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Accumulation of soil organic carbon in aggregates after afforestation on abandoned farmland

Xiaorong Wei · Xuezhang Li · Xiaoxu Jia · Mingan Shao

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Abstract To understand how organic C (OC) accumulates in afforested soils and to quantify the contribution of aggregate-associated OC to OC accumulation, we investigated the changes in soil structure, total soil OC, and aggregate-associated OC from 0- to 10- and 10- to 20-cm depths in afforested forests and adjacent farmlands of northwestern China. We assessed the contribution of macroaggregate-associated OC increase to total soil OC accumulation. Afforestation increased macroaggregate amount, mean weight diameter, and mean geometric diameter but decreased the amount of microaggregate and silt + clay-sized fractions. The improvement of soil structure was greater in surface than subsurface soils and was greater in soils afforested with white birch than in soils afforested with other tree species. Fifty years after afforestation, total soil OC concentrations and stocks and aggregate-associated OC concentrations increased depending on soil depth and tree species. Afforestation increased macroaggregate-associated OC stocks but decreased microaggregate- and silt + clay-associated OC stocks. Soil OC stocks and changes in OC stocks after afforestation mainly depended on macroaggregate-associated OC stocks and their changes. The results from this study suggest that OC accumulation in afforested soils is due to the accumulation of OC in macroaggregates and the redistribution of OC from fine particles to coarser fractions.

X. Wei (✉) · X. Jia · M. Shao
State Key Laboratory of Soil Erosion and Dryland Farming in the Loess Plateau,
Northwest A&F University, Xinong Road, #26,
Yangling, Shaanxi Province, China 712100
e-mail: xrwei78@163.com

X. Li · M. Shao
Key Laboratory of Ecosystem Network Observation and Modelling, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences,
Beijing 100101, China

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Introduction

The organic C (OC) stored in forest soils accounts for 71 % of the C stored in forest ecosystems (IPCC 2007). Afforestation has a large potential to increase both soil OC concentrations and stocks (Laganiére et al. 2010; Wang et al. 2011; Wei et al. 2012a). A meta-analysis showed a 29 % increase in soil OC stocks when cropland was afforested in tropical regions (Don et al. 2011). Wei et al. (2012a) found that soil OC in northwestern China accumulated more rapidly in forest stands aged 18 to 48 years than in forest stands aged 100 or 200 years and that the accumulation of soil OC appeared to be influenced mainly by forest-derived C input. How the OC accumulates and stabilizes in forest soils during afforestation, however, is not well understood. Knowledge of these processes is essential for predicting OC dynamics in afforested soils and assessing the sequestering potential of C by afforestation in various future climatic scenarios.

In forest soils, most OC is occluded with macroaggregates (Caravaca et al. 2004; Bronick and Lal 2005). The physical protection afforded by aggregates determines the stability of new input C in soils and thus the loss of soil OC (Beare et al. 1994; Kristiansen et al. 2006; Razafimbelo et al. 2008). Deforestation, mainly for cultivation, often leads to the disintegration of soil structure and the reduction of water-stable aggregates (Islam and Weil 2000; Golchin and Asgari 2008) and thus the loss of the physical protection of OC from microbial attack (Grandy and Robertson 2007; Raiesi 2007). This promotes the mineralization of organic matter and significant losses of soil OC (Islam and Weil 2000; Golchin and Asgari 2008; Xu et al. 2011). Previous studies showed that conversion from forest to farmland can decrease the amount of macroaggregates and can result in the loss of total soil OC and macroaggregate-associated OC (Grandy and Robertson 2007; Wei et al. 2012b). However, the reverse process, the effects of afforestation of farmland on soil aggregates and the accumulation of OC in aggregates, are not well understood. We hypothesize that (1) afforestation on abandoned farmland improves soil structure and (2) the accumulation of total soil OC is dominated by OC accumulation in macroaggregates.

To test our hypothesis, we investigated the changes in soil structure and the concentrations and stocks of OC in bulk soils and aggregates. The samples were collected from 0- to 10- and 10- to 20-cm depths in afforested soils with five tree species and on the adjacent farmland soils in northwestern China. The tree species investigated were commonly used as afforestation species in the study region. The farmland was used as a control to compare the effects of afforestation on soil structure and OC levels. We assessed the contribution of macroaggregate-associated OC increase to total soil OC accumulation. The objectives were to understand how OC accumulates in soil after afforestation on abandoned farmland and to quantify the contribution of changes in aggregate-associated OC to the accumulation of total soil OC.

Materials and methods

Study site

We performed this study in the Huanglongshan Forest Area in central Shaanxi Province, China (109°38′49″–110°12′47″E, 35°28′49″–36°02′01″N, 1,100–1,300 m above sea level). The area has a continental, monsoon climate with an average annual temperature of 8.6 °C. Mean monthly temperatures range from −22.5 °C in January to 36.7 °C in July. The average annual precipitation is 612 mm, and the average frost-free period is 175 days. The loess-derived soil in the study area is classified as a cinnamon soil, which belongs to the Cambisol soil group according to the FAO system. The soil texture is silt loam. The soil profile is free of stones to a depth of 50 m.

Agricultural activity in the Huanglongshan Forest Area has a history of more than 2,000 years. Some of the farmland was converted to forest in the past, either through natural succession or through ecological restoration programs. The main coniferous tree is Chinese pine (*Pinus tabuliformis*), while the main broadleaf trees are white birch (*Betula platyphylla Suk*), birch-leaved pear (*Pyrus betulaefolia Bge*), Siberian elm (*Ulmus pumila L.*) and sea buckthorn (*Hippophae rhamnoides Linn.*).

Field investigation and soil sampling

The study consisted of paired forest and farmland sites. The farmland was tillage more than 250 years. The crops on the farmland rotated among potato (*Solanum tuberosum L.*), winter wheat (*Triticum aestivum*), maize (*Zea mays L.*), and millet (*Panicum miliaceum L*). The potato was sown in late May and harvested in early August, the winter wheat was sown in early September and harvested in early July of the following year, the maize was sown in late May and harvested in early October, and the millet was sown in mid-June and harvest in late September. The forest was established on the farmland 50 years previously. The forest age was established by the Huanglongshan Forest Bureau. The forest types in this study were birch, pine, buckthorn, pear, and elm. Three replicates of each forest type brought the total number of sites to 15 pairs. The replicates were 2–5-km apart. At each of the paired sites, the forest and farmland sites adjoined each other, the soil type was the same and the selected plots had similar physiographic conditions and slope gradients. We believe the properties between afforested and farmland soils were uniform, and we attribute differences in soil OC between paired farmland and forest to afforestation.

In the farmland at the study site, soil OC concentration at the 0–20-cm depth had not changed in the past 26 years: 5.22 $\mathrm{g\,kg^{-1}}$ in 1983 (n=334) (Wei et al. 2012a) and 5.14 $\mathrm{g\,kg^{-1}}$ in the present study (n=15). The results from an 18-year long-term experiment in the same region showed no changes in OC concentrations in 0–20-cm soils in both fallow (no crops), control (winter wheat without fertilization), and fertilized (winter wheat with N and P fertilization) treatments over time (Wei et al. 2006). Additionally, previous observations at the study site (Wei et al. 2012b) and another site (Lobe et al. 2011) showed that the aggregate distribution and aggregate associated OC concentration no longer changed after 50 years of cultivation on natural vegetation. We therefore believe that the aggregate distribution and aggregate-associated OC concentrations are similar to the soils 50 years ago when the farmland was converted to forest even fertilization and tillage have changed over time.

For each paired site, three forest plots (20×20 m) and three farmland plots (5×5 m) were established in August 2009. Each plot was at least 40 m from the boundary to reduce the possibility of tree litter being added to farmland plots. The dominant plants on the forest floor were bunge needlegrass (*Stipa bungeana Trin.*) and Dahurian bush clover (*Lespedeza daurica* (*Laxm.*) *Schindl.*). The vegetation of the farmland was maize when the samples were collected.

Soil bulk density was measured in each plot at 0–10- and 10–20-cm depths using a stainless steel cutting ring 5.0-cm high by 5.0 cm in diameter. The soil cores were dried at 105 °C for 24 h. Three representative soil samples were randomly collected in each plot for measuring aggregate size distribution and soil OC concentration. The samples were collected at 0–10- and 10–20-cm depths with a tube auger 5.0 cm in diameter. Visible pieces of organic material were removed, and the moist field soil samples were brought to the laboratory and air-dried.

Laboratory analysis

Aggregate size classes were separated by wet sieving through 0.25- and 0.053-mm sieves following the procedures described by Cambardella and Elliott (1993). The macroaggregate (>0.25 mm), microaggregate (0.25–0.053 mm) and silt + clay (<0.053 mm) fractions were dried in an oven at 50 °C for 24 h and then weighed.

A subsample of air-dried, undisturbed soil from each site was ground to pass through a 0.25-mm sieve to measure total soil OC concentration. The OC concentrations of the aggregate fractions and whole soils were analyzed using a VARIO EL III CHON analyzer (Elementar, Germany) at the Testing and Analysis Center of Northwest University, China.

Data analysis

To assess the improvement of soil structure by afforestation, we calculated parameters expressing the size distribution of aggregates (aggregation indices) as follows:

The mean weight diameter (MWD) of aggregates was calculated as (Kemper and Rosenau 1986):

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

where w_i is the weight fraction (percent) in each aggregate class and x_i is the mean diameter of each class (millimeter).

The mean geometric diameter (MGD) of aggregates was calculated as (Kemper and Rosenau 1986):

$$\mathrm{MGD} = \exp\left[\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{w_i} \times \ln \mathrm{x_i}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{w_i}}\right],$$

Stocks of soil OC (megagrams per hectare) were calculated as follows:

$$\text{Stocks of OC} = \mathrm{D} \times \mathrm{BD} \times \mathrm{OC} \times 10,$$

where D is the thickness (centimeters) of the soil layer, BD is the bulk density (grams per cubic centimeter), and OC is the OC concentration (grams per kilogram) of the 0–10- and 10–20-cm soil layers.

Stocks of OC (megagrams per hectare) in each size fraction of the 0–10- and 10–20-cm layers were calculated as follows:

$$\text{Stocks of } \mathrm{OC_i} = \mathrm{M_i} \times \mathrm{OC_i}/1{,}000,$$

where M_i is the aggregate amount in the ith size fraction (megagrams per hectare), and OC_i is the OC concentration of the ith size fraction (grams per kilogram aggregate).

A three-way analysis of variance was conducted to test the effects of afforestation, forest type, and soil depth on: (1) aggregate size distribution, MWD, and MGD; (2) total soil OC concentrations and stocks; and (3) aggregate-associated OC concentrations and stocks. Regression analysis was used to establish the relationships between: (1) changes in MWD and MGD and the changes in aggregate amounts due to afforestation, (2) total soil OC stocks and aggregate-associated OC stocks, and (3) changes in total soil OC stock due to afforestation and changes in aggregate-associated OC stock. The variance and regression analyses were conducted using SAS version 8.

Results

Effects on soil structure

Afforestation significantly improved soil structure, which varied with tree species and soil depth (Table 1). After 50 years of afforestation, macroaggregate amount significantly increased ($P<0.01$), but the microaggregate and silt + clay-sized contribution decreased (Fig. 1). The MWD and MGW values were significantly increased by 50 years of afforestation ($P<0.01$) (Fig. 2). The increases in macroaggregate amount, MWD and MGW, and the decreases in the amount of microaggregate and silt + clay-sized fractions were greater in the 0–10-cm layer compared with the 10–20-cm layer. These results suggest that afforestation on abandoned farmland can improve soil structure and increase the stability of soil aggregates. The improvement was greater in surface than subsurface soil.

Among tree species, the largest increase in macroaggregate amount was observed in soils afforested with pear in the 0–10-cm layer and with elm in the 10–20-cm layer, whereas the smallest increase occurred in soils afforested with buckthorn in the 0–10-cm layer and with pine in the 10–20-cm layer. The largest decrease in the amount of microaggregate and silt + clay-sized fractions and the largest increases of MWD and MGD values were observed in birch-afforested soils in both the 0–10- and 10–20-cm layers. The smallest decrease in the amount of microaggregate and silt + clay-sized fractions occurred in pine-afforested soils in both layers, and the smallest increases of MWD and MGD were observed in soils afforested with elm in the 0–10-cm layer and with pine in the 10–20-cm layer (Figs. 1 and 2). These results indicate that the effects of afforestation on soil structure were species dependent. Birch had the highest potential to improve soil structure while pine had the lowest potential. Additionally, we observed significant correlations between the changes in MWD and MGD and the changes in the amounts of the microaggregate and silt + clay-sized fractions (Table 2), suggesting that the effects of afforestation on MWD and MGD were determined by the changes in the amount of microaggregate and silt + clay-sized fractions.

Table 1 ANOVA results of afforestation, tree species and soil depth on soil variables

	SPP		AFF		SPP × AFF		Depth		SPP × Depth		AFF × Depth		SPP × AFF × Depth	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
Macroaggregate amount	16.1	<0.0001	1,493.1	<0.0001	5.9	0.0008	0.2	0.6951	24.0	<0.0001	0.1	0.8085	26.0	<0.0001
Microaggregate amount	209.4	<0.0001	6,414.0	<0.0001	181.5	<0.0001	1222.2	<0.0001	46.4	<0.0001	65.8	<0.0001	52.5	<0.0001
Silt + clay amount	1.6	0.2067	70.6	<0.0001	1.4	0.2690	5.2	0.0278	1.1	0.3631	0.1	0.7797	0.3	0.8862
Mean weight diameter	37.3	<0.0001	1,712.7	<0.0001	18.2	<0.0001	69.9	<0.0001	6.6	0.0004	28.2	<0.0001	12.3	<0.0001
Mean geometric diameter	14.9	<0.0001	515.2	<0.0001	12.0	<0.0001	27.5	<0.0001	2.0	0.1147	17.3	0.0002	3.7	0.0112
OC in bulk soils	18.1	<0.0001	372.7	<0.0001	4.8	0.0031	174.8	<0.0001	3.8	0.0102	139.4	<0.0001	5.8	0.0009
SOC in bulk soils	3.5	0.0152	260.0	<0.0001	2.8	0.0384	80.1	<0.0001	3.0	0.0284	89.6	<0.0001	7.2	0.0002
OC in macroaggregate	24.4	<0.0001	359.1	<0.0001	15.1	<0.0001	118.4	<0.0001	5.0	0.0024	68.0	<0.0001	8.9	<0.0001
OC in microaggregate	79.6	<0.0001	532.7	<0.0001	19.2	<0.0001	204.8	<0.0001	9.4	<0.0001	187.4	<0.0001	20.9	<0.0001
OC in silt + clay	9.4	<0.0001	67.4	<0.0001	2.5	0.0592	57.2	<0.0001	6.1	0.0006	19.6	<0.0001	7.2	0.0002
SOC in macroaggregate	18.5	<0.0001	587.4	<0.0001	11.1	<0.0001	65.0	<0.0001	5.8	0.0008	51.0	<0.0001	7.6	0.0001
SOC in microaggregate	7.4	0.0002	1.9	0.1790	8.9	<0.0001	2.5	0.1224	1.8	0.1411	17.3	0.0002	1.3	0.2889
SOC in silt + clay	0.3	0.8678	62.6	<0.0001	3.4	0.0168	0.0	0.9187	5.3	0.0015	0.1	0.7595	3.0	0.0310

OC organic carbon concentration, *SOC* organic carbon stock, *SPP* species, *AFF* afforestation

Effects on OC in bulk soils

Soil OC concentrations and stocks were increased significantly 50 years after afforestation ($P<0.05$), and the increases varied with soil depth and tree species (Table 1; Fig. 3). The OC concentrations significantly increased in the 0–10-cm layer ($P<0.01$), with increases of OC concentrations in soils afforested with birch, pear, and elm being higher than those of pine and buckthorn. In the 10–20-cm layer, the OC concentration significantly increased in the birch- and buckthorn-afforested soils ($P<0.05$) (Fig. 3). Therefore, the increase of soil OC concentration by afforestation occurred mainly in the 0–10-cm layer while birch and buckthorn influenced deeper soils.

Afforestation significantly increased soil OC stocks in the 0–10-cm layer, and the increases by pear, elm, and pine were larger than those by birch and buckthorn ($P<0.05$) (Fig. 3). In the 10–20-cm layer, the OC stocks increased by 85 % ($P<0.05$) after afforestation with buckthorn and by 10–37 % ($P>0.05$) after afforestation with other species. The overall increases in soil OC stocks afforested with pear, pine, elm, and buckthorn were significantly greater than that afforested with birch ($P<0.05$) (Fig. 3). These increases in soil OC stocks throughout the 20-cm layer 50 years after afforestation caused the accumulation of OC in surface soils, and the accumulation varied with depth and tree species.

Effects on OC associated with aggregates

Afforestation significantly increased the aggregate-associated OC concentrations ($P<0.01$), and the increases varied with soil depth and tree species (Table 1; Fig. 4). Across the tree species, the concentrations of OC associated with the macroaggregate, microaggregate, and silt + clay-sized fractions increased by 12.9, 9.9, and 3.4 gkg^{-1}, respectively, in the 0–10 cm layer ($P<0.05$) and by 5.1, 2.5 and 1.0 gkg^{-1}, respectively, in the 10–20-cm layer ($P<0.05$). The highest increase was observed in macroaggregates while the smallest increase occurred in the silt + clay-sized fraction, indicating that macroaggregates played an important role in soil OC accumulation during afforestation on abandoned farmland. Among the tree species, the increases of macroaggregate- and microaggregate-associated OC concentrations were significantly higher with birch afforestation in the 0–10-cm layer ($P<0.05$) and were significantly higher with elm afforestation in the 10–20-cm layer ($P<0.05$), implying that the increases of aggregate-associated OC concentrations by afforestation were dependent on tree species and soil depth.

Across species and soil depths, afforestation increased macroaggregate-associated OC stocks but decreased silt + clay-associated OC stocks while microaggregate-associated OC stocks were unaffected by afforestation (Fig. 5). The highest increase in macroaggregate-associated OC stocks

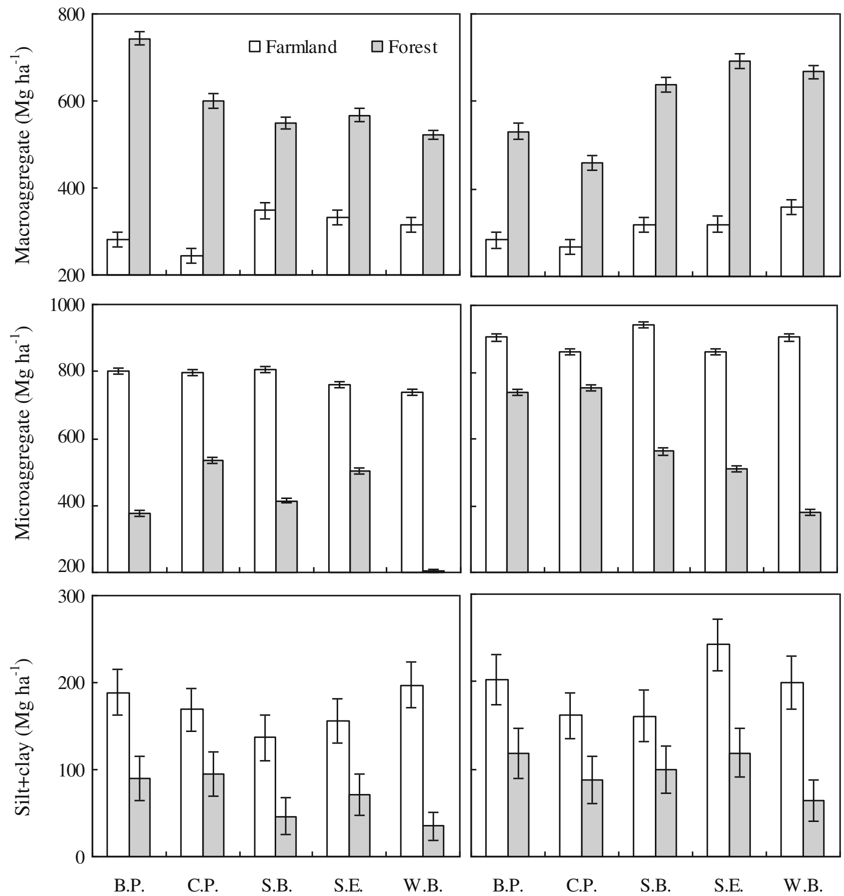

Fig. 1 The effects of afforestation on soil aggregates distribution in 0–10-cm (Left) and 10–20-cm depth (right). Birch-leaved pear (*B.P.*) (*Pyrus betulaefolia Bge*), Chinese pine (*C.P.*) (*Pinus tabuliformis*), sea buckthorn (*S.B.*) (*Hippophae rhamnoides Linn.*), Siberian elm (*S.E.*) (*Ulmus pumila L.*), white birch (*W.B.*) (*Betula platyphylla Suk*)

was observed in birch- and pear-afforested soils in the 0–10-cm layer and in elm-afforested soils in the 10–20-cm layer. Furthermore, macroaggregate-associated OC stocks made up a larger proportion of the total soil OC stocks after afforestation, whereas silt + clay-associated OC stocks made up a smaller proportion of the total OC stocks (Fig. 5). These results suggest a shift of OC from the silt + clay-sized fraction to macroaggregates and an accumulation of OC in macroaggregates, which dominated the OC accumulation in soil.

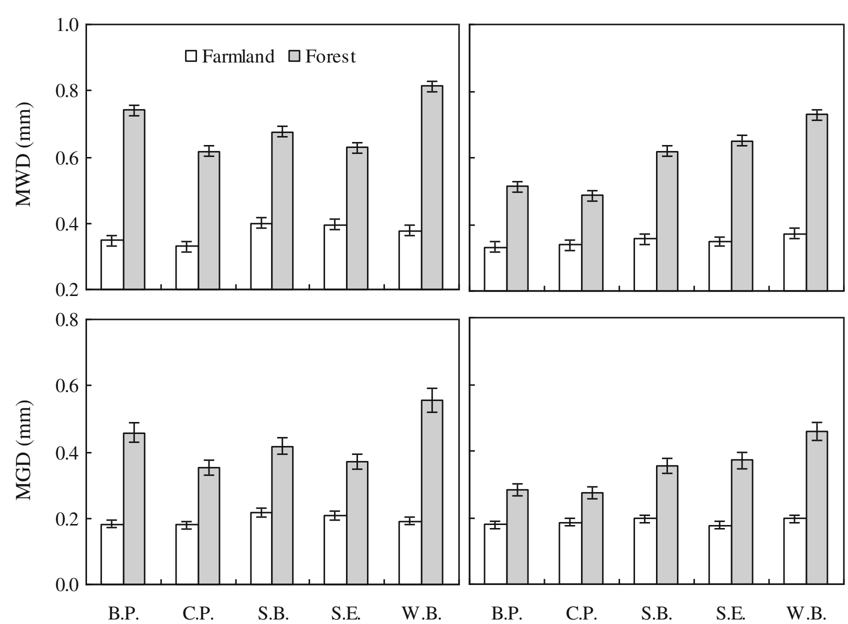

Fig. 2 The effects of afforestation on MWD and MGD of soil aggregates in 0–10-cm (left) and 10–20-cm depth (right). Birch-leaved pear (*B.P.*) (*Pyrus betulaefolia Bge*), Chinese pine (*C.P.*) (*Pinus tabuliformis*), sea buckthorn (*S.B.*) (*Hippophae rhamnoides Linn.*), Siberian elm (*S.E.*) (*Ulmus pumila L.*), white birch (*W.B.*) (*Betula platyphylla Suk*)

Table 2 The relationships between the changes in aggregates amounts and the changes in MWD and MGD of soil aggregates after 50 years afforestation (*n*=30)

	Changes in macroaggregate		Changes in microaggregate		Changes in silt + clay-sized fraction	
	r	*P*	*r*	*P*	*r*	*P*
Changes in MWD	0.413	0.0259	−0.734	<0.0001	−0.913	<0.0001
Changes in MGD	0.201	0.2551	−0.740	<0.0001	−0.887	<0.0001

Across species and soil depths, total soil OC stocks depended on macroaggregate-associated OC stocks (R^2= 0.71, P<0.0001, n=60) and microaggregate-associated OC stocks (R^2=0.25, P<0.0001, n=60), and the dependence on macroaggregate-associated OC stocks was higher than that on microaggregate-associated OC stocks. We further observed a significant contribution of changes in total soil OC stocks after afforestation on the changes in macroaggregate-associated OC stocks (R^2=0.33, P<0.0001, n=30). These results suggest that total soil OC stocks and their response to afforestation were mainly determined by macroaggregate-associated OC stocks and their response to afforestation. However, the relationships between changes in total soil OC stock and changes in aggregate-associated OC stock varied with tree species and soil depth (Figs. 3 and 5). In soils afforested with birch, soil OC accumulation in the 0–10- and 10–20-cm layers resulted from the increase in macroaggregate-associated OC stocks. In soils afforested with buckthorn, OC accumulation in the 0–10-cm layer resulted from the increase of macroaggregate- and microaggregate-associated OC stocks while OC accumulation in the 10–20-cm layer resulted solely from the increase of macroaggregate-associated OC stocks. In soils afforested with pear, elm and pine, OC accumulation in the 0–10- and 10–20-cm layers resulted from the increase of both macroaggregate- and microaggregate-associated OC stocks, and the increase of macroaggregate-associated OC stocks dominated total soil OC accumulation.

Discussion

The improvement of soil structure

We observed a significant increase in the amount of macroaggregates and the values of MWD and MGD after 50 years of afforestation (Figs. 1 and 2), supporting our hypothesis that afforestation on abandoned farmland improves soil structure. This improvement was expected because afforestated soils are not tilled and afforestation increases root biomass, exudates, and litter inputs thus favors the aggregation of soil particles (Tisdall and Oades 1982; Slobodian et al. 2002; Bronick and Lal 2005; Qiu et al. 2012). On the contrary, deforestation has been widely reported to significantly break up macroaggregates and decrease the stability of soil aggregates (Caravaca et al. 2004; Golchin and Asgari 2008; Barreto et al. 2009; Wei et al. 2012b). Literature reporting the response of soil aggregates to afforestation, however, is limited. Here we report 96 % and 93 % increases in macroaggregate amount, 88 % and 72 % increases in MWD and 120 % and 87 % increases in MGW in the 0–10- and 10–20-cm layers, respectively, after 50 years of afforestation. These increases were smaller than the decreases of macroaggregate amount, MWD and MGW after 50 years of cultivation of the forest soils at the same site (Wei et al. 2012b), suggesting that the recovery of soil structure might be slower by afforestation compared with deforestation.

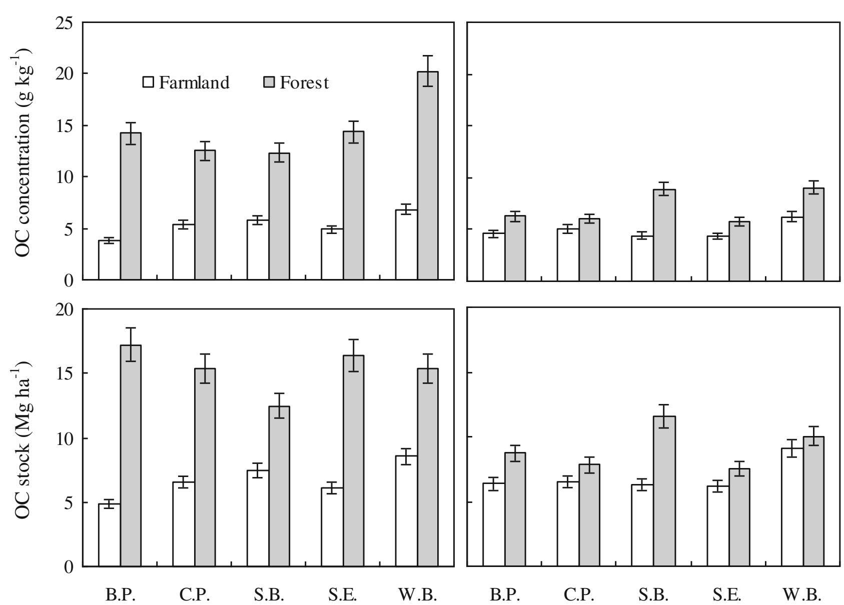

Fig. 3 The effects of afforestation on total soil OC concentrations and stocks in 0–10-cm (left) and 10–20-cm depth (right). Birch-leaved pear (*B.P.*) (*Pyrus betulaefolia Bge*), Chinese pine (*C.P.*) (*Pinus tabuliformis*), sea buckthorn (*S.B.*) (*Hippophae rhamnoides Linn.*), Siberian elm (*S.E.*) (*Ulmus pumila L.*), white birch (*W.B.*) (*Betula platyphylla Suk*)

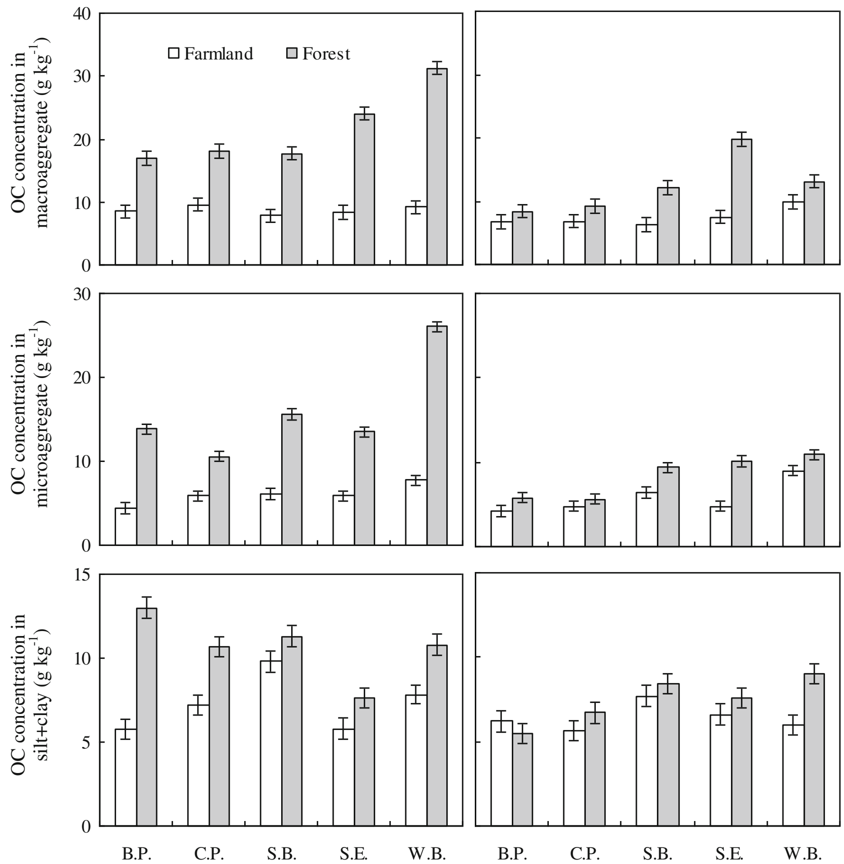

Fig. 4 The effects of afforestation on aggregate-associated OC concentrations in 0–10-cm (left) and 10–20-cm depth (right). Birch-leaved pear (*B.P.*) (*Pyrus betulaefolia Bge*), Chinese pine (*C.P.*) (*Pinus tabuliformis*), sea buckthorn (*S.B.*) (*Hippophae rhamnoides Linn.*), Siberian elm (*S.E.*) (*Ulmus pumila L.*), white birch (*W.B.*) (*Betula platyphylla Suk*)

When soil depth was considered, we observed larger changes in aggregate distribution, MWD and MGW in the 0–10-cm layer than in the 10–20-cm layer (Figs. 1 and 2), suggesting a sensitive response of soil structure in topsoils. This is because most processes affecting aggregation occur in topsoils, consistent with the effects of deforestation on soil structure being mainly observed in topsoils (Wei et al. 2012b).

Our effects of afforestation on soil structure were dependent on tree species (Table 1). Organic materials, transient organic binding agents and root exudates are important in the formation of macroaggregates by binding the relatively stable microaggregate and silt + clay-sized fractions and thus affecting the stability of aggregates (Tisdall and Oades 1982; Bronick and Lal 2005). However, these factors vary greatly with tree species. The litter and roots of coniferous trees, such as pine, generally have relatively higher C/N ratios than the litter from broadleaf trees (birch, pear, elm, and buckthorn) (Gholz et al. 2000; Gordon and Jackson 2000). Indeed, the C/N ratio of pine litter was 35 while the C/N ratio in the litter of deciduous trees ranged from 14 to 21, which is the optimal C/N ratio for litter decomposition (Heal et al. 1997). Decomposition is therefore slower in pine litter than in the litter of deciduous trees. Of the deciduous trees, birch forest produces the most litter and fine roots, which explains our observation that birch has the highest potential to improve soil structure while pine has the lowest potential (Fan et al. 2006).

The accumulation of OC in soil aggregates

It is well established that soil OC can accumulate after afforestation (Laganiére et al. 2010; Wei et al. 2012a), whereas the accumulation of OC in soil aggregates has received less attention. Our results indicate that afforestation enhances OC accumulation in coarse fractions and a shift of OC from fine fractions to coarse fractions (Fig. 5). Furthermore, the increase of macroaggregate-associated OC stocks contributes most to the increase of total soil OC stocks, supporting our hypothesis that the accumulation of total soil OC is dominated by OC accumulation in macroaggregates.

Our results confirm that aggregate-associated OC concentrations in afforested soils were significantly higher than those in farmland soils (Christensen 1992; Glaser et al. 2000; Solomon et al. 2002; Shi et al. 2010). These increases were mainly due to the increased input of new OC in aggregates and the decreased loss of initial OC associated with aggregates through mineralization and depended on tree species. Throughout the 20-cm layer, the highest increase in total soil OC concentrations and macroaggregate- and microaggregate-associated OC concentrations were observed in soils afforested with broadleaf trees while the

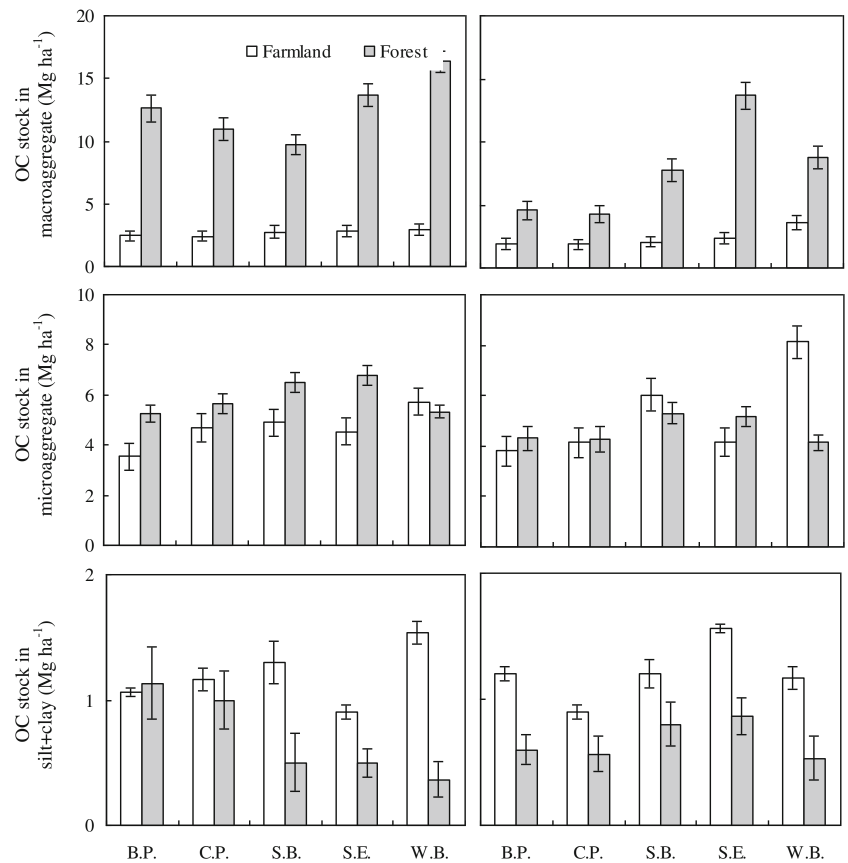

Fig. 5 The effects of afforestation on aggregate-associated OC stocks in 0–10-cm (left) and 10–20-cm depth (right). Birch-leaved pear (*B.P.*) (*Pyrus betulaefolia Bge*), Chinese pine (*C.P.*) (*Pinus tabuliformis*), sea buckthorn (*S.B.*) (*Hippophae rhamnoides Linn.*), Siberian elm (*S.E.*) (*Ulmus pumila L.*), white birch (*W.B.*) (*Betula platyphylla Suk*)

smallest increases occurred in pine-afforested soils (Figs. 3 and 4).

The accumulation of OC in macroaggregates by afforestation has been documented by others (Li et al. 2005; Haile et al. 2008; Foote and Grogan 2010), with most of the macroaggregate-associated OC consisting of recent deposition of C into the soil (Carter 1996). The shift of OC from the silt + clay fraction to macroaggregates after long-term afforestation was expected due to the integration of fine particles into macroaggregates during the establishment of forest (Fig. 1). The increase in macroaggregates by afforestation could physically protect the original and recently added OC from microbial attack and mineralization (Beare et al. 1994; Kristiansen et al. 2006; Razafimbelo et al. 2008; Wu et al. 2012), which favor the accumulation of OC in coarse fractions. Afforestation thus accelerates the incorporation of OC associated with fine particles into coarser fractions, thereby physically protecting it. We therefore conclude that the increase of OC in afforested soils was due to the accumulation of OC in macroaggregates and the redistribution of OC from fine particles to coarser fractions by the integration into macroaggregates.

Changes in aggregate-associated OC stocks are generally related to changes in the amount of aggregates and in the aggregate-associated OC concentrations (Qiu et al. 2012). In our study, the increase of macroaggregate-associated OC stocks after 50 years of afforestation was mainly due to the increases in both macroaggregate amounts and macroaggregate-associated OC concentrations. These results are consistent with the finding that the decrease in macroaggregate-associated OC stocks was due to decreases in both macroaggregate amounts and macroaggregate-associated OC concentrations observed by Wei et al. (2012b) after deforestation at the same site.

The changes in microaggregate-associated OC stocks varied with soil depth, increasing by 26 % in the 0–10-cm layer and decreasing by 12 % in the 10–20 cm layer. In the 0–10-cm layer, the increase in microaggregate-associated OC concentration (165 %) was higher than the decrease in microaggregate amount (48 %), resulting in a net increase in microaggregate-associated OC stocks. The changes in microaggregate-associated OC stocks were therefore mainly due to the increases in microaggregate-associated OC concentrations. The loss of the silt + clay-sized fraction was higher in both the 0–10- and 10–20-cm layers than were the increases of the silt + clay-associated OC concentrations, resulting in a net loss of OC stored in the silt + clay-sized fraction. These findings imply that the decrease in silt + clay-associated OC stocks after afforestation was mainly due to the incorporation of the silt + clay-sized fraction into macroaggregates.

Our study demonstrated a significant increase in macroaggregate-associated OC. However, the average increase in macroaggregate-associated OC stocks after 50 years of afforestation was smaller than the decrease in the macroaggregate-associated OC stocks after 50 years of cultivation on natural forest at the same site (Wei et al. 2012b), implying that the recovery of OC in macroaggregates by afforestation would be less than the loss of OC stored in macroaggregates by forest cultivation.

Conclusion

Our study showed that 50 years of afforestation on abandoned farmland significantly improved soil structure and resulted in the accumulation of OC in bulk soils and macroaggregates. The improvement of soil structure and the accumulation of OC varied with soil depth and tree species. Throughout the 20-cm layer, the increases in total soil OC concentrations and macroaggregate- and microaggregate-associated OC concentrations were higher in soils afforested with broadleaf trees than in pine-afforested soils. The increase of OC in afforested soils was due to the accumulation of OC in macroaggregates and the redistribution of OC from fine particles to coarser fractions by the integration into macroaggregates. The increase of macroaggregate-associated OC stocks was mainly due to the increases in both macroaggregate amounts and macroaggregate-associated OC concentrations. The effects of afforestation on OC accumulation in aggregates at different afforestation stages and in other regions should be further examined so as to establish a more general pattern on soil OC accumulation after afforestation.

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