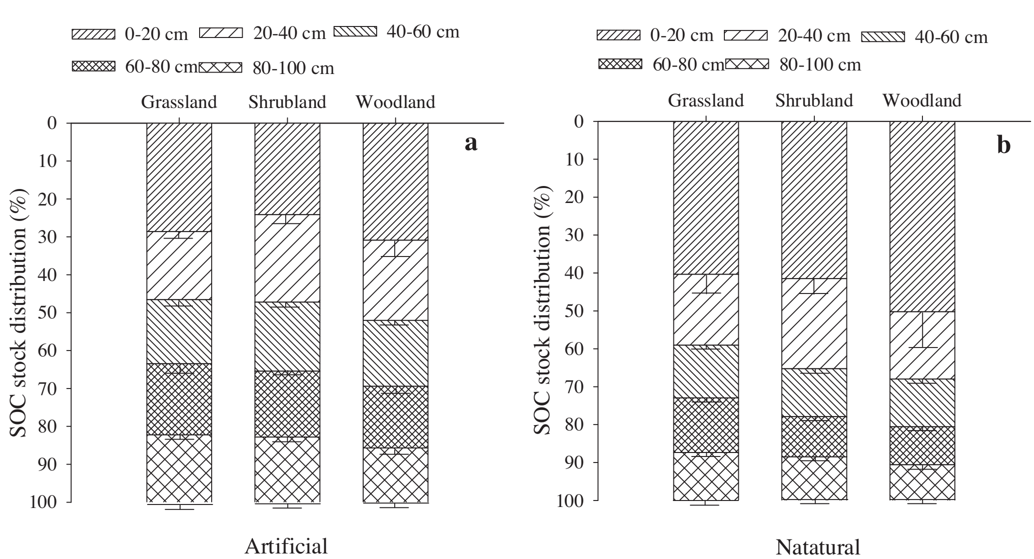

Fig. 4. Distribution of SOC stock (%) in different soil layers under artificial and natural vegetation restoration.

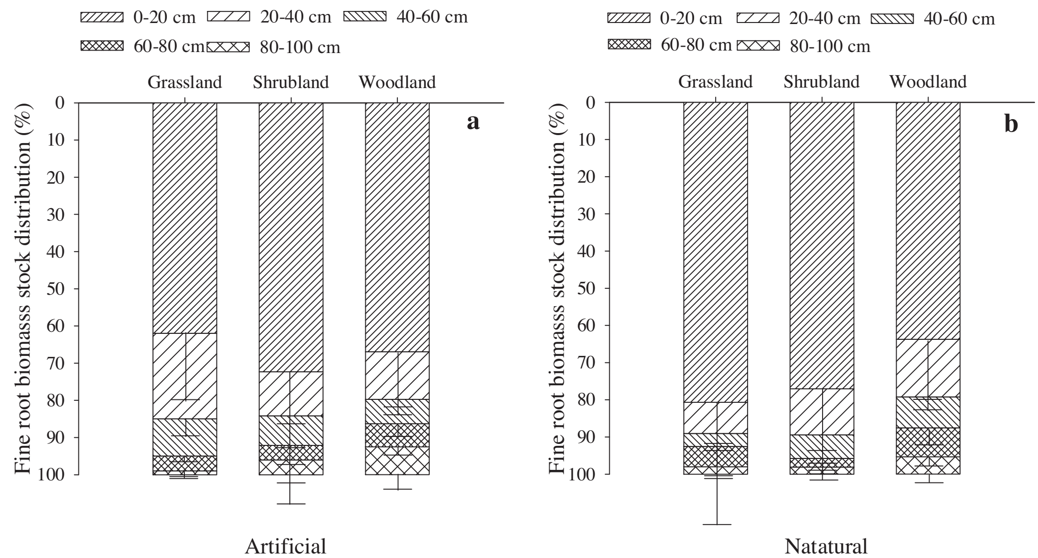

Fig. 5. Distribution of fine root biomass (%) in different soil layers under artificial and natural vegetation restoration.

Table 5
The content ($g\,kg^{-1}$) and ratio of C, N of fine root under artificial and natural vegetation restoration.

Element	Woodland		Shrubland		Grassland	
	Artificial	Natural	Artificial	Natural	Artificial	Natural
C	432.98 ± 32.70	436.11 ± 22.05	459.90 ± 2.75	453.30 ± 43.30	458.46 ± 7.40	425.65 ± 35.35
N	19.52 ± 0.41	9.43 ± 0.30	10.96 ± 0.36	7.58 ± 0.47	20.18 ± 0.83	8.41 ± 0.07
C:N	22.18B	46.25A	41.95B	59.77A	22.72B	50.63A

Values followed by capital letters within rows is significantly different at $P < 0.05$.

vegetation was 2.2 times that for the artificial vegetation (Fig. 2), probably due to the difference in fine root quality (Guo et al., 2007). The decomposition rates of organic matter varied among vegetation types due to the difference in C/N, lignin and cellulose (Vivanco and Austin, 2006). In the study, the fine root C/N of natural vegetation was greater than that of artificial vegetation ($P < 0.05$) (Table 5), which was consistent with previous studies that natural secondary forest had a greater C/N (76.1) than that of plantation (54.5) (Sucre and Fox, 2009; Wang et al., 2010). Natural vegetation (Beech) had a greater content of lignin and cellulose (45% and 30%) than that of plantation (Oak) (28% and 23%) (Sariyildiz et al., 2005), and a lower decomposition rate than artificial vegetation (0.51 vs. 0.66) (Zhang et al., 2013a,b,c). In addition, the soils of natural vegetation had less disturbance and consequently lower decomposition rate of organic matter. Therefore, the response of SOC to the changes of fine root biomass per unit was greater under the natural vegetation.

In fact, the dynamics of SOC are affected by many factors, such as roots (Upson and Burgess, 2013) and litter (Mehta et al., 2012a,b; Orazio et al., 2013). Fine root was studied in the present study due to its important influence on SOC. The contribution of other factors (e.g., litter) should also be considered (Wang et al., 2013).

5. Conclusions

Natural vegetation restoration could lead to a significantly greater SOC stock, fine root biomass and fine root C/N ratio than artificial vegetation restoration. The quantity and quality of fine root are important factors influencing the difference in SOC stock between artificial and natural vegetation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2015.05.031.

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