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# Effects of vegetation restoration and slope positions on soil aggregation and soil carbon accumulation on heavily eroded tropical land of Southern China

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**Abstract**
*Background aim and scope* Soil organic carbon (SOC) accumulation is strongly affected by soil erosion and deposition that differ at slope positions of a watershed. However, studies on the effects of topography on soil aggregation and SOC dynamics, especially after the implementation of vegetation restoration, are rare. Poorly understood mechanisms and a lack of quantification for the suite of ecological benefits brought by the impacts of topography after planting further obstructed our understanding of terrestrial ecosystem carbon (C) sequestration. The purposes of this study are to (1) quantify the impacts of vegetation restoration on size and stability of soil aggregates and the sequestration of C in soil and (2) to address the impacts of various slope locations on aggregates and SOC distribution.

*Materials and methods* The experimental sites were set up in 1959 on a highly disturbed barren land in a tropical and coastal area of Guangdong province in South China. One site received human-induced vegetation restoration (the restored site), while the other received no planting and has remained as barren land (the barren site). The soil in the study sites was a latosol developed from granite. Soil samples were taken from 0 to 20 and 20 to 40 cm soil layer at shoulder and toe slope positions at both sites for comparisons. Soils were analyzed for proportion of soil macroaggregates (>0.25 mm), the SOC in soil layers, and the aggregate soil organic carbon (AOC) at different aggregate sizes.

*Results and discussion* Measurements in 2007 showed that fractions of water stable macroaggregates in 0–40 cm at shoulder and toe slope ranged from 28% to 45%, about one third to one half of those of dry macroaggregates (91–95%) at the restored site. Soil macroaggregates were not detected at barren site in 2007. Average SOC storage in 0–40 cm soil layer of shoulder and toe slope positions at the restored site was 56.5±10.9 Mg C ha$^{-1}$, about 2.4 times of that (23.4± 4.6 Mg C ha$^{-1}$) at barren site in 2007. Since 1959, the soil aggregation and SOC storage are significantly improved at the restored site; opposite to that, soil physical and chemical quality has remained low on the barren land without planting. SOC storage in 0–40 cm at toe slope was 15.9± 1.8 Mg C ha$^{-1}$, which is only half of that (30.9±9 Mg C ha$^{-1}$) at shoulder slope of the barren site; this is opposite to the pattern found at restored site. The ratios of AOC in 0–20 cm to AOC in 20–40 cm at toe slope were lower than those at shoulder slope of the restored site. The comparison of organic carbon sequestered in soils at different slope positions suggest that soil aggregates played a role in sequestering C based upon landscape positions and soil profile depth as a consequence of soil erosion and deposition.

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*Conclusions* Results indicate that vegetation restoration and SOC accumulation significantly enhance soil aggregation, which in turn promotes further organic C accumulation in the aggregates via physical protection. Soil aggregation and soil C accumulation differed between slope positions. Soil aggregation was significantly enhanced in 0–20 cm layer and aggregates absorb C into deep layers in depositional environment (toe slope) under protection from human disturbances. The interactions of erosion–deposition, soil aggregates, and vegetation restoration play important roles on SOC accumulation and redistribution on land.

*Recommendations and perspectives* The positive feedback between SOC and soil aggregates should be evaluated for improving the quantification of the impacts of land use change, erosion, and deposition on the dynamics of SOC and soil structure under the global climate change.

**Keywords** Aggregate soil organic carbon · Deposition · Erosion · Soil aggregation · Soil organic carbon · Vegetation restoration

## 1 Background, aim and scope

Soil aggregate is an important characteristic of soil structure, which is closely linked to soil erodibility, soil water retention, soil biota, soil nutrient availability and buffering capacity, and influences soil carbon (C) accumulation by providing physical protection to soil organic carbon (SOC) (Wu et al. 1990; Beare et al. 1994; Fox and Le Bissonnais 1998; Wang et al. 2001; Six et al. 2000, 2004; Eynard et al. 2006). Management practices and human disturbances can greatly influence soil aggregation and SOC dynamics. For example, non-tillage (NT) improves soil aggregation and soil C accumulation, opposite to tillage management practices (Beare et al. 1994; Olchin et al. 2008). Studies were generally conducted in agro-ecosystems; far fewer studies looked at forest lands. Reforestation and afforestation are efficient ways to control soil erosion, improve ecosystem and environmental quality (Zhou et al. 2002; Ren et al. 2007), and sequester C in soil and vegetation (Shan et al. 2001; Lima et al. 2006; Fornara and Tilman 2008). Although many large-scale reforestation and afforestation projects have been initiated and implemented worldwide (Pinard and Cropper 2000; Shan et al. 2001; Fornara and Tilman 2008), their impacts on interaction between soil aggregates and SOC accumulation are poorly understood and quantified. Further studies are needed to examine the interactive relationships between soil aggregates, SOC, and the important soil chemical and biological processes in response to land use and management changes in forest areas (He et al. 2008, 2009).

SOC accumulation is strongly affected by soil erosion and deposition (which differs at slope positions of a watershed). Liu et al. (2003) pointed out that terrain characteristics have significant impacts on soil C dynamics. Their study also pointed out that it is critical to consider the carbon dynamics at both the eroding and depositional environments to balance the C cycle within a watershed. This was experimentally validated by Van Oost et al. (2004, 2007, 2008). The SOC eroded from upland and re-deposited in low-lying areas can be protected physically against decomposition via soil aggregation (Six et al. 2004; Yadav and Malanson 2007; Berhe et al. 2007). However, studies on the effects of topography (influence erosion and deposition) on soil aggregation and SOC dynamics especially after the implementation of vegetation restoration are rare. Poorly understood mechanisms and a lack of quantification for the suite of ecological benefits brought by the impacts of topography after planting further obstructed our understanding of terrestrial ecosystem C sequestration.

Long-term impacts of global climatic change and land use managements on above- and below-ground C cycling processes in the soil–plant ecosystems are complex and difficult to assess (Xu et al. 2009). Few soil biogeochemical models account for the interactions between SOC and soil aggregates, which might not be adequate for simulating C dynamics and soil structure changes following vegetation recovery. Current soil SOC models (e.g., CENTURY) only consider the impacts of soil texture on SOC decomposition. Developing new process-based algorithms to account for the co-evolution of soil organic materials, soil structure, and SOC decomposition in these models is needed to better represent the C cycle in soils and therefore adequately quantify the influence of land use and climate change at the plot to global scale.

A 10-year, large-scale reforestation program was implemented to counter ecosystem degradation as a result of human disturbances in Guangdong province in South China (Zhou et al. 2008). Reforestation not only contributed to the erosion control but also led to large C sequestration in vegetation and soils in Guangdong province from 1980 to 2000 (Xie et al. 2007; Zhou et al. 2008). However, important biogeochemical cycles of C and nutrient cycling in the forest ecosystems under the impacts of reforestation management in Guangdong are still far from clear. Therefore, we measured properties of soil macroaggregates and SOC contents at shoulder and toe slope positions in two watersheds in Guangdong. One of the watersheds experienced vegetation restoration since 1959 and the other without vegetation recovery. The purposes of this study are to (1) quantify the impacts of vegetation restoration on size and stability of soil aggregates and the sequestration of C in soil and (2) address the impacts of various slope locations on aggregates and SOC distribution.

## 2 Materials and methods

### 2.1 Study site

Study sites were located at Xiaoliang Research Station for Restoration of Tropical Coastal Degraded Ecosystem, Chinese Academy of Sciences. This research station lies in the southern part of Guangdong province in South China (21°27′49″ N, 110°54′18″ E). The annual mean temperature is 23°C. Annual rainfall ranges from 1,400 to 1,700 mm with a distinct variation of dry (from October to April) and wet season (from May to September). Climax vegetation is seasonal monsoon rainforest, which is rarely found at present due to human disturbances. Zonal soil is latosol developed from granite (Yu and Pi 1985). The original top soils were almost eroded due to strong erosion caused by long-term anthropogenic disturbances. By 1959, the study area had deteriorated into barren land. Soil physical and chemical qualities were very low on the deteriorated barren land. The fractions of sand (2 to 0.02 mm), silt (0.02 to 0.002 mm), and clay (<0.002 mm) in the soil profile was 42–51%, 40–50%, and 8–10%, respectively, on the barren land according to Tu and Yao (1983). Concentration of humus was lower than 1%, and concentration of total nitrogen (N) was lower than 0.5‰ in top soils on the barren land (Yu and Pi 1985).

A 6.4-ha watershed (Fig. 1a) was established in 1959 to restore regional vegetation, and eucalyptus was planted as the pioneer forest (referring to as the restored site hereafter). The eucalyptus forest was converted to mixed forest with artificial addition of seedlings of 312 indigenous species at the site in 1975 (Zhou et al. 2002; Ren et al. 2007). By 1994, 192 of the planted indigenous species survived, and the forest had developed into a well-structured broad-leaved mixed forest (Ren et al. 2007; see Fig. 1a). Biodiversity of vegetation and animals at the restored site was significantly improved from 1959 to the 1990 s (Ren et al. 2007).

To benchmark the impacts of vegetation restoration, a 3.7-ha watershed close to the restored site was selected in 1959 as the control where any activities of artificial environment improvement including human planting were excluded (referring to as the barren site hereafter). By 2007, no significant natural vegetation recovery occurred within the barren site, and only small shrubs, ferns, and vines are sparsely found in the gullies (see Fig. 1b). The topography of both sites is similar with a slope of 3–7° from shoulder position to the middle position and <3° from middle position to toe position (Yao et al. 1984).

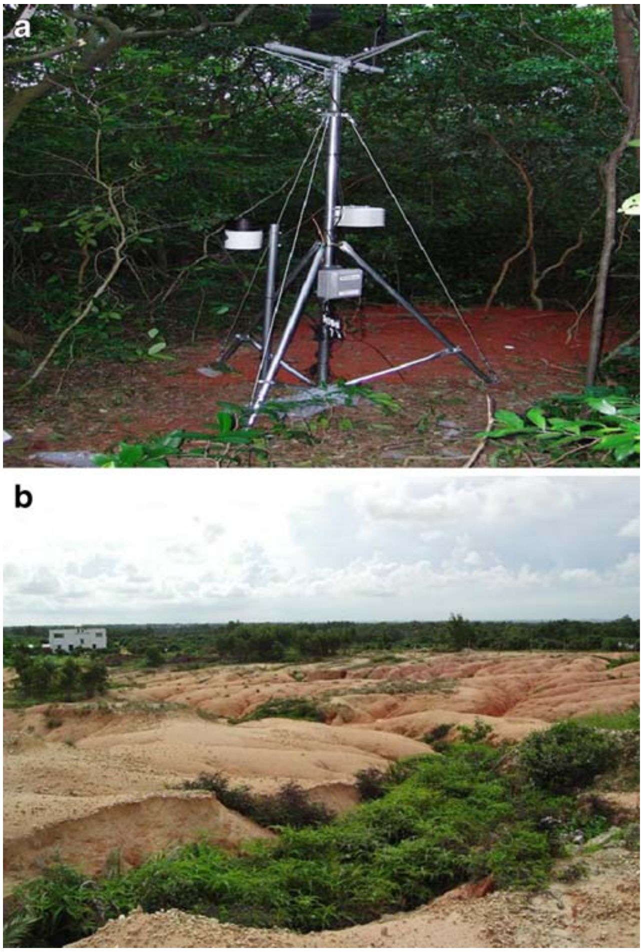

**Fig. 1** Experimental watershed: the restored site (**a**) and the barren site (**b**). The instrumentation in plate (a) is an automatic weather station (Photographed by Xinyi Tang in 2007)

### 2.2 Soil sampling

Because soil aggregate stability is markedly influenced by the soil moisture (Rogowski and Kirkham 1962), we collected soil samples during the dry season of 2007 to avoid the impacts of soil moisture changes on sampling and the measurement. Five randomly located sampling blocks (20×20 m each) at the shoulder and the toe positions, respectively, in both sites were selected. Within each block, one composite sample was collected by combining five subsamples for each 20-cm soil layer (i.e., 0–20 and 20–40 cm). In total, 20 composite samples were collected from each site. In laboratory, the samples were bulked, thoroughly mixed, air dried, and sieved at 2 mm. Large pieces of roots, litter, and stones (>2 mm) were removed. The samples were then triturated and sieved at 0.25 mm. Soil bulk density samples were collected using stainless steel cores (5 cm in diameter and in height). One bulk density sample from each soil layer (0–20 and 20–40 cm) was collected at each sampling block.

Another sampling differed from the above was applied for the measurements of soil aggregates. One composite, by bulking five subsamples, was collected from each 20-cm soil layer (0–20 and 20–40 cm) using spade within each block. Following the procedures outlined in Kemper and Rosenau (1986), each sample was hand-broken into 10–12 mm in diameter and thoroughly bulked before being air-dried. Roots and large pieces of litter were removed. Samples were then taken to laboratory in hard plastic boxes (one box for each sample) to prevent detachment. In laboratory, samples were air dried to measure size and stability of macroaggregates (> 0.25 mm).

### 2.3 Dry and wet sieving

About 200 g soils from each air-dried aggregate sample was taken and weighed. A stack of eight 15-cm diameter sieves with screen openings of 10, 7, 5, 3, 2, 1, 0.5, and 0.25 mm was used for dry sieving. The residual soil on each sieve was weighed respectively with small stones and sands (>0.25 mm) removed.

Another 100 g of soil from each air-dried aggregate sample was weighed and wet-sieved based on Yoder's method (1936). Wet sieving was used to measure the fractions of water stable aggregates (WSA) or the stability of wet aggregates. A stack of five 15-cm diameter sieves with screen openings of 5, 2, 1, 0.5, and 0.25 mm was used for wet sieving. Soils were soaked for 3 min and then shaken for 3 min according to the procedure of Kemper and Rosenau (1986). Wet-sieved residual soils at each size were oven-dried at 35°C for 48 h and then weighed respectively with small stones and sands removed.

Microaggregates (<0.25 mm) were addressed in this study because they were difficult to detect on barren land with very low soil qualities; macroaggregates were good indicators of change in soil quality.

### 2.4 Soil bulk density and organic carbon measurements

The soil bulk density was estimated by dividing the oven-dry weight (24 h at 105°C) of the soil sample by the core volume. The SOC concentration (%) and the aggregate soil organic carbon (AOC) concentration (percent) in the aggregated soil at each size were determined by wet combustion with $K_2Cr_2O_7$ (Soil and Plant Analysis Council Staff 2000). AOC was expressed as an organic C concentration in the aggregate size class of sand-free aggregate. AOC represents the amount of organic C absorbed in the soil aggregates, while SOC represents total organic C content of the soils.

### 2.5 Aggregates stability

The size fraction and weighted mean diameter (WMD) of aggregates were calculated by the following methods (Andrew et al. 1962):

1. Size fraction

$$= \sum(\text{weight percentage of aggregates in a given size})$$

2. Weighted mean diameter

$$= \sum(\text{weight percentage of aggregates} \times \text{average diameter}) \div \sum(\text{weight percentage of aggregates})$$

Weight percentage of aggregates indicates the proportion of soil macroaggregates in the measured soils with small stones and sands removed. WMD was used as aggregates stability index.

### 2.6 Data analysis

With measured SOC concentration and bulk density, we calculated SOC storage in the top 40-cm soil layer at shoulder and toe slope positions at both sites. Soil properties (including soil aggregates, the concentrations of SOC and AOC, and bulk density) at different slope positions in the same soil layer (0–20 or 20–40 cm) at both sites were compared. Macroaggregates were divided and compared at large (>2 mm) and small sizes (0.25–2 mm; Elliott 1986). Multiple comparisons between means were tested using two-tailed Student's *t* test at a level of $P<0.05$. The significance of the correlation between AOC concentrations and sizes of macroaggregates was tested by Pearson's correlation analysis at a level of $P<0.05$.

## 3 Results

### 3.1 Soil organic carbon storage

Table 1 shows the measurements of SOC concentrations, bulk density, and calculation of SOC storage in 0–20 and 20–40 cm at slope positions of each site. SOC concentrations were very low and did not change significantly with depth at the barren site. However, SOC concentrations in 0–20 cm layer were about two times of those in 20–40 cm layer at the restored site. SOC storage in 0–40 cm layer at toe slope position was 15.9±1.8 Mg C $ha^{-1}$, about half of that (30.9±9 Mg C $ha^{-1}$) at the shoulder slope at the barren site; this is opposite to pattern found at the restored

**Table 1** Field measurements of soil organic carbon (SOC) concentration (%, $n$=5), bulk density (g cm$^{-3}$, $n$=5), and calculations of SOC storage (Mg C ha$^{-1}$) at the experimental sites

Standard deviations are in brackets. Different small letters in a column within the same soil layer (0–20 or 20–40 cm) between different slope positions in a given experimental site (restored site or barren site) indicate significantly different values ($P$<0.05)

| Soil layers (cm) | Position | SOC concentration | Bulk density | SOC storage |
|---|---|---|---|---|
| Restored site | | | | |
| 0–20 | Shoulder slope | 1.06 (0.45)a | 1.46 (0.05)a | 31.07 (13.23)a |
| | Toe slope | 1.59 (0.39)a | 1.36 (0.06)a | 43.14 (10.77)a |
| 20–40 | Shoulder slope | 0.60 (0.44)a | 1.47 (0.11)a | 17.60 (13.02)a |
| | Toe slope | 0.74 (0.12)a | 1.43 (0.17)a | 21.22 (4.26)a |
| Barren site | | | | |
| 0–20 | Shoulder slope | 0.50 (0.22)a | 1.61 (0.01)a | 15.98 (7.08)a |
| | Toe slope | 0.31 (0.05)a | 1.56 (0.09)a | 9.70 (1.66)a |
| 20–40 | Shoulder slope | 0.48 (0.18)a | 1.55 (0.01)a | 14.92 (5.58)a |
| | Toe slope | 0.23 (0.02)b | 1.35 (0.07)b | 6.23 (0.63)b |

site (64.4±11.6 Mg C ha$^{-1}$ at toe slope and 48.7±18.6 Mg C ha$^{-1}$ at shoulder slope). The average SOC storage in 0–40 cm layer of shoulder and toe slope positions at the restored site was 56.5±10.9 Mg C ha$^{-1}$, about 2.4 times of that (23.4±4.6 Mg C ha$^{-1}$) at the barren site.

### 3.2 Fractions and stability of soil macroaggregates

Table 2 shows the results of fractions of macroaggregates by dry and wet sieving. Soil macroaggregates were not detected by dry and wet sieving at the barren site. Fractions of dry macroaggregates ranged from 91% to 95% from 0 to 40 cm depth at shoulder and toe slope positions, about two to three times of those of WSA (28–45%) at the restored site. The fractions of large size (>2 mm) dry macroaggregates ranged from 55% to 75%, about 1.5 to 3.8 times of those (20–37%) of small size (0.25–2 mm) dry macroaggregates. This was opposite to pattern that about 0.7–0.9 of WSA was small in size. The fraction of large size dry macroaggregates in 0–20 cm at toe slope was significantly enhanced (about 36% higher than that at the shoulder slope), while the fraction of small size dry macroaggregates in 0–20 cm at toe slope was about half of that at shoulder slope at the restored site. Although the fraction of total dry macroaggregates in 0–20 cm at toe slope was not significantly enhanced, the fraction of total WSA in 0–20 cm at toe slope was significantly enhanced with about 60% higher than that at shoulder slope at the restored site.

Aggregates stability indexes (i.e., the WMD) in Table 3 shows that the stability of dry macroaggregates in 0–20-cm layer at toe slope was significantly improved with about 41% higher than that at shoulder slope at the restored site. On the other hand, the stability of WSA in 0–40-cm layer at shoulder slope was not significantly different from that at toe slope position at the restored site. The values of WMD were 0 in 0–40-cm layer at the barren site due to no macroaggregate detection.

**Table 2** Weight percentage (%, $n$=5) of macroaggregates

| Soil layers (cm) | Position | Dry sieving | | | | Wet sieving | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Large | Small | Total | Ratio[a] | Large | Small | Total | Ratio |
| Restored site | | | | | | | | | |
| 0–20 | Shoulder slope | 55 (3)Aa | 37 (2)Ba | 91 (4)a | 1.5 | 7 (1)Aa | 21 (5)Ba | 28 (5)a | 0.3 |
| | Toe slope | 75 (5)Ab | 20 (2)Bb | 95 (5)a | 3.8 | 13 (1)Ab | 32 (1)Ba | 45 (2)b | 0.4 |
| 20–40 | Shoulder slope | 59 (4)Aa | 34 (2)Ba | 93 (5)a | 1.7 | 3 (0)Aa | 25 (4)Ba | 28 (4)a | 0.12 |
| | Toe slope | 61 (3)Aa | 32 (1)Ba | 93 (3)a | 1.9 | 8 (2)Aa | 32 (6)Ba | 40 (6)a | 0.25 |
| Barren site | | | | | | | | | |
| 0–40 | Shoulder slope | 0 | 0 | 0 | | 0 | 0 | 0 | |
| | Toe slope | 0 | 0 | 0 | | 0 | 0 | 0 | |

Weight percentage of aggregates indicates the fraction of soil macroaggregates (>0.25-mm, Elliott 1986)in the measured total soil with small stones and sands removed. Standard errors are in brackets. Different small letters in a column within the same soil layer (0–20 or 20–40 cm) between different slope positions indicate significantly different values ($P$<0.05). Different capital letters in a row within the dry or wet sieving between the large and small size [large macroaggregates size >2 mm, small macroaggregates size is 0.25–2 mm (Elliott 1986)] macroaggregates indicate significantly different values ($P$<0.05)

[a] Ratio stands for the ratios of fraction of large to small size aggregates

**Table 3** Weighted mean diameter (WMD, mm, $n$=5) of macroaggregates

| Soil layers (cm) | Position | Dry-sieving | Wet-sieving |
|---|---|---|---|
| Restored site | | | |
| 0–20 | Shoulder slope | 3.63 (0.26)a | 1.60 (0.14)a |
| | Toe slope | 5.13 (0.31)b | 1.73 (0.12)a |
| 20–40 | Shoulder slope | 3.29 (0.35)a | 1.03 (0.12)a |
| | Toe slope | 4.07 (0.15)a | 1.48 (0.29)a |
| Barren site | | | |
| 0–40 | Shoulder slope | 0 | 0 |
| | Toe slope | 0 | 0 |

Macroaggregates size >0.25 mm (Elliott 1986). Number in the parenthesis indicates the standard error. Different small letters in a column within the same soil layer (0–20 or 20–40 cm) indicate significantly different values ($P<0.05$)

### 3.3 Aggregate soil organic carbon concentration

The results through dry sieving showed that AOC concentrations positively correlated with sizes of dry macroaggregate in 0–20 cm at the toe slope at restored site ($r$=0.756, $n$=40, $P<0.05$). However, both dry- and wet-sieving results showed that the AOC concentrations did not change significantly with aggregate sizes in 20–40 cm at shoulder and toe slope positions (Figs. 2 and 3). AOC concentration doubled the overall SOC concentration in 0–20 cm at the shoulder slope at the restored site (Table 4). The ratios of AOC in 0–20 cm to AOC in 20–40 cm at toe slope were 1.6 (by wet sieving) and 2.0 (by dry sieving), lower than those (2.7 by wet sieving and 4.8 by dry sieving) at shoulder slope at the restored site.

## 4 Discussion

### 4.1 Impacts of slope positions on soil aggregation and SOC accumulation

Comparisons of soil aggregates and SOC between shoulder and toe slope position show the impacts of slope position on the interactions of soil aggregation and SOC. Fractions of WSA in 0–20 cm at the toe slope were significantly higher than that at the shoulder slope of the restored site (see Table 2). This indicated that part of the water stable macroaggregates at small sizes displaced at shoulder slope, transported by surface flow, and redeposited in 0–20 cm at the toe slope, and/or the depositional materials accelerated the development of WSA at toe slope location. This is consistent with other studies, where smaller stabilized aggregates were transported from upland to lowland because they are more erodible and more transportable in flowing water compared to larger unstable aggregates (Rai et al. 1954; Imeson 1985).

Our study demonstrated that slope positions have significant impacts on soil C dynamics of a watershed, and the impacts were different within watersheds with or without vegetation cover. At the barren site without vegetative recover and soil aggregation, SOC concentration and storage at the toe slope was significantly lower than that at the shoulder slope (especially in 20–40-cm soil layer); this is opposite to the pattern found at restored site (see Table 1). The result is explained by erosion-removing soluble C and nutrients from the eroded soils (Morgan and Rickson 1995) and the materials deposited without soil aggregation being more depleted in SOC and nutrients at the barren site due to the lack of adequate soil structure (i.e., soil aggregates) to capture and retain SOC and nutrients. Conversely, the AOC concentration doubled the SOC concentration in 0–20 cm at the shoulder slope at the restored site (see Table 4), suggesting that organic C was more absorbed in aggregated soils. The ratios of AOC in 0–

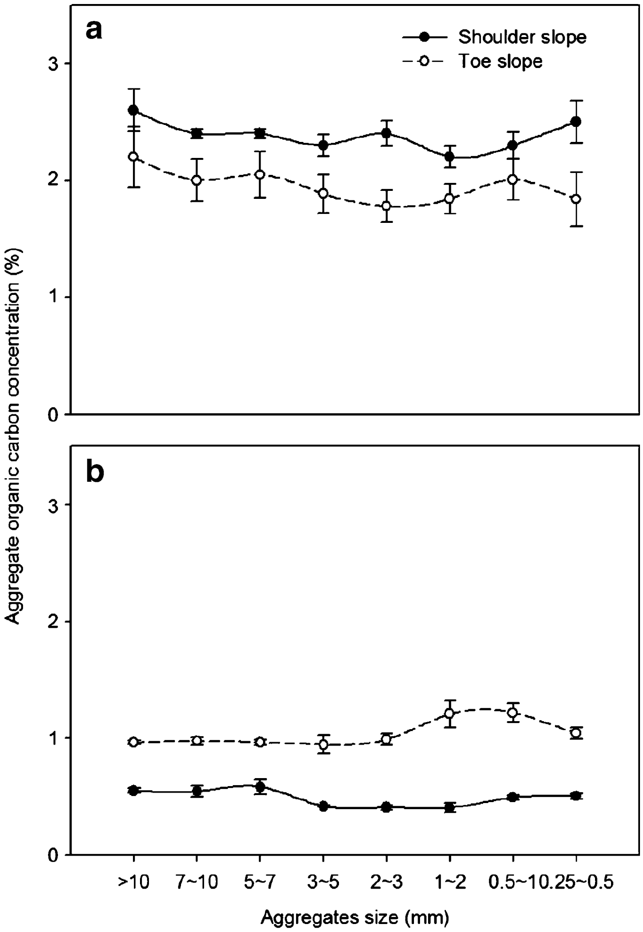

**Fig. 2** Dry stable macroaggregates organic carbon concentrations in the topsoil layer (0–20 cm) (**a**) and the subsoil layer (20–40 cm) (**b**) at the restored site. The *error bars* represent the standard error

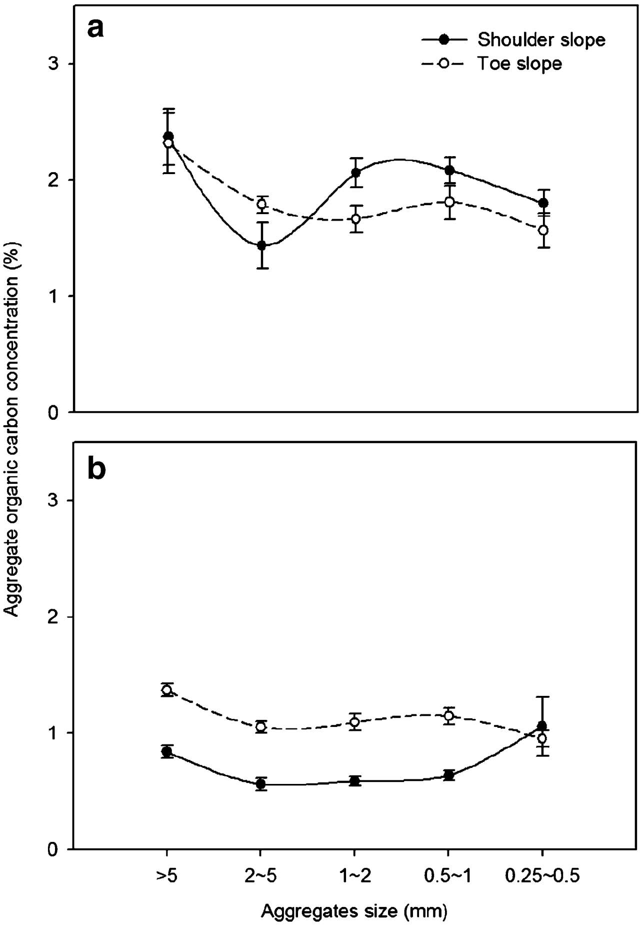

**Fig. 3** Water-stable macroaggregates organic carbon concentrations in the topsoil layer (0–20 cm) (**a**) and the subsoil layer (20–40 cm) (**b**) at the restored site. The *error bars* represent the standard error

20 cm to AOC in 20–40 cm at toe slope were lower than those at shoulder slope. This might indicate that soil aggregates have the capability of absorbing dissolved organic carbon (DOC); DOC leaches into the 20–40-cm layer in depositional environment.

The role of soil aggregates played in sequestering C apparently differed with landscape positions and soil profile depth as a consequence of soil erosion and deposition. At the toe slope position at the restored site, the SOC concentration in 0–20 cm was close to that in the aggregates (AOC), in contradictory with the findings at the shoulder slope as described above. This can be explained by the impact of soil erosion and deposition at this site, as erosion can preferentially transport light materials (e.g., litter) from shoulder slope to toe slope to increase the SOC concentration. This process cannot increase the AOC. It is only through long-term complex biological processes that AOC can be increased, and this was manifested by the measurements in the 20–40-cm layer at the toe slope. A 25% enrichment in AOC (compared with SOC) was observed in the 20–40-cm layer because this soil layer had been developed ahead of the 0–20 cm and was not under the direct impact of soil erosion and deposition.

## 4.2 Effects of vegetation restoration on soil aggregation and SOC accumulation

Field measurements collected in 2007 showed that soil aggregation and SOC storage were significantly improved at the restored site due to vegetation recovery and biomass input; comparatively, the soil's physical and chemical qualities were low at the barren site without vegetative recover. The SOC accumulation was partly caused by the enhanced soil aggregation that provided microenvironments for absorbing particle organic matter and physical protection of SOC from decomposition (Beare et al. 1994; Six et al. 2000; Bossuyt et al. 2002). Additionally, soil organic matter (SOM) acts as a major binding agent and stabilizer to natural soil aggregates as well as the critical inorganic binding agents such as oxides and calcium for the stabilization of organic matter and aggregates (Greenland et al. 1962; Six et al. 2004). Measurements at the restored site in 2007 indicated that half of the dry macroaggregates (about 90% in soils measured by dry sieving) were water stable, in which organic C were well protected from erosion and decomposition caused by runoff. Results in 2007

**Table 4** Comparison of average concentrations (percent) of aggregate soil organic carbon (AOC) and total soil organic carbon (SOC) concentrations (%) at the restored site

| Soil layer (cm) | Position | AOC | | SOC ($n$=5) |
|---|---|---|---|---|
| | | Dry-sieving ($n$=40) | Wet-sieving ($n$=25) | |
| 0–20 | Shoulder slope | 2.4 (0.12)aA | 1.9 (0.20)aA | 1.06 (0.20)aB |
| | Toe slope | 2.0 (0.13)aA | 1.8 (0.20)aA | 1.59 (0.17)aA |
| 20–40 | Shoulder slope | 0.5 (0.13)aA | 0.7 (0.19)aA | 0.60 (0.20)aA |
| | Toe slope | 1.0 (0.12)aA | 1.1 (0.20)aA | 0.74 (0.05)aB |

Number in the parenthesis indicates the standard error. Different small letters in a column within each soil layer (0–20 or 20–40 cm) between different slope positions indicate significantly different values ($P<0.05$). Different capital letters in a row indicate significantly different values ($P<0.05$)

showed that soil aggregation and SOC storage were significantly improved at the restored site since 1959, which was opposite to that at the barren site. Other studies also showed that the aggregates provide physical/chemical protection on SOC from decomposition and therefore promote the accumulation of C in soil (Six et al. 2004; Yadav and Malanson 2007). This suggests that SOC accumulation from vegetation biomass contributes to the enhancement of aggregation and vice versa. On the other hand, soil aggregation cannot be improved on heavily eroded land without vegetation restoration (i.e., the barren site), which might keep the soil structure that limits plant growth and C accumulation.

We studied only some of the physical aspects of soil aggregates and SOC here. We realize that many biochemical processes associated with aggregates may have been altered and should be further investigated in the future. For example, studies have shown that denitrification decreases with an increase of aggregate size, while phosphorus (P) desorption from large aggregates is much higher than from small aggregates (Seech and Beauchamp 1988; Wang et al. 2001). Other studies show that short- and long-term plant P availability will probably be influenced by soil aggregation in P-deficient tropical soils (Linquist et al. 1997; Wang et al. 2001). N and P dynamics and their relationships with the properties of soil aggregates will, therefore, influence short- and long-term nutrient availability in soils, plant growth, and C sequestration. In addition, soil aggregation, AOC, and non-AOC are also influenced by factors such as slope direction, gradient, and length (i.e., the topography), soil taxonomy, plant growth, soil animals, and precipitation, which influence the biogeochemical processes. More researches in multiple areas with varying ecosystems, topography, soil types, and climatic conditions are needed in the future.

## 5 Conclusions

Our results clearly suggest that vegetation recovery can facilitate SOC accumulation from biomass input; this contributes to the enhancement of soil aggregation and vice versa. Compared to the restored site, erosion at the barren site removed soluble organic C from the eroded soils, and the materials deposited without soil aggregation were more depleted in SOC. Small size WSA displaced at shoulder slope redeposit in 0–20-cm layer at depositional locations. Soil aggregation and soil C accumulation differed between slope positions. Soil aggregation was significantly enhanced in 0–20 cm and aggregates absorb C into deep layers in depositional environment under protection from human disturbances. The interactions of erosion–deposition, soil aggregates, and vegetation restoration play important roles on SOC accumulation and redistribution on land.

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