Soil structure and carbon distribution in subsoil affected by vegetation restoration

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ABSTRACT

The depth of sampling is an important factor for evaluating soil stability. The objective of this study was to test soil aggregate particle-size fractions and soil organic carbon (SOC) in water-stable aggregate by vegetation restoration through 0–60 cm soil profile. We collected soil samples in 30 years old *Robinia psendoacacia* (Rr); *Platycladus orientalis* (Po); *Pinus tabulaeformis* (Pt); abandoned land (Ab), and slope cropland (Sc), which were separated into > 2, 2–1, 1–0.25, 0.25–0.053, and < 0.053 mm fractions. The > 0.25 mm water-stable aggregates (WSA) and mean weight diameter (MWD) were calculated in 0–60 cm soil depth. Results showed that soil aggregate fractions (> 0.25 mm) of four vegetation types were significantly ($P < 0.05$) higher in 40–60 cm soil depth under Po, Pt, and Ab compared with Sc and the SOC distribution in macro-aggregates (> 0.25 mm) under Rr, Po, Pt, and Ab was higher more than 37.7, 92.4, 92.5, 79.1%, respectively in 40–60 cm compared with Sc additionally, > 0.25 mm WSA and MWD was significantly higher in Pt soil in 20–40 cm, 40–60 cm soil depth ($P < 0.05$). The results demonstrated that soil stability was enhanced and SOC content was increased after converting slope cropland to forest, especially under Pt forest that greatly influenced the subsoil.

Keywords: grain to green program; soil depth; soil aggregate; soil organic carbon; Loess Plateau

The influences of soil organic carbon (SOC) contents on aggregate formation and stabilization have been widely reported (Six et al. 2002). Recent studies showed that soil aggregate stability was vital for carbon (C) sequestration (Chivenge et al. 2011). As an indicator of soil susceptibility to runoff and erosion, soil aggregate stability is considered one of the main soil characteristics regulating soil erodibility (Barthès and Roose 2002), and is related to soil organic matter contents and compositions (Bronick and Lal 2005). In addition, soil aggregate stability can be influenced by the content of > 0.25 mm water-stable aggregates (WSA), and mean weight diameter (MWD). However, previous studies mostly focused on surface soil depth (Mikha and Rice 2004), and soil aggregate stability in subsoil was largely ignored (blow 30 cm). Recent studies indicated that subsoil C may be even more important in terms of source and/or sink for CO_2 than topsoil C (Wang et al. 2008), and the factors controlling C dynamics in topsoil and subsoil may be different (Salomé et al. 2010). Therefore, understanding the soil carbon contents distribution of different soil aggregate sizes in subsoil is essential to investigate the mechanisms to regulate C dynamics in subsoil.

Although soil aggregate stability is a highly complex indicator assessed by a wide range of soil properties, land management and vegetation recovery are among the very important influencing factors (Duffková et al. 2005, Shrestha et al. 2007). In China, soil erosion is one of the environmental problems attention should be paid to urgently (Bennett 2008), especially in Loess Plateau. To counteract soil erosion and other environmental problems, the grain to green program (GTGP)

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agrarian policy was designed by Chinese government in 1999 with the target of converting low-yield sloped croplands to forests, shrubs, and grasslands, which covered up to 26 867 million ha by the end of 2008 (Jia 2009). At present, it is the first and the most ambitious 'payment-for-ecosystem-services' programs in China. Although the initial goal of GTGP was to control soil erosion in China, it also plays a significant role in soil aggregate stability, which relates to the soil structures and SOC of aggregates with different sizes. However, relatively little information is available on the contents and distribution of soil carbon in aggregates with different sizes in subsoil resulted from GTGP implication.

The objectives of this paper are: (a) measuring the distribution of soil aggregates in soil depths of 0–20, 20–40, and 40–60 cm; (b) evaluating the contribution of soil organic carbon to soil aggregates with different sizes, and (c) elucidating the effects of different vegetation types on soil stability.

MATERIAL AND METHODS

Study sites. The study was conducted in the Dunshan catchment (36°30'45''–36°30'28''N), which is located at the central region of the hilly Loess Plateau, Ansai County, China (36°30'45''–37°19'31''N, 108°51'44''–109°26'18''E). Ansai is a typical county characterized by semi-arid climate and hilly Loess landscape. Annual average temperature and precipitation are 8.8°C and 505 mm, respectively. 60% of precipitation falls between July and September (only about 300 mm in dry years and more than 700 mm in wet years). Accumulated temperature above 0°C and 10°C are 3733°C and 3283°C, respectively. On average, there are about 157 frost-free days and 2415 h sunshine time. Arable farming land mostly distributes on the slope lands without irrigation. The soil in this region is classified as Calciustepts soil (Table 1), highly erodible with an erosion modulus of 10 000–12 000 t/km^2/year before the restoration efforts began in this region.

The Dunshan catchment has been an experimental site of the Institute of Soil and Water Conservation (CAS) since 1973. Beginning in the late 1970s, slope cropland was replanted with shrubs and woods, mainly *Robinia pseudoacacia* L., *Platycladus orientalis*, and *Pinus tabulaeformis*, to control soil erosion. Abandoned croplands were also generated during this period due to the extremely low productivity of the land and long distance from farmers' residences. Wild grasslands and shrub lands were usually found on steep slopes, which were abandoned for being not suitable for cultivation. However, these sites were often used for pasture and/or firewood, so the wild vegetation was of limited coverage or even barren for long periods. After more than 30 years of comprehensive management, ecological environment of the catchment was improved. In 1999, most of slope lands were closed for vegetation restoration in this region under GTGP.

Soil sampling and preparation. In September 2012, based on the land use history, 30 year old *Robinia psendoacacia* (Rr); *Platycladus orientalis* (Po); *Pinus tabulaeformis* (Pt); abandoned land (Ab), and a traditional slope cropland (Sc) with less fertilizers utilization were selected in the Dunshan catchment. Three 30 m × 20 m plots were established for each vegetation type. All sites located on the same physiographical units with the same slope aspects, same elevation of ca. 1250 mm and with a spatial distance of ca. 1200 m.

After removing the litter layer, using aluminum bags undisturbed soil samples were collected in an 'S' shape pattern with three replicates for depths of 0–20, 20–40 and 40–60 cm from each plot on the same day. Samples were collected at a distance of at least 80 cm from trees. Then soil sample was dried at room temperature. Each soil sample was sieved (8 mm) to remove large roots and stones. For the determination of soil bulk density and soil total C, three additional soil cores were randomly taken from each subplot per soil layer with

Table 1. General soil properties (0–20 cm)

Parameter	Maximum	Minimum	Mean	*CV* (%)
TOC (g/kg)	6.83	4.45	5.01	4.98
Total N (g/kg)	0.52	0.29	0.33	3.83
Bulk density (g/cm^3)	1.52	1.14	1.28	2.67
Sand (2–0.05 mm %)	33.13	24.53	29.22	4.12
Silt (0.05–0.002 mm %)	68.45	59.39	63.56	5.34
Clay (< 0.002 mm %)	7.57	6.12	6.82	3.71
pH	8.9	7.8	8.2	4.21

Mean values of parameters in the table were calculated from data for all experimental plots. *CV* – coefficient of variation; TOC – total organic carbon three replicates using a soil auger equipped with a stainless-steel cylinder (5 cm in diameter and height). Soil samples were air-dried and hand-sieved through a 2 mm mesh to remove roots and other debris. A portion of each air-dried soil sample was ground to pass a 0.1 mm mesh for soil total C and total N analyses. Soil pH was determined using 1:2.5 soil-to-water ratio.

Water stable aggregate fractions. Aggregate fractionation by wet sieving was conducted following methods adapted in Elliott (1986) to obtain four aggregate size fractions. 100 ± 0.02 g of air-dried soil was submerged in deionized water on top of a 2 mm sieve. After slaking for 5 min, the sieve was moved up and down with an undulating motion 50 times in 2 min before the wet soil samples were collected in each respective pre-weighed pan. The contents of each pan were dried at 60°C and weighed to determine the proportion of soil in each size fraction. The soil in each fraction was weighed, grounded and analyzed for SOC. SOC content (g/kg) was determinated using $K_2Cr_2O_7$ oxidation method (Bao 2000).

Statistical analyses. Mean weight diameters (MWD) were determined (Shepherd et al. 2001) as:

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

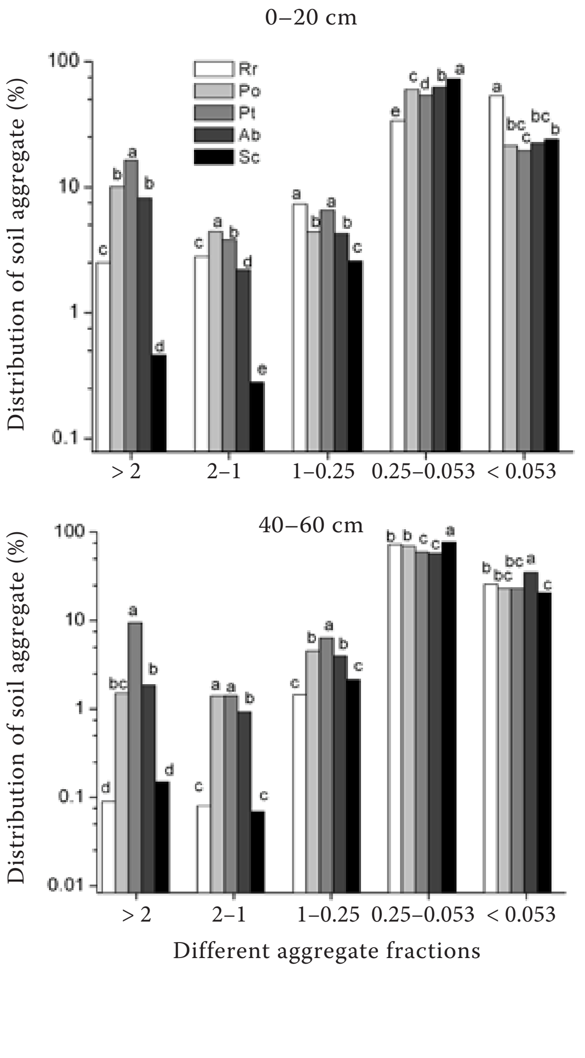
Where: x_i – mean diameter of each size class (2, 2–1, 1–0.25, and 0.25–0.053 mm), and w_i – proportion of each size class to the total sample.

The mean water stable aggregates (> 0.25 mm WSA, %) was calculated as a general indicator of aggregate stability using the formula:

$$WSA = \frac{\sum_{i=1}^{n} m_i}{m} \times 100\%$$

Where: m_i – total weight of > 0.25 mm aggregates, and m – total weight of sample used (Shepherd et al. 2001).

Measured data were analyzed using Origin 7.5. All statistical analyses were carried out with SPSS 17.0. One-way ANOVA followed by the Duncan test ($P < 0.05$) was used to compare distribution of water-stable aggregation, distribution of SOC content, WSA (> 0.25 mm) and MWD of different vegetation types.



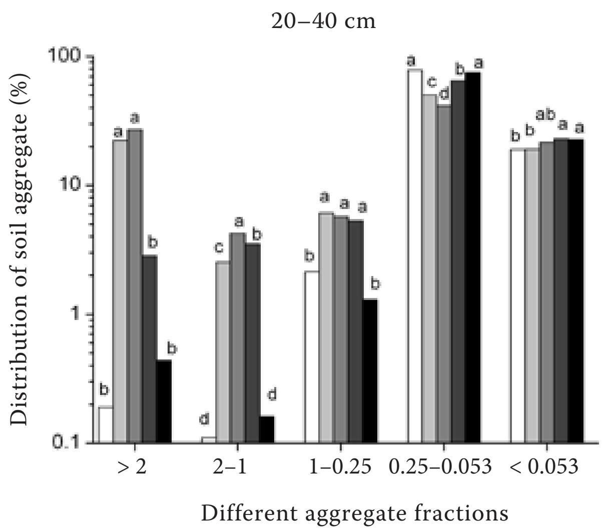


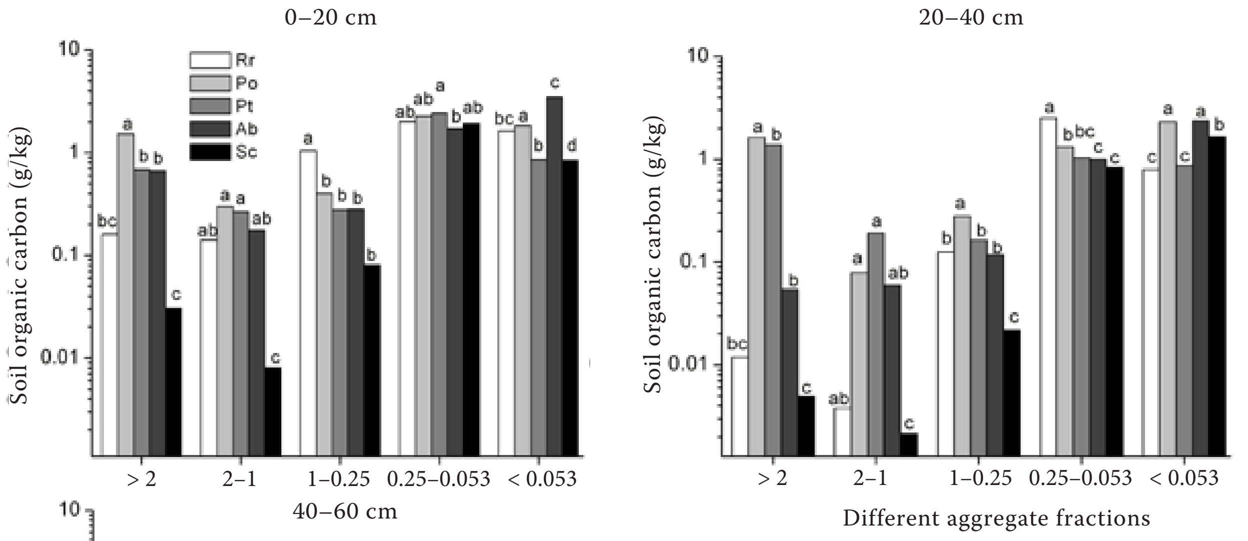
Figure 1. Distribution of soil aggregate fractions of different vegetation types: *Robinia psendoacacia* (Rr); *Platycladus orientalis* (Po); *Pinus tabulaeformis* (Pt); abandoned land (Ab), and a traditional slope cropland (Sc). Different lowercase letters represent statistical significance at 0.05 levels

RESULTS AND DISCUSSION

Distribution of water-stable aggregation. Soil aggregate fractions of different vegetation types are shown in Figure 1. The averaged < 0.25 mm aggregate fractions of five vegetation types were 89.3, 80.7 and 91.8% for 0–20, 20–40 and 40–60 cm soil depths, respectively. It indicates that the micro-aggregates (< 0.25 mm) were more stable and persistent. The possible reason probably was that macro-aggregates (> 0.25 mm) in highly erodible soil in Loess Plateau were prone to cause aggregate slaking and such aggregates could readily disintegrate into smaller units. Similar results were obtained by Huang et al. (2010), which suggested that macro-aggregates (> 0.25 mm) fractions from severely eroded Ultisols decreased with the increase of particle sizes compared with slightly and moderately eroded Ultisols.

We observed that soil aggregate fractions (> 0.25 mm) of four vegetation types were significantly higher ($P < 0.05$) compared with slope cropland in 0–20 cm, whereas significant values also existed in Po soil, Pt soil, and Ab soil in 40–60 cm soil depth. It indicates that vegetation restoration could affect the soil macro-aggregates (> 0.25 mm) fractions and thereby improve the soil structure and soil stability of both surface soil and subsoil. Zheng et al. (2011a) suggested that soil aggregate with size of > 0.25 mm was higher after land use change, and that in the forest soil it was higher than in slope farmland soil. Therefore, after converting slope farmland to forest, the water stable aggregate fractions with the size of > 0.25 mm increased greatly, indicating that soil could positively accelerate remediation and rehabilitation after vegetation restoration.

Distribution of soil organic carbon. SOC distribution in soil aggregate fractions of different vegetation types was shown in Figure 2. Micro-aggregates (< 0.25 mm) of five vegetation types had higher SOC content than macro-aggregates. However, SOC contents in macro-aggregates (> 0.25 mm) of Rr, Po, Pt, and Ab were greater than that of Sc, suggesting that the distribution of SOC contents appeared to have shifted from the micro-aggregates (< 0.25 mm) in low C input systems to



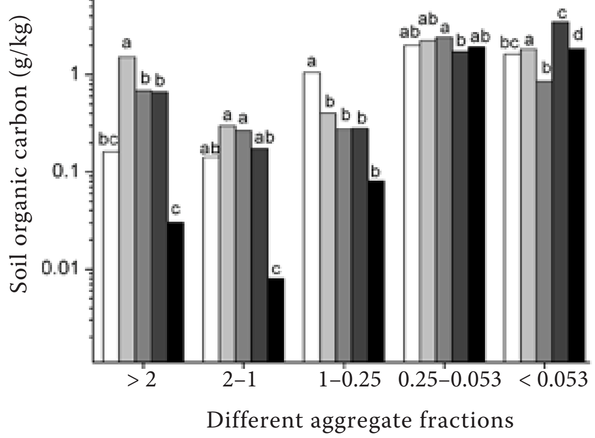


Figure 2. Distribution of soil organic carbon of different vegetation types: *Robinia psendoacacia* (Rr); *Platycladus orientalis* (Po); *Pinus tabulaeformis* (Pt); abandoned land (Ab), and a traditional slope cropland (Sc). Different lowercase letters represent statistical significance at 0.05 levels

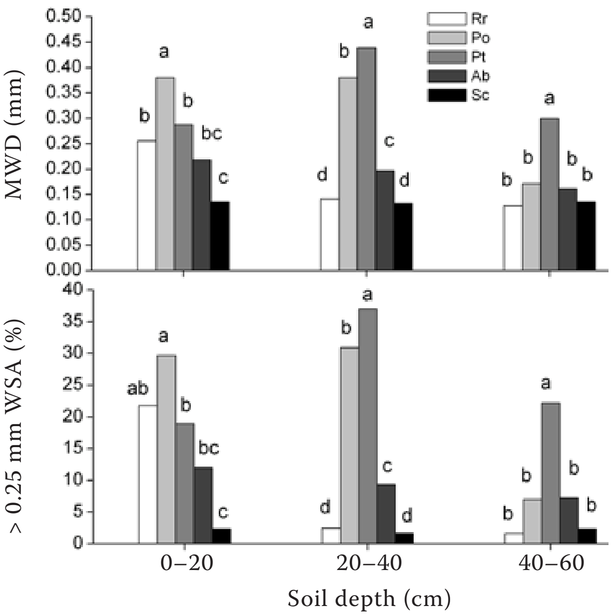


Figure 3. > 0.25 mm water-stable aggregates (WSA) and mean weight diameter (MWD) of different vegetation types under different soil depths. *Robinia psendoacacia* (Rr); *Platycladus orientalis* (Po); *Pinus tabulaeformis* (Pt); abandoned land (Ab), and a traditional slope cropland (Sc). Different lowercase letters represent statistical significance at 0.05 levels

the macro-aggregates in high C input systems. It was mainly due to micro-aggregate formation within macro-aggregates (Golchin et al. 1994). Micro-aggregates occluded in the macro-aggregates can serve as an indicator for C sequestration (Denef et al. 2004). Several studies also revealed the importance of micro-aggregates formed within macro-aggregates to C sequestration in soils (Six et al. 2000). Additionally, enhanced C sequestration through C stabilization within the micro-aggregates within the macro-aggregates was confirmed in afforested and forested soils (Six et al. 2002).

We observed that the SOC distribution in macro-aggregates (> 0.25 mm) of Rr, Po, Pt, and Ab remained high in 40–60 cm soil depth compared with Sc, by 37.7, 92.4, 92.5, and 79.1%, respectively. The reason probably might be the influence of roots. Several studies suggested plant roots were important binding agents at the scale of macro-aggregates (e.g. Thomas et al. 1993). The direct effect of roots on aggregation was the greatest with perennial vegetation species due to the enmeshment of their extensive fine root systems with soil.

Soil aggregate stability. Soils with higher MWD and WSA were likely to have greater resistance to soil degradation and erosion (Celik 2005). > 0.25 mm WSA and MWD (mm) of five vegetation types at different soil depths were shown in Figure 3. It demonstrates that soil aggregate stability of forest converted from farmland was better than slope cropland and it would help to maintain soil stability. The results were similar with Jafarian and Kaviana (2012). Zheng et al. (2011b) also reported that the conversion of cropland to forestland improved soil structure and nutrient. After the vegetation recovery, soil physical structure degradation was limited, thus the soil was likely to have low infiltration rates and prone to erosion. In addition, in this study, > 0.25 mm WSA and MWD were significantly higher in Po soil than other two forest types in the 0–20 cm soil depth, and they were significantly higher in Pt soil in 20–40 cm and 40–60 cm soil depths. This phenomenon demonstrated that Po forest positively affected soil structure in topsoil while Pt forest greatly influenced the subsoil. The results imply that severely erodent soil in the Loess Plateau could be reversed by vegetation restorations on a large spatial scale. Especially, choosing appropriate vegetation could effectively improve soil properties and soil structure.

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