

Dynamics of soil aggregate-associated organic carbon along an afforestation chronosequence

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Abstract

Aims The objectives of this study were to determine the dynamics of aggregate-associated organic carbon (OC) along an afforestation chronosequence on abandoned farmland of China, and to examine the contributions of changes in aggregate-associated OC to changes in total soil OC.

Methods We investigated the dynamics of OC associated with aggregates along an afforestation chronosequence. Water-stable aggregates were isolated, and the OC concentrations in total soil and the aggregates were measured.

Results Averaged across the entire chronosequence, afforestation led to 116, 128 and 108 % average increases in OC concentrations in macroaggregates, microaggregates and the <0.053 mm size class, respectively, in the top 20 cm of soil. The OC stocks in macroaggregates

increased by averages of 651 and 473 % at 0–10 and 10–20 cm depths, respectively, mostly within the first 24 years. The OC stocks in microaggregates decreased during the first 35 years and then increased during 48–200 years of afforestation. Averaged across the entire chronosequence, the increases in OC stocks in macroaggregates accounted for 83 and 100 % of the total increase in OC stocks in soils at 0–10 and 10–20 cm depths, respectively.

Conclusion Our results indicated that the accumulation of OC in soils after afforestation on abandoned farmland was mainly due to the accumulation of OC in macroaggregates.

Keywords Abandoned farmland · Afforestation age · Chinese pine · OC accumulation · OC turnover · Soil aggregate · Soil depth

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Introduction

The carbon (C) in forest ecosystems accounts for 60 % of the total C in terrestrial ecosystems, 70 % of which is stored in the soil (IPCC 2007). The afforestation of agricultural land has been widely used as a practical approach to protect soils from degradation and erosion and to rehabilitate degraded ecosystems (Zomer et al. 2008). This conversion of land use can increase the amount of organic C (OC) in soils. The conversion of agricultural land to forest has globally increased soil OC at a rate of 0.34–0.50 Mg ha⁻¹ year⁻¹, depending on climate, soil texture and stand age (Post and Kwon

2000; Laganière et al. 2010; Li et al. 2012). Zhang et al. (2010) and Deng et al. (2014) found that the “Grain for Green” project implemented across China, which aimed to improve degraded ecosystems by converting low-yield sloped cropland into grassland and woodland, increased soil OC on a regional scale at rates of 0.33–0.37 Mg ha⁻¹ year⁻¹. Martens et al. (2003) reported that the conversion of agricultural land to forest in Central America resulted in the accumulation of soil OC at the rate of 1.60 Mg ha⁻¹ year⁻¹. The accumulation of OC in soils has generally been assumed to be due to a higher input of OC to soils and to a lower loss of original OC from soils (Paul et al. 2002; Wei et al. 2012). The distribution of OC in soil fractions and their contributions to total changes in soil OC following afforestation, however, were not well addressed but would provide an explanation of the mechanism behind OC accumulation in soils after the afforestation of agricultural land.

Distributions of soil aggregates and aggregate-associated OC respond quickly to changes in land use and can be used as tools for measuring changes in soil structure and OC content (Nie et al. 2014; Six and Paustian 2014; Wang et al. 2014). The incorporation of OC in aggregates can physically protect OC from microbial decomposition and oxidation and is often used as an index to assess the stability of the OC in soils after changes in land use (Grandy and Robertson 2006; Fan et al. 2013; Wei et al. 2013a, b; Six and Paustian 2014). The conversion of farmland to forest usually leads to the aggregation of soil particles, which increases the coarse fraction and decreases the fine fraction of soil aggregates. Such effects have been extensively reported by comparing the soils from forested and agricultural land (Kaiser et al. 2010; Six et al. 2002; Degryze et al. 2004; Devine et al. 2014) or from paired adjacent forests and farmland on which forests were established (Galdo et al. 2003; Fan et al. 2013; Wei et al. 2013a). Relatively little, however, is known about the temporal dynamics of aggregates and aggregate-associated OC following afforestation. This information is important for revealing how soil OC responds to the conversion of farmland to forests and for assessing the stability of the newly sequestered OC by afforestation.

We investigated the dynamics of OC associated with aggregates following the conversion of farmland to forests. In the chronosequence used in this study, forests had been established on adjacent farmland at different times. Water-stable aggregates were isolated, and the OC concentrations in total soil and aggregates were

measured. Our objectives were to determine the dynamics of aggregate-associated OC along the afforestation chronosequence and to examine the contributions of the changes in aggregate-associated OC to changes in total soil OC.

Materials and methods

Study sites

The study sites were located in the Huanglongshan Forest in central Shaanxi Province, China (35°28'49"-36°02'01"N, 109°38'49"-110°12'47"E). The area has a continental, monsoon climate with an average annual temperature of 8.6 °C, an average annual precipitation of 612 mm, and an average frost-free period of 175 days. The soil is classified as a cinnamon soil, which develops on loess and belongs to the Cambisol soil group according to the FAO system. The soil profile is free of stones to a depth of 50 m. The dominant types of land use in the area are forest and farmland. Agricultural activity in the area has a history dating back more than 2000 years. The forests that have been established on abandoned farmland are mainly secondary and planted forests of different ages. The major forest types are Chinese pine (*Pinus tabuliformis* Carr.), Liaodong oak (*Quercus liaotungensis* Koidz.) and birch (*Betula platyphylla* Suk.). The dominant crops are maize (*Zea mays* L.) and millet (*Panicum miliaceum* L.).

Field investigation, soil sampling and laboratory analysis

We estimated the effects of afforestation on aggregate-associated OC by identifying an afforestation chronosequence in three replicate stands in natural-succession forests with stand ages of 100 and 200 years and planted forests with stand ages of 7, 18, 24, 35 and 48 years. These forests have never been harvested due to the implementation of a project by the Chinese government to protect natural forests. The stand ages of natural-succession forests were identified by Yang and Hou (2005), and the stand ages of planted forests were identified with the help of the Huanglongshan Forest Bureau. The ages of all forests were confirmed by hole-boring technique. The forests contained Chinese pine, and the farmlands were planted with maize or millet. The forest floors were dominated by bunge needlegrass

(*Stipa bungeana* Trinius) and Dahurian bush clover (*Lespedeza daurica* (Laxm.) Schindl.).

Each aged forest stand was paired with adjacent farmland on which the forest had been established. The soil types of a paired forest and farmland were the same, and the selected replicate stands had similar physiographic conditions and slope gradients. We therefore believe that the soil properties of the paired forests and farmland were uniform, and we ascribed the differences in OC in the total soil fraction and aggregate fractions to the effects of afforestation. Previous observations at the study sites (Wei et al. 2013b) and in the South African Highveld (Lobe et al. 2011) indicated that the aggregate distributions and the aggregate-associated OC concentrations had remained stable after 50 years of cultivation on natural vegetation. In our study, the farmland had been cultivated for more than 50 years before it was converted to forest (Wei et al. 2013a). The OC concentrations in soils and aggregates in the farmland 100 or 200 years ago cannot be directly quantified, so we assumed that the aggregate distributions and the aggregate-associated OC concentrations in the currently selected farmland were similar to those of the soils before the forests were established. If the OC in soils and aggregates in the farmland continued to decrease over time in our study, then our calculations would overestimate the actual increase in OC concentrations and stocks after conversion for the forest stands aged 100 and 200 years.

Three forest plots (20×20 m) and three farmland plots (5×5 m) were established at each paired forest stand and adjacent farmland in August 2009. Each plot was at least 40 m from the forest-farmland boundary. Tree density and herbage were determined for each forest stand. Five trees were randomly selected to determine height, diameter at breast height and crown density. The values of these parameters for the stands with ages of 18, 24, 48, 100 and 200 years have been reported by Wei et al. (2012). The values for the stand aged 7 years were similar to those for the stand aged 18 years, and the values for the stand aged 35 years were similar to those for the stand aged 24 years (data not shown). We did not measure the biomass for the farmland, because the aboveground biomass was harvested and removed each year.

One soil sample was collected from each plot using a stainless-steel cutting ring (5 cm in height by 5 cm in diameter) to determine the bulk densities at 0–10 and 10–20 cm depths. Three additional samples were

collected from 0–10 to 10–20 cm depths at each plot with a soil-coring kit (5.0 cm diameter). The samples were combined as a composite sample for the isolation of water-stable aggregates and the measurement of OC concentration in both total soils and the aggregates. The organic layer was removed from the surfaces of the forest plots before sampling. Visible pieces of organic material were removed from the soil samples. The soil samples were transported to the laboratory and air dried.

Water-stable aggregates were isolated 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 <0.053 mm size classes were dried in an oven at 50 °C for 24 h and then weighed.

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

Data analysis

The mean weight diameter (MWD) and mean geometric diameter (MGD) were calculated to assess the improvement of soil structure by afforestation as in Kemper and Rosenau (1986):

$$MWD = \sum_{i=1}^n x_i \times w_i \quad (1)$$

$$MGD = \exp \left[\frac{\sum_{i=1}^n w_i \times \ln x_i}{\sum_{i=1}^n w_i} \right] \quad (2)$$

where w_i is the mass fraction (%) of aggregates in the i th size class to the total mass of the sample, and x_i is the mean diameter of each class (mm).

Soil OC stocks (kg m^{-2}) in total soils were calculated as:

$$\text{Soil OC stocks} = \frac{D \times BD \times OC}{100} \quad (3)$$

where D is the thickness (cm) of the soil layer, BD is the bulk density (g cm^{-3}) and OC is the OC concentration (g kg^{-1}) at the 0–10 or 10–20 cm soil depths.

Stocks of OC (g m^{-2}) in each aggregate size class at the 0–10 and 10–20 cm depths were calculated as:

$$\text{Stocks of OC}_i = \frac{D \times BD \times w_i \times \text{OC}_i}{10} \quad (4)$$

where OC_i is the OC concentration of the i th aggregate size class (g kg^{-1} aggregate).

The absolute and relative changes in these variables were calculated using farmland soil as a control for each stand age. A three-way analysis of variance was conducted to examine the direct and interactive effects of land-use change (afforestation), stand age and soil depth on: 1) aggregate distribution, MWD and MGD, 2) total soil OC concentration and stock and 3) aggregate-associated OC concentration and stock. To determine the effect of aggregate distribution on soil OC, we examined the relationships between aggregate proportions and OC concentration and stock in total soils. We also examined the relationships between total OC concentration and aggregate-associated OC concentration and between total OC stock and aggregate-associated OC stock. To determine the contribution of OC accumulation in aggregates to the accumulation in total soils, we examined the relationships between changes in total OC stock and changes in aggregate-associated OC stock. These relationships were established by linear or nonlinear regression analysis. The variance and regression analyses were conducted using JMP version 10 software.

The dynamic behavior or turnover of soil OC is generally determined by the balance between inputs and outputs of the OC to and from soil and is most often quantified as the OC mean residence time (MRT). The MRT of soil OC is defined as the average time the carbon stays in the soil (Fröberg et al. 2011). In our study, the dynamics of total soil OC concentration and stock and of aggregate-associated OC concentration along the afforestation chronosequence were fitted with the first-order model that was most commonly used (Six and Jastrow 2002):

$$C = C_e - (C_e - C_0) \times e^{-kt} \quad (5)$$

where t is the time since afforestation (year), C_e is the OC concentration (g kg^{-1}) or stock (kg m^{-2}) when soil reaches a new steady state, C_0 is the initial OC concentration (g kg^{-1}) or stock (kg m^{-2}) before afforestation ($t=0$), k is the turnover rate constant (year^{-1}) and $C_e - C_0$ is the potential increase in OC when soil reaches a new

steady state. We assessed the C_0 by fitting the first order model rather than using OC in farmland soils as C_0 due to the variations of OC in farmland among sites. The parameters of the first-order model (C_0 , C_e and k) were obtained by fitting the model across the three replications along the afforestation chronosequence. All farmland soils were pooled as time zero and afforested soils were pooled as different times when fitting the model. The model fitting was conducted using exponential model with 3 parameters in JMP software (version 10).

The MRT was calculated as:

$$\text{MRT} = \frac{1}{k} \quad (6)$$

The overall input rate of OC due to afforestation (I) across the 200 years of afforestation was calculated as:

$$I = k \times C_e \quad (7)$$

Because the changes in aggregate-associated OC stocks after land-use changes were determined by the changes in aggregate proportion and aggregate-associated OC concentration (Qiu et al. 2012; Wei et al. 2013b), we did not calculate these parameters of the stock of aggregate-associated OC.

Results

The dynamics of aggregation along the afforestation chronosequence

Afforestation increased the proportion of macroaggregates while decreasing the proportion of microaggregates and the <0.053 mm size class compared with farmland (Fig. 1, Table 1). The changes in the proportion of aggregates following afforestation, however, were not affected by soil depth, as indicated by the lack of interactions between afforestation and soil depth, or stand age, except for the <0.053 mm size class (Table 1). For example, regardless of stand age, the proportion of macroaggregates increased by 43–499 and 6–230 % at the 0–10 and 10–20 cm depths, respectively, and the proportion of microaggregates decreased by 17–60 and 3–38 % at the 0–10 and 10–20 cm depths, respectively. The largest changes in the distribution of aggregates generally occurred within the first 24 years across the 0–10 and 10–20 cm depths (Fig. 1).

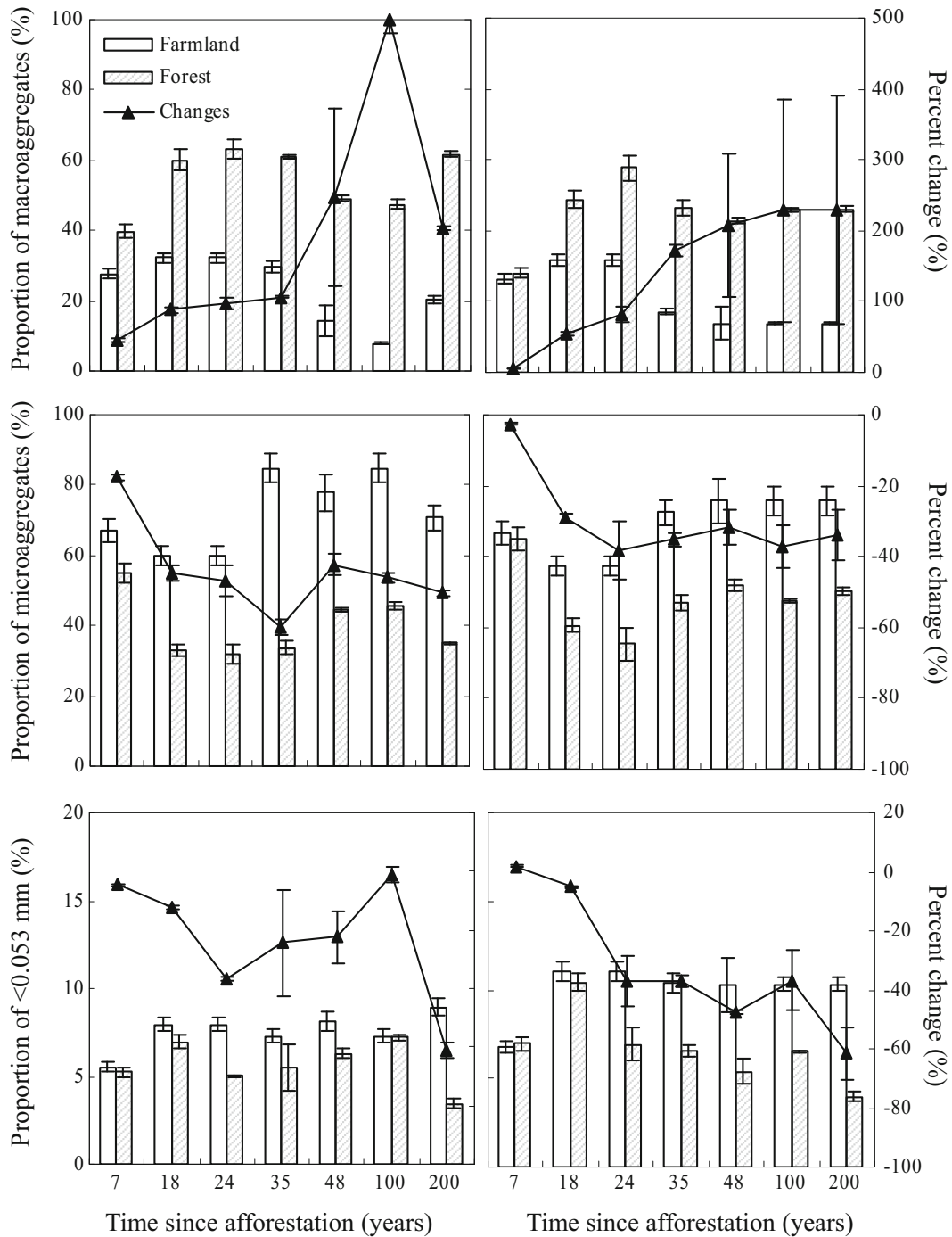


Fig. 1 Dynamics of soil aggregate proportions at the 0–10 (*left*) and 10–20 cm (*right*) depths along the afforestation chronosequence. *Dashed lines* are percent changes of aggregate proportions. *Error bars* are the standard errors of the mean

Afforestation consistently increased MWD and MGD (as indicated by the lack of interactions between afforestation and stand age), with the most rapid increases occurring during the first 24 years (Fig. 2,

Table 1). The changes in MWD were independent, but the changes in MGD were dependent, on soil depth (Table 1). MWD increased by 39–344 and 5–185 % at the 0–10 and 10–20 cm depths, respectively, and MGD

Table 1 Results of variance analysis for all variables

	MA	MI	SC	MWD	MGD	OC	SOC	MA-OC	MI-OC	SC-OC	MA-SOC	MI-SOC	SC-SOC
F													
Afforestation	141.03	107.49	31.53	144.59	110.82	167.81	113.24	81.97	90.21	42.84	146.04	1.49	5.05
Stand age	0.71	0.59	0.09	0.69	0.25	43.11	14.13	9.81	6.41	4.28	2.87	0.08	0.06
Soil depth	5.09	2.33	13.82	4.84	8.56	65.94	36.05	59.93	60.57	14.63	38.79	18.14	0.87
Afforestation×Stand age	0.11	1.02	16.88	0.08	0.14	34.66	9.49	11.77	14.52	6.34	1.51	4.67	1.36
Afforestation×Soil depth	1.91	2.14	0.87	2.00	5.52	45.62	23.47	35.34	36.30	1.32	28.78	5.62	0.26
Stand age×Soil depth	0.12	0.12	0.03	0.07	0.29	9.48	1.20	2.40	4.08	3.30	0.64	0.00	2.03
Afforestation×Stand age×Soil depth	0.02	0.16	2.61	0.13	0.11	20.44	5.35	5.20	7.67	1.24	0.79	0.39	0.15
P													
Afforestation	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.23	0.03
Stand age	0.40	0.45	0.77	0.41	0.62	<0.01	<0.01	<0.01	0.02	0.045	0.10	0.78	0.80
Soil depth	0.03	0.13	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.36
Afforestation×Stand age	0.74	0.32	<0.01	0.78	0.71	<0.01	<0.01	<0.01	<0.01	0.02	0.23	0.04	0.25
Afforestation×Soil depth	0.17	0.15	0.36	0.16	0.02	<0.01	<0.01	<0.01	<0.01	0.27	<0.01	0.02	0.61
Stand age×Soil depth	0.73	0.73	0.87	0.79	0.60	<0.01	0.28	0.13	0.05	0.08	0.43	0.99	0.16
Afforestation×Stand age×Soil depth	0.88	0.69	0.11	0.72	0.74	<0.01	0.03	0.03	<0.01	0.27	0.38	0.53	0.70

Bold values were significant at $P < 0.05$

MA proportion of macroaggregates (%), MI proportion of microaggregates (%), SC proportion of <0.053 mm size class (%), MWD mean weight diameter (mm), MGD mean geometric diameter (mm), OC OC concentration in total soils (g kg^{-1}), SOC OC stock in total soils (kg m^{-2}), MA-OC OC concentration in macroaggregates (g kg^{-1}), MI-OC OC concentration in microaggregates (g kg^{-1}), SC-OC OC concentration in <0.053 mm size class (g kg^{-1}), MA-SOC OC stock in macroaggregates (g m^{-2}), MI-SOC OC stock in microaggregates (g m^{-2}), SC-SOC OC stock in <0.053 mm size class (g m^{-2})

increased by 50–331 and 5–217 % at the two depths, respectively.

The dynamics of OC in total soils along the afforestation chronosequence

The concentration and stock of OC in total soils significantly increased following afforestation on abandoned farmland, and the increases were larger at the 0–10 cm depth than at the 10–20 cm depth ($P < 0.01$ for the interaction between afforestation and soil depth) (Fig. 3, Table 1). The increases in soil OC after afforestation were affected by stand age ($P < 0.01$ for the interactions between afforestation and stand age), and the effects of stand age varied with soil depth ($P < 0.05$ for the interactions among afforestation, stand age and soil depth). Across the entire afforestation chronosequence, the OC concentration and stock increased by 26–363 and 53–261 %, respectively, at the 0–10 cm depth and by 5–153 and 0–130 %, respectively, at the 10–20 cm

depth. At the 0–10 cm depth, the increases were larger in afforestation stands with ages of 100 and 200 years than in stands with ages of 7–48 years. At the 10–20 cm depth, the increases were larger in stands with ages of 24–200 years than in stands with ages of 7–18 years.

The predictions by the first-order model suggested mean residence times of OC concentrations were 50 and 78 years at the 0–10 and 10–20 cm depths, respectively. The OC concentration would increase by 365 and 111 % at the 0–10 and 10–20 cm depths, respectively, with potential increases of 34.3 and 9.0 g kg^{-1} , respectively, when the steady state was reached (Table 2). The overall input rate of OC concentration was 0.88 and 0.22 $\text{g kg}^{-1} \text{ year}^{-1}$ for the two soil depths, respectively. The mean residence times of OC stocks were 36 and 45 years at the two depths, respectively. The potential accumulation of OC stocks were 2.4 and 0.9 kg m^{-2} at the 0–10 and 10–20 cm depths, respectively, when the steady state was reached, with the overall input rate of 0.10 and 0.04 $\text{kg m}^{-2} \text{ year}^{-1}$ (Table 2).

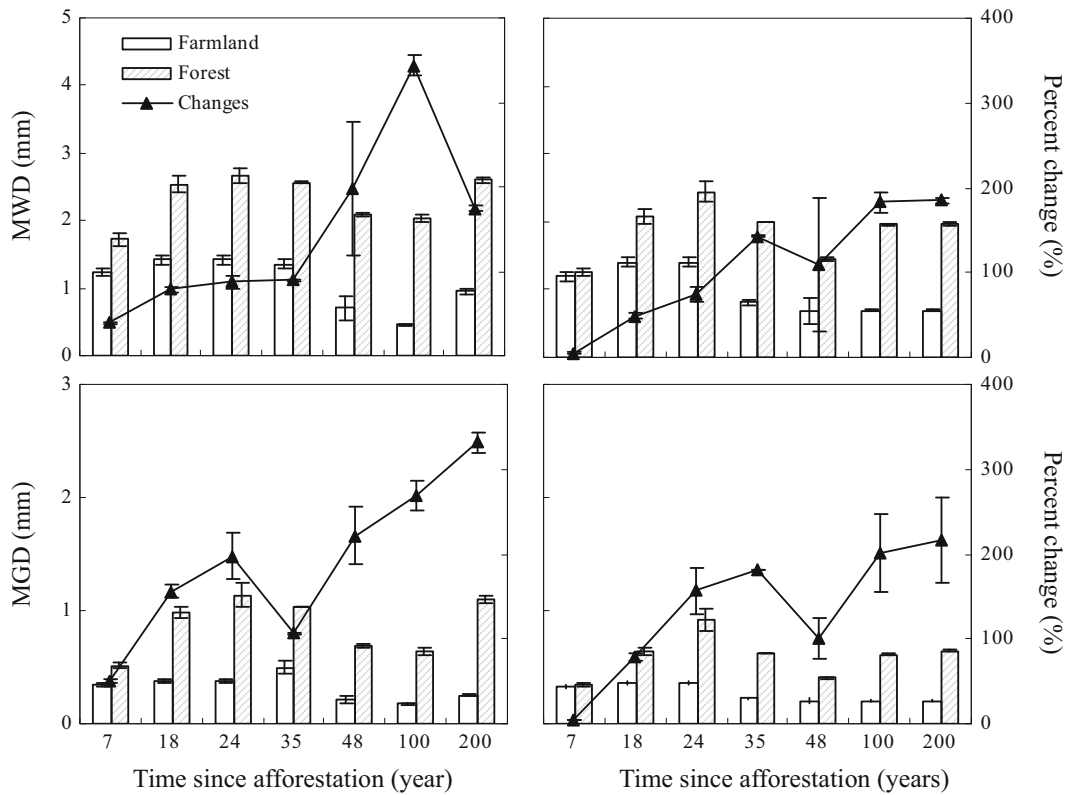


Fig. 2 Dynamics of mean weight diameter (MWD) and mean geometric diameter (MGD) of soil aggregates at the 0–10 (left) and 10–20 (right) cm depths along the afforestation chronosequence.

Dashed lines are percent changes of MWD and MGD. Error bars are the standard errors of the means

The dynamics of OC in aggregates along afforestation chronosequence

At the 0–10 cm depth, the averaged OC concentrations in macroaggregates across the farmland and afforested land were 30 and 87 % higher than the OC concentrations in microaggregates and the <0.053 mm size class ($P<0.05$). At the 10–20 cm depth, the averaged OC concentrations in macroaggregates were 23 and 45 % higher ($P<0.05$), respectively. Afforestation increased the OC concentration in aggregates, which varied with soil depth and stand age (Fig. 4, Table 1). The rapid increases were observed for the first 100 years, and the relative increases were larger at the 0–10 than at the 10–20 cm depth. Additionally, the increases in OC concentrations varied with aggregate size class at both soil depths. The OC concentrations at the 0–10 cm depth increased by averages of 150, 184 and 116 % in the macro- and microaggregates and the <0.053 mm size class, respectively. The OC concentrations at the 10–20 cm depth increased by averages of 68, 60 and 99 %,

in the macro- and microaggregates and the <0.053 mm size class, respectively.

The mean residence times of OC concentrations in the macro- and microaggregates and the <0.053 mm size class were 31, 28 and 20 years, respectively, at the 0–10 cm depth and 48, 45 and 42 years, respectively, at the 10–20 cm depth (Table 2). The turnover-rate constant of OC concentration increased as aggregate size decreased, following the order of macroaggregates < microaggregates < <0.053 mm size class (Table 2). The predicted increases in OC concentrations when a steady state was reached were larger at the 0–10 than at the 10–20 cm depth, depending on the aggregate size class. The predicted increases in OC concentration in macro- and microaggregates at the 0–10 cm depth were 75 and 49 % higher, respectively, than that in the <0.053 mm size class. The predicted increases in OC concentration in the macroaggregates and the <0.053 mm size class at the 10–20 cm depth were 56 and 55 % higher, respectively, than that in microaggregates.

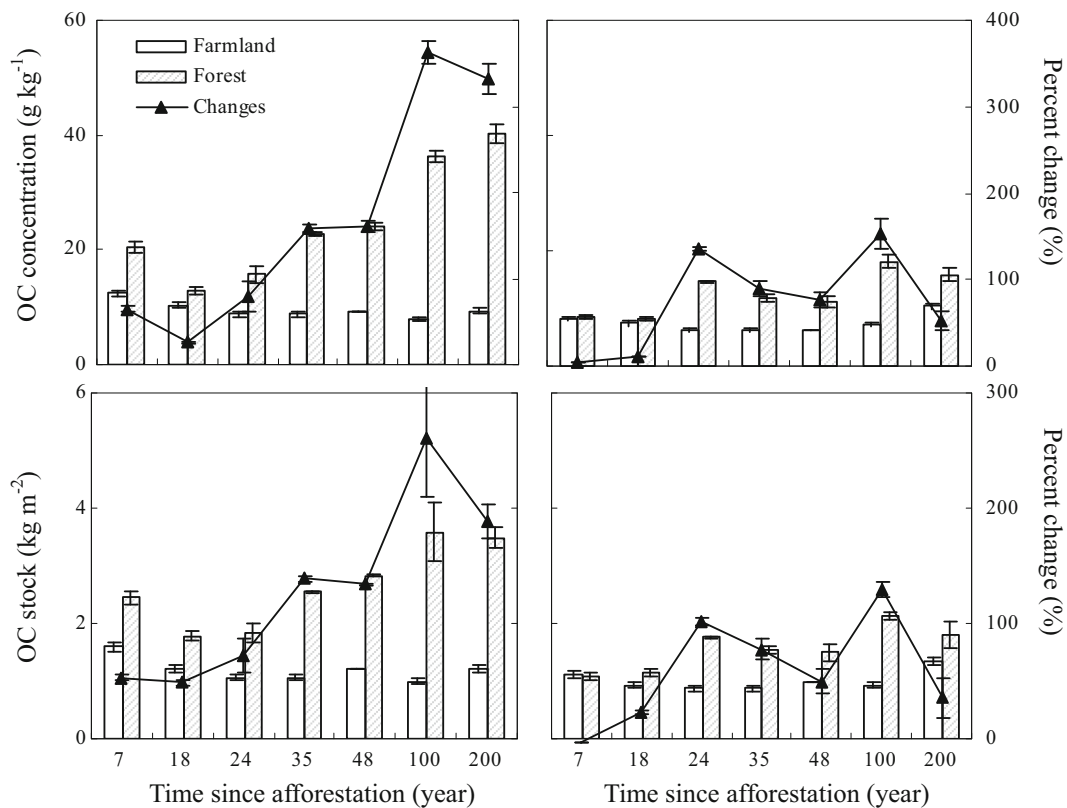


Fig. 3 Dynamics of total soil OC concentration and stock at the 0–10 (*left*) and 10–20 (*right*) cm depths along the afforestation chronosequence. *Dashed lines* are percent changes of OC concentrations and stocks. *Error bars* are the standard errors of the means

The effects of afforestation on the stocks of OC in the aggregates varied with aggregate size class and soil depth (Fig. 5, Table 1). The OC stocks in macroaggregates were significantly increased by afforestation

($P < 0.01$), and the increase was significantly higher at the 0–10 cm depth than the 10–20 cm depth ($P < 0.01$ for the interactions between afforestation and soil depth). For example, the OC stocks in macroaggregates

Table 2 Parameters describing total soil and aggregate-associated organic C (OC) dynamics

	OC concentration		OC stock		OC concentration					
	Total soils				Macroaggregates		Microaggregates		<0.053 mm size class	
Soil depth	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm
OC at steady state ^a	43.7	17.0	3.6	1.9	40.8	17.8	32.6	11.4	23.6	12.1
Potential increase ^b	34.3	9.0	2.4	0.9	27.9	7.1	23.8	4.5	16.0	7.0
Turnover-rate constant (year ⁻¹)	0.020	0.013	0.028	0.022	0.032	0.021	0.036	0.022	0.049	0.024
Mean residence time (year)	50	77	36	45	31	48	28	45	20	42
Overall input rate ^c	0.876	0.217	0.100	0.042	1.308	0.371	1.179	0.254	1.147	0.288

^a The OC at a steady state is the C_e from the first-order model. The units are g kg^{-1} for OC concentration and kg m^{-2} for OC stock

^b The potential increase is the $C_e - C_0$ from the first-order model. The units are g kg^{-1} for OC concentration and kg m^{-2} for OC stock

^c The units are $\text{g kg}^{-1} \text{ year}^{-1}$ for OC concentration and $\text{kg m}^{-2} \text{ year}^{-1}$ for OC stock

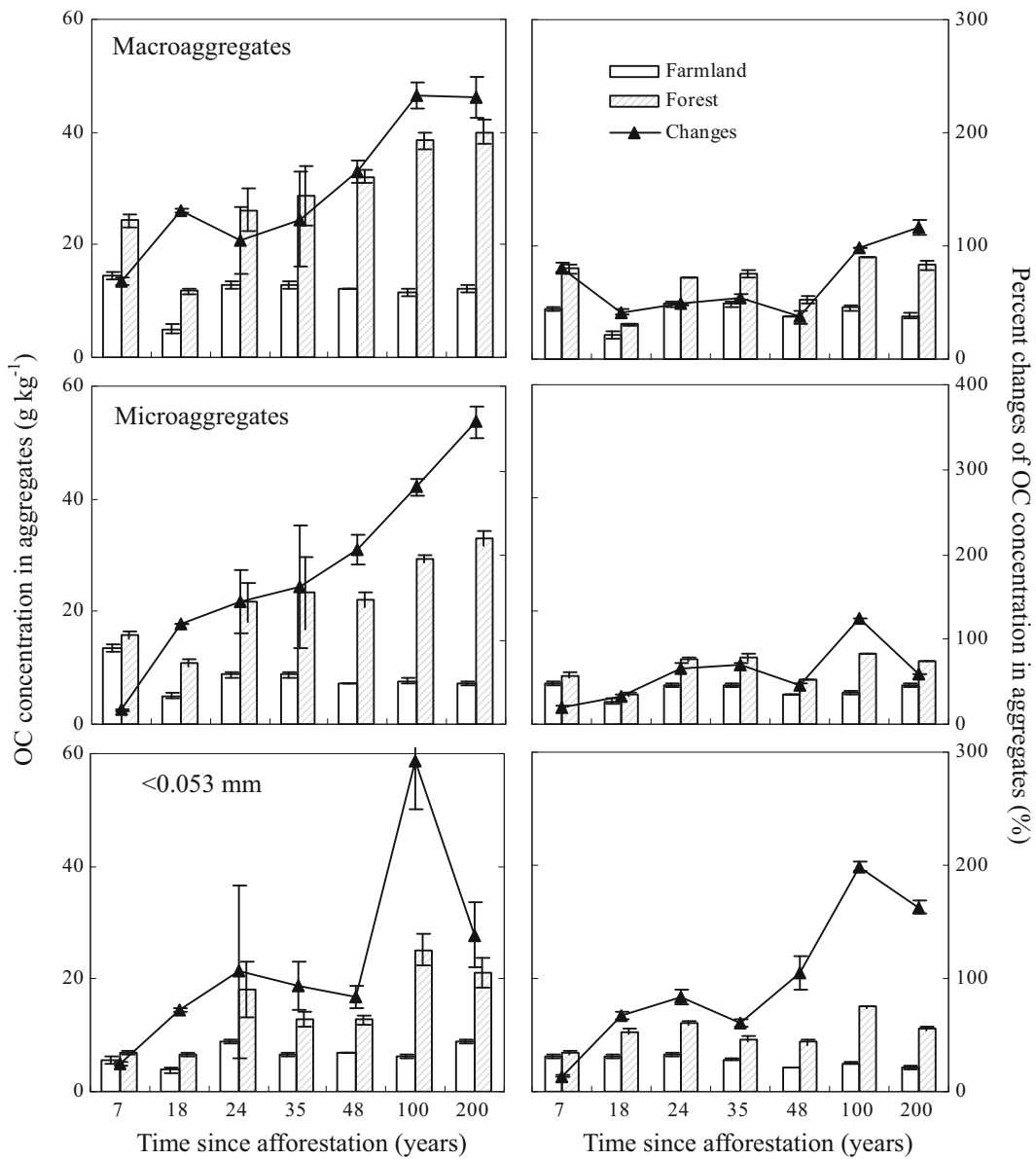


Fig. 4 Dynamics of aggregate-associated OC concentration at the 0–10 (left) and 10–20 (right) cm depths along the afforestation chronosequence. Dashed lines are percent changes of OC

concentrations in aggregates. Error bars are the standard errors of the means

increased by averages of 651 and 473 % at the 0–10 and 10–20 cm depths, respectively, with most of the increases occurring during the first 24 years. The OC stocks in microaggregates were not affected by afforestation ($P=0.23$), but there was a significant interaction between afforestation and stand age ($P=0.04$) or soil depth ($P=0.02$). At the 0–10 cm depth, the OC stocks in microaggregates was not affected by afforestation during the first 35 years

of afforestation (except for the 18 years forest that was significantly decreased) but increased during 48–200 years of afforestation. At the 10–20 cm depth, the OC stock in microaggregates decreased during the first 35 years of afforestation but was not affected during 48–200 years of afforestation. The OC stocks in the <0.053 mm size class were increased by afforestation, but the effect was independent of stand age or soil depth.

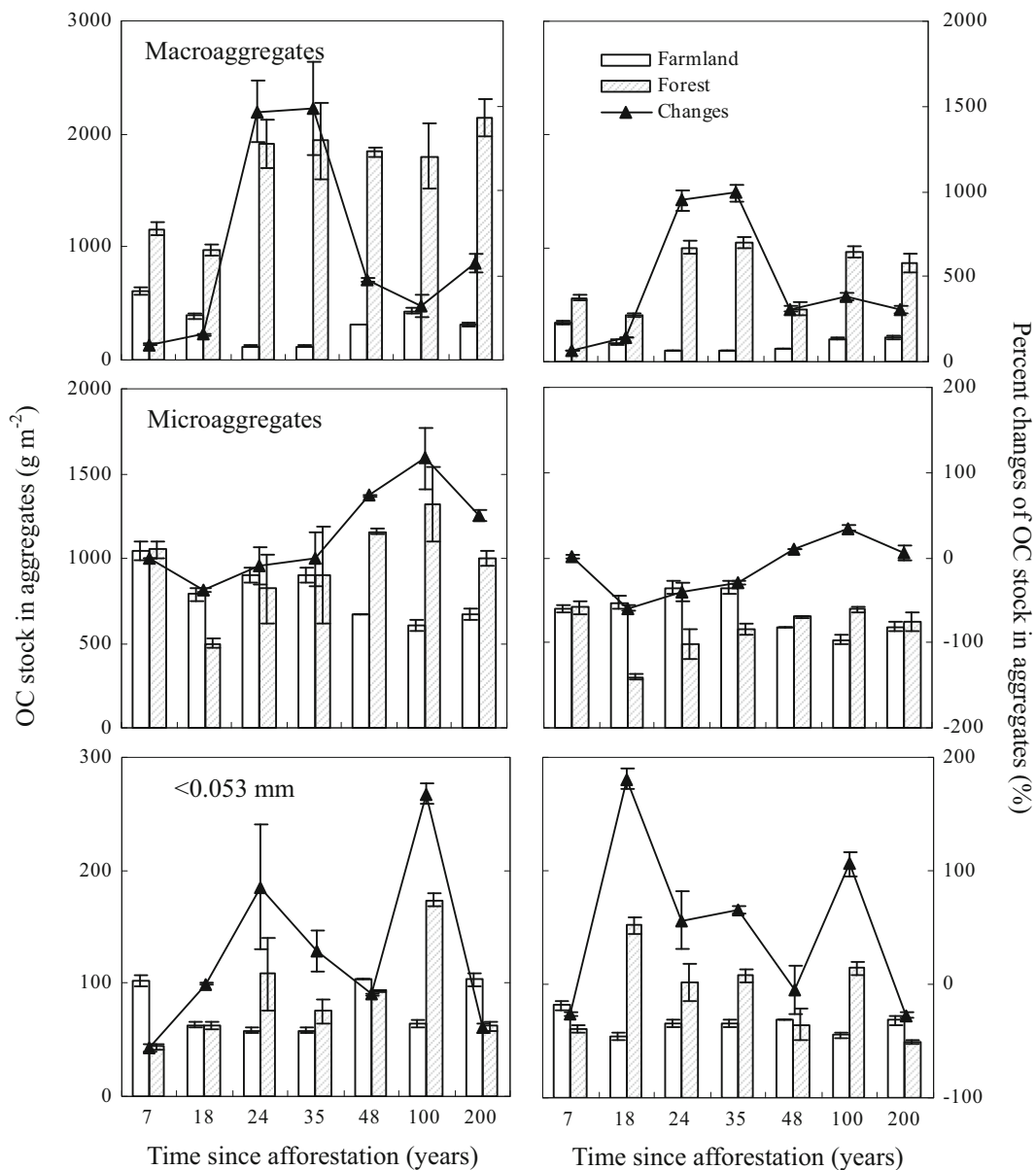


Fig. 5 Dynamics of aggregate-associated OC stock at the 0–10 (*left*) and 10–20 (*right*) cm depths along the afforestation chronosequence. *Dashed lines* are percent changes of OC stocks in aggregates. *Error bars* are the standard errors of the means

Relationship between OC accumulations in aggregates and total soils

The OC concentration and stock in total soils were positively correlated with the proportion of macroaggregates but negatively correlated with the proportions of microaggregates and the <0.053 mm size class (Fig. 6). The OC concentration in total soils was also positively correlated with the OC concentrations in the aggregate size classes (Fig. 7). The OC concentration in total soils,

however, was more dependent on the OC concentrations in macro- and microaggregates than on the OC concentrations in the <0.053 mm size class. For example, the slopes and R^2 of the linear relationships between total soil OC concentration and OC concentration in macro- or microaggregates were higher than those between total soil OC concentration and OC concentration in the <0.053 mm size class. Similarly, the OC stock in total soils was positively correlated with the OC stocks in aggregates (Fig. 7). The OC stocks in total soils were

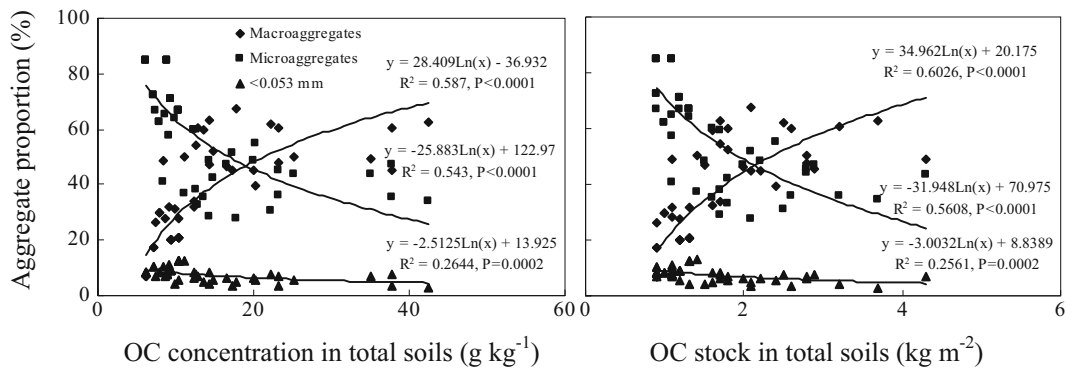


Fig. 6 Relationships between aggregate proportion and total soil OC concentration and stock

more dependent on the OC stocks in macro- and microaggregates than on those in the <0.053 mm size class.

Our results further showed that the accumulation of OC in total soils was mainly due to the accumulation of OC in macro- and microaggregates at the 0–10 cm depth but also to the accumulation of OC in macroaggregates at the 10–20 cm depth. At the 0–10 cm depth, the increases in OC stocks in macro- and microaggregates accounted for 86 and 13 %, respectively, of the total increase in OC stocks. At the 10–20 cm depth, the increases in OC in macroaggregates accounted for 100 % of the total increase in OC stocks. Furthermore, the accumulation of OC stocks in total soils significantly increased with the accumulation of OC in macro- and microaggregates (Fig. 8).

Discussion

Initial decreases in soil OC during the first few years after conversion of farmland to forest have been widely observed and are possibly due to the lower productivity of the new forest and the higher loss of OC from soil

disturbance (Vesterdal et al. 2002; Don et al. 2009; Deng et al. 2014). An analysis by Deng et al. (2014) showed that soil OC stocks along the 0–100 cm soil profile decreased within the first 5 years of conversion of cropland to grassland or forest following the implementation of the Grain for Green project. Laganière et al. (2010) reported that soil OC stocks decreased by an average of 5.6 % during the first 10 years after the conversion of agricultural land to forest, but Compton and Boone (2000) and Vesterdal et al. (2002) reported that soil OC was not affected during the first 30 years of afforestation.

We did not observe an initial decrease in OC concentration or stock in soils, perhaps because the depth of the soil sampled in this study was relatively lower than that in the other studies (Fig. 3). Soil OC is considered to be more vulnerable in the topsoil than the subsoil to land-use changes and other soil management (Don et al. 2011; Wei et al. 2014b). For example, OC stocks responded more in 0–20 cm soils than in soils below 20 cm following the implementation of the Grain for Green project (Deng et al. 2014; Song et al. 2014). Vesterdal et al. (2002) found that 30 years of afforestation on arable land led to the redistribution of OC along

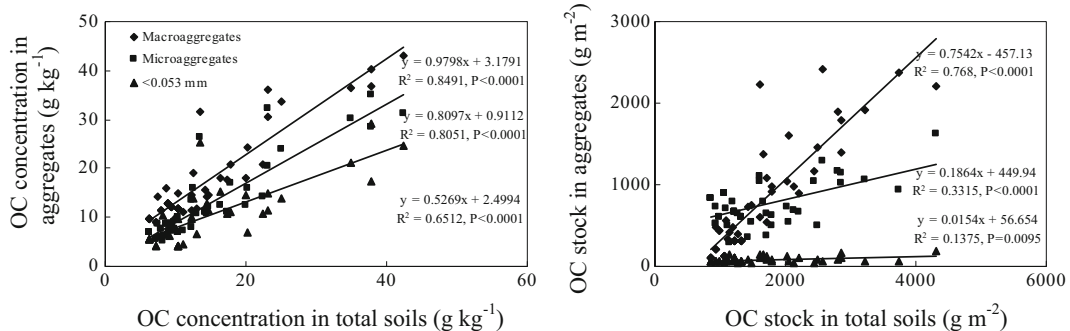


Fig. 7 Relationships between OC concentrations in total soils and in aggregates and between OC stocks in total soils and in aggregates

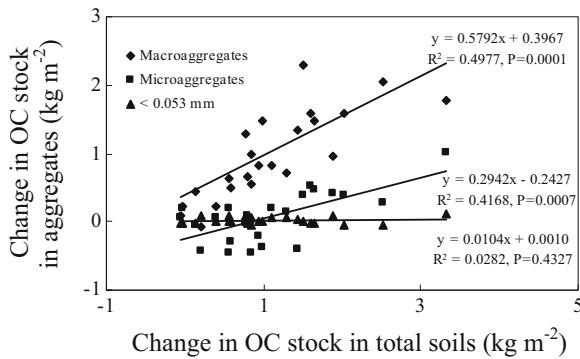


Fig. 8 Relationships between changes in OC stock in total soils and in aggregates. Changes in OC stocks were calculated as the difference between forest soil and adjacent farmland soil for each stand age

the soil profile but to no change in soil OC concentration. Afforestation may result in significant increase in OC in the topsoil, but no change or decrease in the deep soil at the initial few years of afforestation, therefore the lower the soil depths concerned, the greater the observed losses of soil C following afforestation would be observed.

The absence of an initial decrease in OC concentration or stock in soils may also have been due to the relatively lower initial soil OC concentration of the farmland in our study. The accumulation of OC in soils after afforestation on farmland is generally related to initial soil OC concentration, a large accumulation in initially low OC soils but a loss in initially high OC soils (Deng et al. 2014; Song et al. 2014). Deng et al. (2014) suggested that initial soil OC stock was the main factor affecting OC accumulation in 0–100 cm soils 40 years after the conversion of cropland to forest or grassland. Lugo and Brown (1993) observed a significant accumulation of OC after the conversion of cropland to forest having a low initial SOC concentration. Farmland soils in studies that observed initial declines in soil OC were not severely eroded, likely received much crop residues after harvest, and had high levels of OC. The conversion of farmland to forest in those studies would thus likely lead to a decline in soil OC in the early stages because less biomass is returned relative to the previous farmland. In the Huanglongshan region, however, farmland suffers soil erosion, and crop residues are removed, resulting in relatively lower soil OC levels. Afforestation reduces soil erosion in the early stages of afforestation in the region, decelerating losses of OC from erosion.

Our results demonstrated a significant accumulation of OC in macroaggregates following afforestation with Chinese pine. These results were supported by the

theory of hierarchical aggregation and by other experimental investigations. The theory of hierarchical aggregation states that OC concentration increases with increasing aggregate size, because larger aggregates are composed of small particles plus organic binding agents (Elliott 1986). This theory has been applied to the relationships between reductions in aggregates proportions and the loss of soil OC and between increases in aggregates proportions and the accumulation of soil OC after land-use changes (Six et al. 2000, 2004; Puget et al. 2005; McCarthy et al. 2008; Spohn and Giani 2011). In our study, afforestation significantly increased the concentration of soil OC and the proportion of macroaggregates but decreased the proportions of microaggregates and the <0.053 mm size class (Figs. 1 and 3), in agreement with the findings by Wei et al. (2013a) in the same region. As predicted by the theory of hierarchical aggregation, the significant increase in OC concentration in total soils with the proportion of macroaggregates but the decrease with the proportion of microaggregates and the <0.053 mm size class were thus expected.

Wei et al. (2013a) observed 54–233, 43–168 and 12–66 % increases in OC concentrations in the macro- and microaggregates and <0.053 mm size class after 50 years of afforestation on farmland in the same region. They also observed 175–564 % increases in OC stocks in macroaggregates, with most of the increase observed in broadleaved forests. Gao et al. (2013) demonstrated that OC accumulated mainly in the macro- and microaggregate fractions in loamy soils at the 0–30 cm depth more than 30 years after conversion of farmland to aspen (*Populus simonii*) woodland in Ningxia, China. Increases in OC concentration in aggregates along a successional forest sequence have also been reported (Chen et al. 2010; Jiménez et al. 2011). Several other studies have found higher aggregate OC concentrations in forests relative to adjacent farmland (Gelaw et al. 2013; Devine et al. 2014; Liu et al. 2014), further suggesting accumulation of OC in aggregates.

In the present study, the turnover-rate constant of OC after the conversion of farmland to forest increased as aggregate size classes decreased (Table 2). This was expected because the newly input OC was first associated with fine particles and then incorporated into micro- and macroaggregates due to the aggregation of soil particles, which is consistent with our observation that macro- and microaggregates have a relatively larger potential to sequester OC (Table 2, Six et al. 2000; Wei et al. 2013a).

We observed larger absolute or relative increases in OC concentration in macro- and microaggregates at the 0–10 cm depth than at the 10–20 cm depth. The relative increase in OC concentration in the <0.053 mm size class was larger at the 10–20 cm depth than at the 0–10 cm depth, but the absolute increase was larger at the 0–10 cm depth (Fig. 4). The absolute or relative increases in the OC concentrations in aggregates at steady states were also larger at the 0–10 cm depth (Table 2). This was because the newly input C from forest litter is first incorporated in the topsoil and is then transported to the subsoil. This pattern has been widely observed around the world (Gao et al. 2013; Wei et al. 2013a; Devine et al. 2014; Gelaw et al. 2013).

The OC stocks in macroaggregates in the present study increased with stand age, while the OC stocks in microaggregates were not affected or decreased in the first few years and then increased or were not affected along the afforestation chronosequence, depending on soil depth (Fig. 5). The changes in aggregate-associated OC stocks were governed by the changes in mass within a given aggregate size class and by the changes in OC concentration within the aggregate size class (Qiu et al. 2012; Wei et al. 2013b). Our observations showed that the increases in OC stocks in macroaggregates were due to the increases in both macroaggregates proportion and macroaggregate-associated OC concentration, which varied with stand age. During the initial stage of afforestation (7–48 years), the recovery of soil structure and the increase in macroaggregates proportion were relatively higher compared to the increase in OC concentration in macroaggregates, suggesting that the increases in the OC stocks were determined by increases in aggregate mass. During the later afforestation stage (48–200 years), the increases in OC concentration were larger than the increases in aggregate mass, suggesting that the increases in OC stocks were more dependent on increases in OC concentration in aggregates. Similarly, the change in microaggregate-associated OC stock was due to decreases in microaggregates proportion during the early afforestation stage and was due to increases in OC concentration during the later stage. The proportion of microaggregates decreased while the OC concentration in microaggregates increased during the afforestation (Figs. 1 and 4). We therefore conclude that the changes in OC stocks in macro- and microaggregates were mainly due to the recovery of soil structure during the early stage but to the increase in OC concentration in aggregates during the later stage of the afforestation.

Our results suggested that the accumulation of OC after afforestation was mainly due to the accumulation of OC in macroaggregates. Afforestation significantly increased macroaggregates proportions and macroaggregate-associated OC concentrations (Wei et al. 2013a). Additionally, an increase in OC concentration can accelerate the aggregation of particles (Six et al. 2000, 2004), which can physically protect OC from microbial decomposition and mineralization (Razafimbelo et al. 2008). Interactions between OC and increases in macroaggregation may enhance the accumulation of OC in soils. This pattern is supported by the observations that total OC in forest soils was dominated by the OC in macroaggregates (Bronick and Lal 2005; Gao et al. 2013; Wei et al. 2013a) and is also consistent with the findings that the loss of OC in total soils was mainly due to the loss of macroaggregate-associated OC after the conversion of natural vegetation to agricultural land (Qiu et al. 2012; Wei et al. 2013b).

The incorporation of the newly input and recalcitrant OC into aggregates reduces their vulnerability to decomposers (Six et al. 2004; Lehmann et al. 2007). Soil aggregates, particularly macroaggregates, however, are sensitive to soil disturbance caused by ploughing, which will break down the macroaggregates and reduce the stability of macroaggregate-associated OC (Solomon et al. 2002; Six and Jastrow 2002; Six and Paustian 2014). For example, Grandy and Robertson (2006) observed significant decreases in the proportion of macroaggregates and macroaggregate-associated OC concentration 60 days after the tillage of previously uncultivated soils. Our previous studies suggested that the largest decrease in the proportion of macroaggregates, macroaggregate-associated OC and forest-derived OC were observed only 4 years after the conversion of forest to cropland (Wei et al. 2013b, 2014a). We therefore suggest that the OC in macroaggregates in afforested land is susceptible to soil disturbance or any conversion to cropland, and the afforested land should be carefully managed to prevent the loss of sequestered OC in the soil.

We have demonstrated in this study that afforestation with Chinese pine on abandoned farmland significantly improved soil structure and increased the OC concentrations of soil aggregates. The afforestation with Chinese pine sequestered an estimated 3.3 kg m^{-2} OC in the top 20 cm of the soil at steady states, mainly accumulated in macroaggregates. The effects of coniferous forests on soil OC, however, significantly differ from

those of broadleaved forests (Laganière et al. 2010; Kasel et al. 2011; Wei et al. 2013a). For example, the litter and roots of broadleaved trees have relatively lower C/N ratios than coniferous trees (Gholz et al. 2000), which will influence the decomposition of organic materials in the soil (Heal et al. 1997). Additionally, broadleaved forests have a greater potential to improve soil structure than coniferous forest (Fan et al. 2006; Wei et al. 2013a). We therefore recommend that the dynamics of OC in aggregates following afforestation with broadleaved species should be further examined to establish a more general pattern of soil OC dynamics after afforestation. Also, forest-derived and farmland-derived OC in aggregates should be differentiated, and the dynamics following afforestation should be studied further, to provide basic information of how afforestation affects the accumulation of soil OC.

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