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Soil organic carbon sequestration in soil aggregates in the karst Critical Zone Observatory, Southwest China

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Abstract: Soil organic carbon (SOC) sequestration in aggregates under land use change have been widely concerned due to intimate impacts on the sink (or source) of atmospheric carbon dioxide (CO_2). However, the quantitative relationship between soil aggregation and SOC sequestration under land uses change has been poorly studied. Distribution of aggregates, SOC contents in bulk soils and different size aggregates and their contributions to SOC sequestration were determined under different land uses in the Puding Karst Ecosystem Observation and Research Station, karst Critical Zone Observatory (CZO), Southwest China. Soil aggregation and SOC sequestration increased in the processes of farmland abandonment and recovery. SOC contents in micro-aggregates were larger than those in macro-aggregates in restored land soils, while the opposite results in farmland soils were obtained, probably due to the hindrance of the C-enriched SOC transport from macro-aggregate into micro-aggregate by the disturbance of agricultural activities. SOC contents in macro-aggregates exponentially increased with their proportions along successional land uses. Macro-aggregates accounted for over 80% on the SOC sequestration in restored land soils, while they accounted for 31–60% in farmland soils. These results indicated that macro-aggregates have a great potential for SOC sequestration in karst soils.

Keywords: soil nutrition decline; carbon cycling; agricultural management; calcareous soil; karst small watershed

Soil organic carbon (SOC) storage and stabilization are closely linked with agricultural productivity, resistance to water and soil erosion, water purification and greenhouse gas emission (Tommaso et al. 2018). Land use change strongly affects SOC storage due to the changes in litter input in quantity and quality and the rate of soil organic matter (SOM) decomposition (Rittl et al. 2017). Land use change and cultivation practices are important factors controlling SOC storage and stabilization through affecting aggregate formation and stabilization (John et al. 2005). Aggregate hierarchy theories state the SOC turnover among different size aggregates (Six et al. 2000), and provide mechanistic explanation for the SOC dynamics under land use change and agricultural management (Six et al. 2004). Further understanding of the relationship between soil aggregation and SOC sequestration under land use change is essential to develop land management practices toward the enhancement of soil carbon sink capacity.

Watershed is regarded as a basic unit of terrestrial-aquatic ecosystems, which can provide abundant information about biogeochemical cycles of nutritive elements (Manzoni and Porporato 2011). In the ecologically fragile karst region of Southwest China, intensive agricultural activities lead to lots of environmental problems such as rocky desertification and soil nutrition decline, and subsequently social issues occur such as arable land reduction and poverty of residents (Wang et al. 2004). Long-term observation of water, soil, vegetation and air along successional land uses and gradient of human

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disturbance have been conducted in a typical karst small watershed near the Chenqi village in the Puding Karst Ecosystem Observation and Research Station, Guizhou province since 2009 (Ni et al. 2017). This small watershed was selected as one site of the karst Critical Zone Observatory (CZO) for researches on ecological restoration and agricultural sustainability in 2016. Soil carbon (C) dynamics in the processes of soil degradation or recovery is one of the key scientific questions of the karst CZO, due to SOC as a crucial index of soil productivity affecting the karst ecological restoration.

The lowest SOC content in farmland compared to that in bushland, grassland and forest land was reported in karst soil in Southwest China (Han et al. 2015, 2017). However, soil aggregation and SOC sequestration and the quantitative relationships between them under land use change have been poorly studied. In the present study, the soils at 0–10, 10–20 and 20–30 cm depth from secondary forest land, bushland, abandoned orchard land, grassland, abandoned farmland and farmland in the small karst watershed were collected to analyse distribution of aggregates, SOC contents in bulk soils and different size aggregates and contributions of them to SOC sequestration. The objectives of this study were (1) to study the changes in soil aggregation and SOC sequestration under land use change; (2) to identify the quantitative relationship between soil aggregation and SOC sequestration along successional land uses, and (3) to assess the contribution of different size aggregates to SOC sequestration in karst soils.

MATERIAL AND METHODS

Study region. The study area is located in the small watershed (26°15.779'–26°16.710'N, 105°46.053'–105°46.839'E), a typical karst peak-depression landform, with an area of 1.3 km^2 in the Puding county, Guizhou province, Southwest China. The region has a sub-tropical monsoonal climate, with an average annual air temperature of 15.1°C and mean annual precipitation of 1315 mm (Zhao et al. 2010). The altitude of study area ranges from 1310–1524 m a.s.l., and the average slope of the hills is more than 40°. The calcareous soils (Acrisols) mainly developed from the limestone of upper Guanling Formation of middle Triassic. The soils are unevenly distributed on the bedrocks and their thickness ranges from 10 cm to 160 cm. Seriously degraded agricultural lands were widely abandoned under the 'Grain for Green Programme' (GGP) in the 1990s, then they have been restored to varying degrees due to different abandonment time. Thus, successional land uses in the study area are presented as follows: farmland, abandoned farmland, grassland, bushland and secondary forest land.

Table 1. Location and land use change of sampling sites

Sampling site	Altitude (m a.s.l.)	Slope	Current land use	Land use change
SF	1442	30°	secondary forest land	primary forest had been deforested for more than 50 years
BL1	1466	32°	bushland	no change, natural evolution
BL2	1425	34°	bushland	no change, natural evolution
BL3	1404	27°	bushland	no change, natural evolution
BL4	1401	31°	bushland	no change, natural evolution
BL5	1370	17°	bushland	farmland had been abandoned for 8 years and evolved to bushland
AO1	1365	30°	abandoned orchard land	pear orchard had been abandoned for 8 years and evolved to bushland
AO2	1350	30°	abandoned orchard land	pear orchard had been abandoned for 8 years and evolved to bushland
GL	1376	32°	grassland	farmland had been abandoned for 5 years and evolved to grassland
AF1	1335	30°	abandoned farmland	farmland had been abandoned for 2 years, covered by weed
AF2	1333	24°	abandoned farmland	farmland had been abandoned for 2 years, covered by weed
FL	1335	24°	farmland	cultivation over 50 years

SF – secondary forest land; BL – bushland; AO – abandoned orchard land; GL – grassland; AF – abandoned farmland; FL – farmland

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Soil sampling and analyses. According to the successional land uses, the soils from secondary forest land (SF), bushland (BL), abandoned orchard land (AO), grassland (GL), abandoned farmland (AF) and farmland (FL) in the study area (Table 1) were collected at 0–10, 10–20 and 20–30 cm depth, since the changes of SOC controlled by land use change mainly occur in the soil layer of 0–30 cm (Chaopricha and Marín-Spiotta 2014). Soil samples were air dried at room temperature and the litters, roots and stones were removed. The dried soil samples were separated into two portions, one portion was ground and passed through 150 μm sifter to be used for the analysis of bulk soils, another portion without any grind was used for aggregate separation by the wet sieving (Choudhury et al. 2014). Soil samples were separated into macro-aggregate (250–2000 μm), micro-aggregate (53–250 μm) and silt + clay-sized fraction (< 53 μm) in water through 2000, 250 and 53 μm sifter. The moist aggregates were dried at 55°C, weighed, ground and passed through 150 μm sifter.

The carbonates were removed from powder samples of bulk soils and different size aggregates using 0.5 mol/L hydrochloric acid (HCl) for 24 h (Midwood and Boutton 1998). The moist samples were dried at 55°C, ground and passed through 150 μm sifter to be used for the analysis of SOC content. The SOC content was calibrated due to loss of carbonate in this process.

The SOC content was analysed by combustion using an elemental analyser (Elementar, Vario TOC cube, Hanau, Germany), in the Laboratory of Surficial Environment Geochemistry, China University of Geosciences (Beijing), the reproducibility was determined by standard material Low Organic Content Soil OAS (CatNo B2152, 1.55 ± 0.06%). The measured value corresponded to the actual value.

Data statistics. The contribution G_k (%) of different size aggregates to SOC sequestration is calculated according to the modified equation (Choudhury et al. 2014):

$$G_k = \frac{X_k \times M_k}{\sum_{k=1}^{n} (X_k \times M_k)} \times 100$$

Where: X_k (mm) – mean diameter of relevant size aggregates; M_k (%) – mass proportion of relevant size fraction aggregates; k – type of aggregates (k = 1, 2, 3 indicate macro-aggregates, micro-aggregates and silt + clay sized fractions, respectively).

The quantitative (linear, exponential and logarithmic) relationships between proportion and SOC content of aggregates were identified. Then the equation and correlation coefficient (R^2) from the regression line of them were obtained. The above statistical analyses were performed using the SPSS 18.0 (SPSS Inc., Chicago, USA).

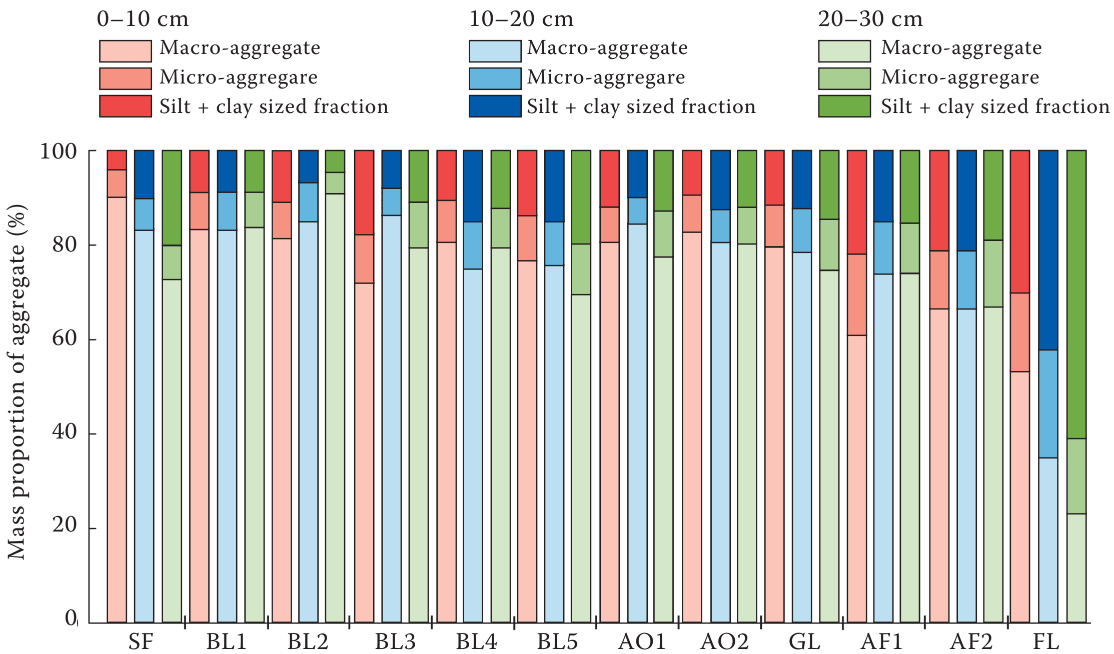

Figure 1. Aggregate distribution at different depths. SF – secondary forest land; BL – bushland; AO – abandoned orchard land; GL – grassland; AF – abandoned farmland; FL – farmland

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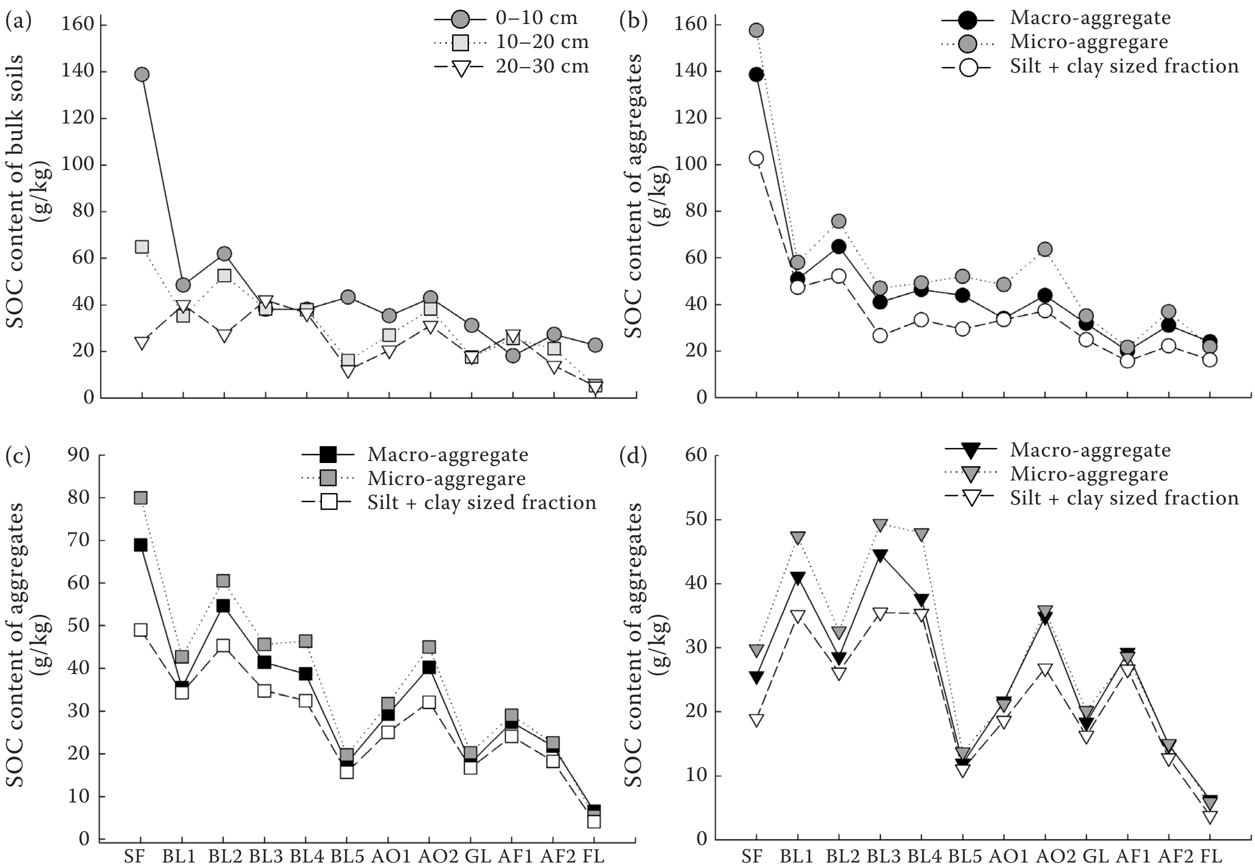

Figure 2. (a) Soil organic carbon (SOC) content in bulk soils at different depths, SOC content in different size aggregates at (b) 0–10 cm depth; (c) 10–20 cm depth and (d) 20–30 cm depth. SF – secondary forest land; BL – bushland; AO – abandoned orchard land; GL – grassland; AF – abandoned farmland; FL – farmland

RESULTS AND DISCUSSION

The effects of land use change on soil aggregation and SOC sequestration. The proportion of macro-aggregates in 0–10 cm depth soil decreased with land uses as follows: secondary forest land (90%), abandoned orchard land (82%), grassland (80%), bushland (78%), abandoned farmland (64%) and farmland (53%) (Figure 1). Although there was no remarkable difference in macro-aggregate proportions between secondary forest land, abandoned orchard land, grassland and bushland in 10–20 cm and 20–30 cm depth soils, macro-aggregate proportions in 10–30 cm depth soils were significantly lower in farmland compared to that in these land soils. The proportions of micro-aggregates and silt + clay-sized fractions showed an opposite trend with the variations of macro-aggregate proportion along with land use types and soil depth. Since macro-aggregate proportion directly indicates soil aggregation, the effects of land use and soil depth on the proportion of micro-aggregates and silt + clay-sized fractions are not discussed below. The SOC content in 0–10 cm depth bulk soils decreased with land uses as follows (Figure 2a): secondary forest land (138.8 g/kg), bushland (45.9 g/kg), abandoned orchard land (39.2 g/kg), grassland (31.1 g/kg), abandoned farmland (22.7 g/kg) and farmland (22.6 g/kg). The SOC contents in different land uses were intensively affected by soil depth and varied irregularly with depth. Yet, the SOC contents in 10–30 cm depth soils were significantly lower in farmland than that in other land soils. These results indicate that both soil aggregation and SOC sequestration increased in the processes of farmland abandonment and recovery, and changes of them were intensively affected by soil depth. Liao et al. (2016) reported that the conversion of cropland to orchard increased the SOC content and macro-aggregate proportion in karst soils, but it was affected by soil depth. Similar results were reported in the soils converted from cropland to planted forest and vegetation restoration (DeGryze

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et al. 2004, Zhao et al. 2014). Macro-aggregates are more sensitive to cultivation management than small size aggregates, which results from the restriction of macro-aggregate formation (Six et al. 2004). After farmland abandonment and recovery, reduced soil disturbance improves soil aggregation.

Meanwhile, adequate organic debris entered into SOC pool in restored land soils due to non-straw return in farmland in the study area (Liu et al. 2017). Abundant SOM accelerated microbial activities that control soil aggregation (Six et al. 2004). Larger SOC contents in restored land soil resulted from adequate organic debris supplement and reduced rate of SOC decomposition in aggregates by spatial inaccessibility (Dungait et al. 2012). In addition, a variation of soil aggregation and SOC sequestration under land use change were likely affected by soil depth due to highly heterogeneous karst soils and the time of farmland abandonment (Liao et al. 2016).

The SOC contents were higher in macro-aggregates than those in micro-aggregates in 0–30 cm depth soils of farmland, while the opposite results were observed in the soils of restored lands (Figure 2a,b,c). According to aggregate hierarchy theory by Six et al. (2000), C-enriched fresh particulate organic matter (POM) inside macro-aggregates is bound into micro-aggregates in no-tillage soils. Generally, SOC decomposition rate in micro-aggregates is lower than that in macro-aggregate because of aggregate stabilization that increases with decreasing aggregate size (Six et al. 2004). Therefore, SOC contents were larger in micro-aggregates than in macro-aggregates

Table 2. The quantitative relationship between proportion and soil organic carbon (SOC) content in aggregates

Depth (cm)	MA/MA-C	R^2	MI/MI-C	R^2	SC/SC-C	R^2
Linear relation (y = C)						
0–10	$y = 1.95x - 100.18$	0.44	$y = -6.96x + 124.83$	0.47	$y = -2.37x - 70.49$	0.53
10–20	$y = 0.80x - 27.25$	0.42	$y = -2.81x + 64.35$	0.41	$y = -1.01x + 42.50$	0.56
20–30	$y = 0.49x - 9.54$	0.47	$y = -3.162x + 59.68$	0.45	$y = -0.51x + 31.26$	0.51
0–30	$y = 0.92x - 32.67$	0.30	$y = -3.99x + 79.53$	0.30	$y = -0.97x + 43.92$	0.36
Exponential relation 1 (y = ln[C], ln is log for base-e)						
0–10	$y = 0.04x + 0.88$	0.64	$y = -0.13x + 5.19$	0.75	$y = -0.06x + 4.35$	0.74
10–20	$y = 0.04x + 0.52$	0.71	$y = -0.13x + 4.69$	0.73	$y = -0.06x + 4.10$	0.82
20–30	$y = 0.03x + 1.05$	0.70	$y = -0.16x + 4.78$	0.61	$y = -0.04x + 3.66$	0.79
0–30	$y = 0.04x + 0.83$	0.61	$y = -0.14x + 4.82$	0.55	$y = -0.05x + 3.98$	0.72
Exponential relation 2 (y = lg[C], lg is log for base-10)						
0–10	$y = 0.02x + 0.38$	0.64	$y = -0.06x + 2.25$	0.75	$y = -0.03x + 1.89$	0.74
10–20	$y = 0.02x + 0.23$	0.71	$y = -0.06x + 2.04$	0.73	$y = -0.03x + 1.78$	0.82
20–30	$y = 0.01x + 0.46$	0.70	$y = -0.07x + 2.08$	0.61	$y = -0.02x + 1.59$	0.79
0–30	$y = 0.02x + 0.36$	0.61	$y = -0.06x + 2.10$	0.55	$y = -0.02x + 1.73$	0.72
Quadratic equation relation ($y = \sqrt[2]{C}$)						
0–10	$y = 0.13x - 3.26$	0.54	$y = -0.46x + 11.77$	0.61	$y = -0.19x + 8.49$	0.64
10–20	$y = 0.08x - 0.70$	0.56	$y = -0.29x + 8.62$	0.56	$y = -0.12x + 6.86$	0.70
20–30	$y = 0.06x + 0.78$	0.58	$y = -0.35x + 8.56$	0.54	$y = -0.07x + 5.77$	0.65
0–30	$y = 0.08x - 0.49$	0.45	$y = -0.34x + 9.42$	0.43	$y = -0.10x + 6.77$	0.54
Cubic equation relation ($y = \sqrt[3]{C}$)						
0–10	$y = 0.05x + 0.08$	0.57	$y = -0.16x + 5.28$	0.66	$y = -0.07x + 4.19$	0.67
10–20	$y = 0.03x + 0.60$	0.61	$y = -0.12x + 4.32$	0.62	$y = -0.05x + 3.68$	0.74
20–30	$y = 0.02x + 1.15$	0.62	$y = -0.14x + 4.35$	0.57	$y = -0.03x + 3.26$	0.70
0–30	$y = 0.03x + 0.75$	0.51	$y = -0.13x + 4.57$	0.48	$y = -0.04x + 3.62$	0.61

x – mass proportion of macro-aggregates (MA), micro-aggregates (MI) and silt + clay-sized fractions (SC), respectively; y – transformed mathematic value of SOC content in macro-aggregates (MA-C), micro-aggregates (MI-C) and silt + clay-sized fractions (SC-C), respectively

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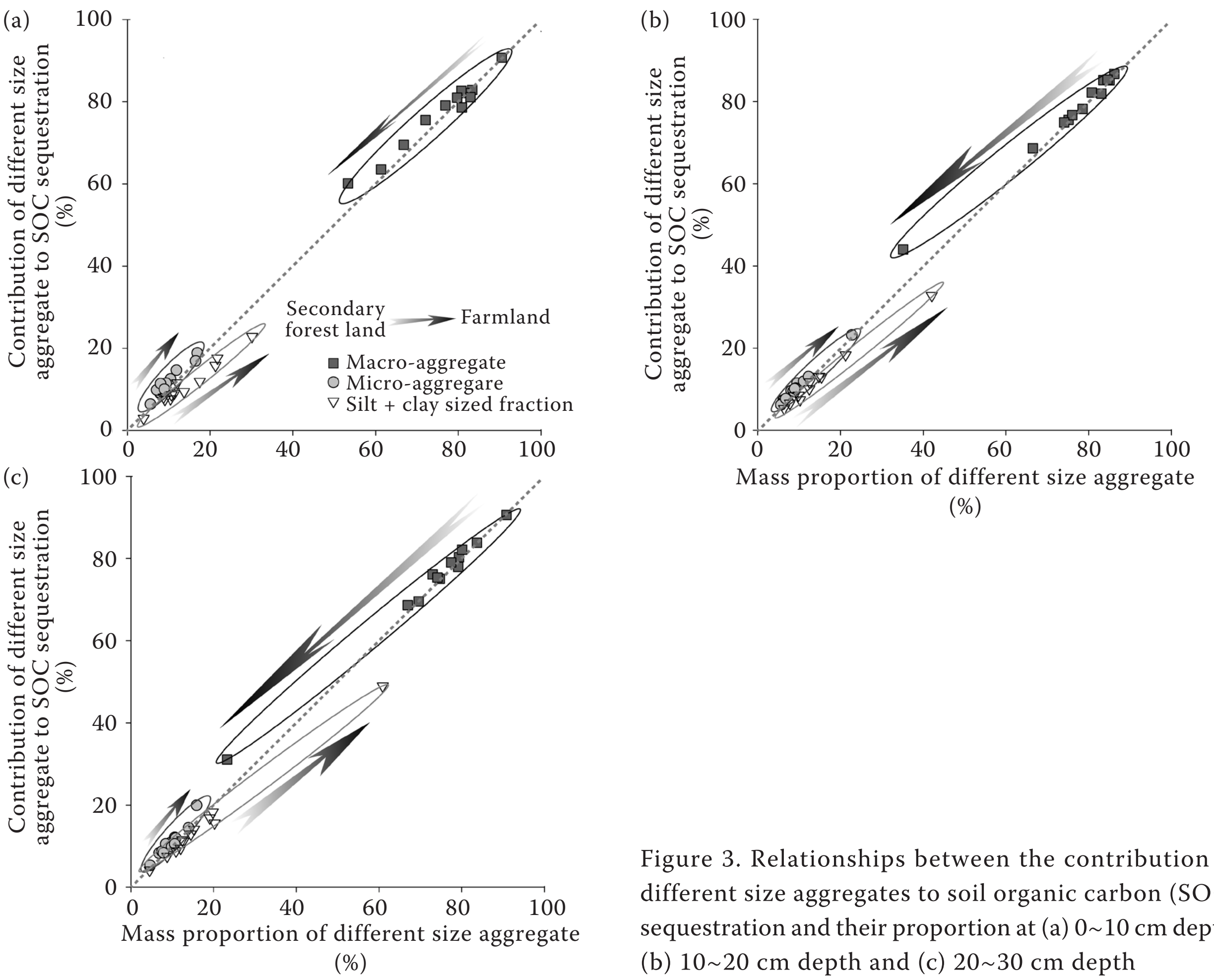

Figure 3. Relationships between the contribution of different size aggregates to soil organic carbon (SOC) sequestration and their proportion at (a) 0~10 cm depth; (b) 10~20 cm depth and (c) 20~30 cm depth

in restored land soils. Tillage management restricts the formation of macro-aggregate, as well as the transfer of fresh POM into micro-aggregates (Six et al. 2000). Thus, C-enriched SOM remains in macro-aggregates in farmland soils.

Relationship between soil aggregation and SOC sequestration. The exponential relationship between proportion and SOC content of aggregates along successional land uses in 0–30 cm depth soils was more reasonable than the linear and power relationships, as shown in Table 2. Positive correlation between proportion and SOC content of macro-aggregates, the negative correlation between them of micro-aggregates and silt + clay-sized fraction were also shown in Table 2. Spohn and Giani (2011) reported a sigmoidal correlation between MWD (mean weight diameter that can indicate the degree of soil aggregation) and SOC content, and suggested that sandy particles limited soil aggregation and SOC sequestration. However, in this study, less sandy particles and abundant calcium are critical for the stabilization of SOC and soil aggregation (Clough and Skjemstad 2000). Thus, the positive exponential correlation between proportion and SOC content of macro-aggregates indicated a potential of SOC sequestration on macro-aggregates in karst soils. Macro-aggregates in 0–30 cm depth soils were a dominant contribution to SOC sequestration (over 80%) in restored lands while only accounted for 31–60% in farmland soils (Figure 3). This study supported the statement that enhancive SOC sequestration after farmland abandonment and recovery was mainly stocked in macro-aggregates in karst soils.

In conclusion, soil aggregation and SOC sequestration were enhanced after farmland abandonment and recovery, and increased SOC sequestration was mainly stocked in macro-aggregates. SOC contents in macro-aggregates exponentially increased with their proportions along successional land uses. Contribution of macro-aggregates to SOC sequestration increased from 31–60% to over 80% in the processes of farmland abandonment and recovery, which indicates a great potential for SOC sequestration in macro-aggregates in karst soils.

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