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Effects of vegetation restoration on the aggregate stability and distribution of aggregate-associated organic carbon in a typical karst gorge region

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Abstract. Land use changes have a major impact on soil structure and soil nutrients. The influences of vegetation restoration on aggregate stability and soil carbon storage have been studied extensively, but the distribution of aggregate-associated carbon is not yet understood. The objective of this work was to study the influences of vegetation restoration on aggregate stability and distribution of soil organic carbon (SOC) associated with water-stable aggregates (WSAs) in a karst gorge region. The experiment was carried out in 2012 and included four land use types: bare land (BL), grassland (GL), shrubland (SL), and woodland (WL). Soil samples were collected from the 0–20, 20–40, and 40–60 cm depths, and aggregates were separated by a wet-sieving method. Aggregate stability and aggregated-associated SOC were determined, and the relationships between water-stable aggregation with SOC were examined. The results showed that total SOC and SOC associated with WSAs of various sizes were the highest at a soil depth of 0–20 cm. In addition, the SOC contents of the WSAs increased as the soil aggregate sizes decreased. The SOC contents of the WSAs < 0.25 mm were highest except in the bare land, and the SOC contents of the aggregates < 0.25 mm comprised the majority of the total aggregate SOC contents. The aggregates were dominated by particles with sizes > 5 mm under dry-sieving treatment, while aggregates were predominantly comprised of WSAs < 0.25 mm under wet-sieving treatment. At a soil depth of 0–60 cm, the mean weight diameter (MWD), geometrical mean diameter (GMD), and fractal dimensions (D) of the dry aggregates and water-stable aggregates in the different types of land were ranked, in descending order, as WL > GL > SL > BL. The contents of WSAs > 0.25 mm, MWD, and GMD increased significantly, in that order, and the percentage of aggregate destruction (PAD) and fractal dimensions decreased significantly as the soil aggregate stability improved. SOC contents increased after vegetation restoration, and the average SOC content of WL was 2.35, 1.37, and 1.26 times greater than that in the BL, GL, and SL, respectively. We conclude that woodland and grassland facilitated WSA stability and SOC protection; thus, promoting the natural restoration of vegetation by reducing artificial disturbances could effectively restore the ecology and prevent soil erosion in karst regions.

1 Introduction

Soil aggregates are the basic units of soil structures and contribute to soil carbon sequestration function and carbon stabilization (Cerdà, 1996; Mekonnen et al., 2015; Brevik et al., 2015). Good soil structures provide solid foundations for the storage and stabilization of organic carbon (Jastrow, 1996; Mao et al., 2007; Gelaw, 2013). The particle sizes of aggregates affect their abilities to store organic carbon as well as the distributions of their stored organic carbon components (Abu-Hamdeh et al., 2005; Liu and He, 2009). The distribution and stability of soil aggregates is closely related to the erosion resistance of soil and, therefore, are effective indicators of erosion sensitivity (Guo et al., 2007; Rachman et

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al., 2003; Valmis et al., 2005). According to Le Bissonnais (1996, 1997), soil erosion is primarily a result of the destruction of soil aggregates. Young (1980) and Bryan (2000) determined that aggregate stability affects the erodibility and nutrient holding capacity of soil. The formation and stability of the water-stable aggregates in soil are dependent on soil organic carbon (SOC), simultaneously vegetation communities affect SOC content via the addition of outer soil organic matter and in turn contribute to the formation of soil aggregates (Gabarrón-Galeote et al., 2013; Mekonnen et al., 2015). Impact of land use changes on aggregate stability and distribution of aggregate-associated SOC have always been research hotspots (Unger, 1997; Dimoyiannis, 2012; Stanchi et al., 2015). Jastrow (1996) researched the formation and stabilization of macroaggregates and process of C aggradation under different disturbances. Burri et al. (2009) concluded that revegetation measures increased soil aggregate stability by substantially accelerating vegetation development and by promoting soil formation process. Also, Mataix-Solera et al. (2011) found that low-severity fires do not produce notable changes in aggregate stability, but high-severity fires can induce important changes in this property.

China's karst region comprises an area of 3.44×10^6 km^2. The ecosystems that have developed from the karst landforms in this region are characterized by simple ecological community structures, small environmental capacities, and weak resistance to disturbance. These ecologically vulnerable areas are subjected to significant land degradation and stony desertification (Yuan et al., 2002; Yan et al., 2013). The SOC pool is the largest carbon pool in the karst system (Pan and Cao, 1999); the transfer of carbon in the karst system is predominantly controlled by soil carbon. Excessive land utilization and management often result in the destruction of soil structures, the disturbance of the foundations for organic carbon sequestration, the acceleration of soil carbon pool activity, and increased levels of soil erosion (Bai et al., 2013; Tang et al., 2014). Previous studies concerning the stability of soil aggregates and the characteristics of the organic carbon in those aggregates have primarily been conducted in the Loess Plateau (Liu et al., 2013; Qi et al., 2011) and hilly red soil regions (Guo et al., 2007; Yan et al., 2007). Studies regarding the karst region have only recently been conducted in karst plateau (Li et al., 2013) and cluster-peak depression region (Lu et al., 2012). Due to strong karstification, the karst region possesses a unique surface–underground structure and soil erosion different from that in the Loess Plateau and hilly red soil regions, showing that soil leakage underground occurs in addition to soil erosion on the surface (Zhang et al., 2010; Xu, 2014; Yan et al., 2013). Previous studies concerning the distribution of the soil aggregates, aggregate stability, and distribution and mineralization of the organic carbon in the aggregates (Wei et al., 2011; Tan et al., 2014) of the karst region have primarily consisted of single-factor studies. In addition, due to the differences in surface vegetation, litter, and roots resulting from the strong spatial heterogeneity of karst soil, the properties of the soil in different regions vary greatly (Li et al., 2013). Soil degradation in the karst region is characterized by an imbalance of soil aggregate particle composition and a decrease in aggregate stability. Soil erosion and tillage tend to damage water-stable aggregates (WSAs), and fine particles as well as SOC wrapped inside are susceptible to surface water migration loss. Thus, further investigation into changes of SOC content and aggregates stability in process of vegetation degradation/restoration has important theoretical and practical significance in revealing the evolution of soil quality in karst region.

In this paper, the effects of vegetation restoration on aggregates stability and the distribution as well as accumulation of aggregate-associated SOC were analyzed by studying bare land (BL), grassland (GL), shrubland (SL), and woodland (WL), soils typical to the gorge region of the karst plateau in Guizhou Province, China. Furthermore, the influencing mechanism of vegetation restoration on the stability of soil structures and sequestration of organic carbon were investigated in order to provide references concerning the restoration and reconstruction of degenerated karst ecosystems.

2 Materials and methods

2.1 Study area

The study area was located in the Huajiang Gorge (25°40′–25°42′ N, 105°37′–105°39′ E) demonstration area of Guanling County in Guizhou Province, China. This area, located on the eastern slope of the Yunnan–Guizhou Plateau tilting toward the hills in Guangxi, is a typical gorge region on the karst plateau, with an altitude of 500–1200 m and a relative height difference of 700 m. This region is characterized by a mid-subtropical humid monsoon climate, with sufficient heat, an annual average temperature of approximately 18 °C, and an average annual rainfall of 1200 mm. The typical soils in this area are Calcisol Leptosols according to WRB-based soil classification (IUSS working group, 2015), which are badly structured, dry, and barren.

The zonal vegetation in this area is comprised of mid-subtropical broadleaved evergreen forests. Due to the influence of several factors, such as lithology, drought, soil, and human activity, this area has experienced significant levels of vegetative degradation and is characterized by fragile ecosystems and a small environmental carrying capacity. The arbor forests, shrubs, and herbs in this region primarily consist, respectively, of *Pteroceltis tatarinowii*, *Toona sinensis*, and *Sapium sebiferum*; *Pyracantha fortuneana*, *Dodonaea viscosa*, *Zanthoxylum bungeanum*, and *Rosa cymosa*; and *Imperata cylindrica*, *Arthraxon hispidus*, *Taraxacum mongolicum*, and *Dicranopteris dichotoma*. Four typical land cover types including BL, GL, SL, and WL were selected for studying the changes of aggregates stability and aggregate-associated SOC in June 2012. The land types were selected

Table 1. Basic properties of study plots.

Vegetation types	Altitude (m a.s.l.)	Slope (°)	Vegetation cover (%)	Dominant species	Land use
BL	696	20.2	< 10	*Imperata cylindrica* and *Arthraxon hispidus*	Farmland abandoned 1 year, with disturbance of tillage and pasture
GL	710	22.1	70	*Imperata cylindrica*, *Leucas mollissima*, and *Taraxacum mongolicum*	Natural recovery for 5 years, with less human disturbance
SL	694	25.4	60	*Pyracantha fortuneana*, *Rosa cymosa*, and *Dodonaea viscosa*	Natural recovery for 9 years, with disturbance of pasture
WL	704	20.0	80	*Toona sinensis*, *Pteroceltis tatarinowii*, and *Sapium sebiferum*	Natural recovery for 16 years, with less human disturbance

based on the topography unit features with similar slope direction, position, bedrock, and vegetation restoration status, also in accordance with the principle of typical and representative. It should be noted that BL, GL, SL, and WL were farmlands before vegetation restoration. The characteristics of the sample plots are shown in Table 1.

2.2 Sample collection and analysis

Three research plots with a 20 m × 20 m horizontal projection area were established for each land cover type. After removing litters from soil surface, undisturbed soil were sampled at depths of 0–20, 20–40, and 40–60 cm by 5-point quincunx sampling method (Zhou, 2003) using a shovel in each research plot. The soil samples of each soil layer from the five points were mixed together as the plot's samples, and a total of 36 mixed soil samples were collected for the purposes of the study. All soil samples were brought back to laboratory and spread flat on kraft papers, broken into 10 mm clods along their soil cracks, and air-dried indoors.

The separation and water stability of aggregates was determined using the conventional dry-sieving and wet-sieving method (Perfect et al., 1992; Unger, 1997). This method was used to identify the disintegration processes of the soil aggregates under dissipation and expansion (Qi et al., 2011). Firstly, the air-dried soil samples were mixed well, and approximately 1 kg of soil samples was obtained by quartering and sieving the samples with sieves with mesh sizes of 8, 5, 2, 1, 0.5, and 0.25 mm. Secondly, a total of 100 g of the dry-sieved aggregates with different size fractions was weighed and placed on sieves with mesh sizes of 5, 2, 1, 0.5, and 0.25 mm. The soil samples became saturated after being wet for 10 minutes. The soil samples were shaken vertically for 5 min at an amplitude of 3 cm and a frequency of 30 times/minute. Finally, the residue on the sieves was collected, dried at 60 °C, and weighed (Sainju et al., 2003). The total SOC and SOC associated with water-stable aggregates were determined through oxidation with potassium dichromate and external heating (Bao, 2005).

2.3 Data calculation and analysis

The aggregate stability index (ASI) was determined by transfer matrix method (Shi, 2005). The PAD, mean weight diameter (MWD), and geometrical mean diameter (GMD) were determined by dry–wet sieving method (Yan et al., 2007; He et al., 2011). Since fractal theory can characterize the soil particle distribution and structural features, it has been widely applied to the study of soil structure fractal since the 1980s. Fractal dimension based on the weight distribution were calculated to characterize the distribution and stability of aggregates (Tyler and Wheatcraft, 1989; Yang et al., 1993).

All statistical analyses were performed using Excel 2003 and SPSS 18.0 software. The data conform to normal distribution upon Kolmogorov–Smirnov test (K–S test) and homogeneity of variance test. The one-way analysis of variance (one-way ANOVA) and least significant difference values were used to compare the differences among the various data sets. Pearson's correlation coefficient was used to evaluate the correlations among the different factors. The significance level was defined as $\alpha = 0.05$.

3 Results

3.1 Effects of vegetation restoration on total organic carbon and distribution of SOC associated with water-stable aggregates

The results showed that the organic carbon contents of the aggregates with various particle sizes differed significantly based on the type of vegetation (Fig. 1). The total organic carbon content of the study area ranged from 10.25 to 34.07 g kg^{-1}. The organic carbon contents of the soil in the WL, SL, GL, and BL were highest at a soil depth of 0–20 cm and decreased as the soil depth increased. The total organic carbon contents of the various soil layers were ranked, in descending order, as WL > SL > GL > BL.

The contents of SOC associated with water-stable aggregates were different and had no obvious regularity between

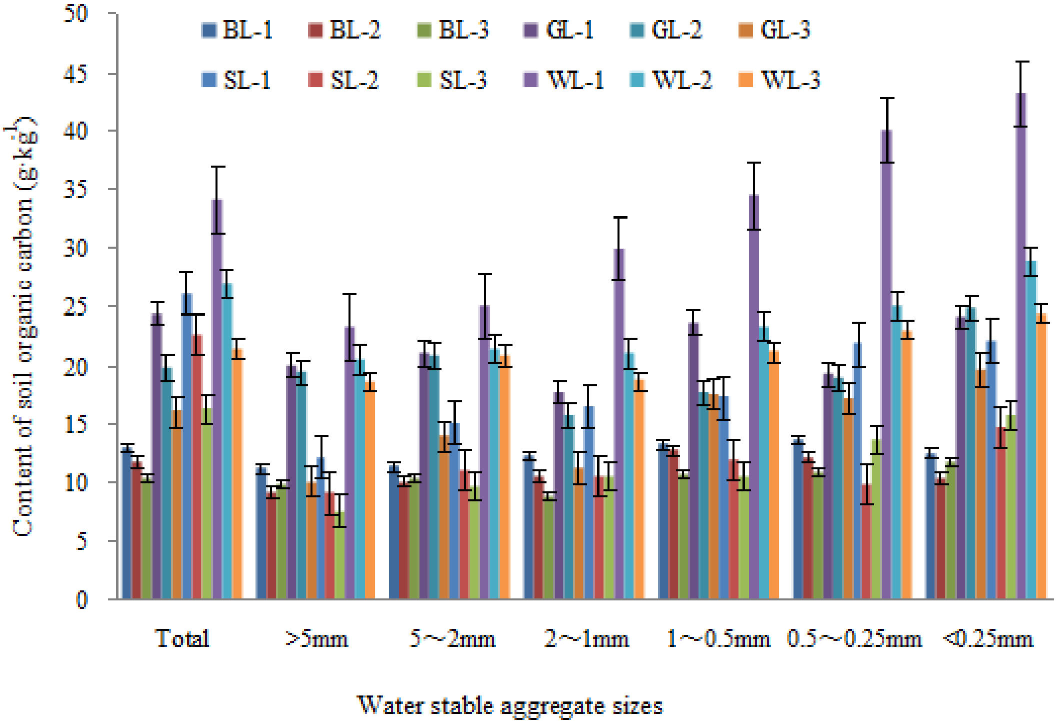

Figure 1. SOC in different water-stable aggregate sizes under different vegetation types (mean ±SE, $n = 3$. BL1, BL2, BL3, GL1, GL2, GL3, SL1, SL2, SL3, WL1, WL2, and WL3 represent 0–20 (1), 20–40 (2), and 40–60 cm (3) soil layers of bare land (BL), grassland (GL), shrubland (SL), and woodland (WL), respectively).

Table 2. Contribution rates of water-stable aggregates organic carbon to SOC under different vegetation types (%, mean ±SE, $n = 3$).

Vegetation types	Layer cm^{-1}	WSA sizes (%)					
		> 5 mm	5–2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	< 0.25 mm
BL	0–20	5.38 ± 0.33d	17.68 ± 0.9bc	11.6 ± 1.27c	14.82 ± 1.08c	21.19 ± 0.19b	25.32 ± 0.46a
	20–40	4.92 ± 0.19d	13.92 ± 0.31c	12.65 ± 0.21c	16.42 ± 0.95b	16.78 ± 0.16b	27.88 ± 1.43a
	40–60	3.45 ± 0.20e	15.87 ± 1.05bc	13.6 ± 0.61c	10.49 ± 0.56d	19.78 ± 0.96b	41.08 ± 1.81a
GL	0–20	7.56 ± 0.21b	17.65 ± 0.57a	16.99 ± 0.38a	16.44 ± 0.45a	8.55 ± 0.23b	18.85 ± 0.35a
	20–40	2.43 ± 0.07d	18.45 ± 0.61b	22.37 ± 0.56a	18.57 ± 0.60b	11.26 ± 0.31c	24.10 ± 0.50a
	40–60	2.58 ± 0.15d	19.3 ± 0.95b	17.04 ± 0.6b	17.54 ± 0.57b	11.27 ± 0.34c	27.72 ± 0.73a
SL	0–20	4.24 ± 0.11d	9.84 ± 0.29c	9.28 ± 0.22c	9.11 ± 0.3c	11.71 ± 0.15b	26.51 ± 0.33a
	20–40	1.68 ± 0.10d	6.56 ± 0.41c	9.00 ± 0.34b	9.56 ± 0.46b	7.49 ± 0.40c	18.28 ± 0.65a
	40–60	1.26 ± 0.05d	7.85 ± 0.56c	11.26 ± 0.42b	12.44 ± 0.67b	11.42 ± 0.44b	32.18 ± 1.06a
WL	0–20	16.81 ± 0.19bc	17.29 ± 0.73b	14.66 ± 0.19c	9.39 ± 0.16d	5.49 ± 0.62e	22.19 ± 0.20a
	20–40	16.58 ± 0.19b	24.38 ± 0.78a	11.13 ± 0.21c	7.78 ± 0.54d	5.06 ± 0.11d	20.37 ± 0.36a
	40–60	13.91 ± 0.18b	24.99 ± 0.82a	16.25 ± 0.1b	9.95 ± 0.40c	6.43 ± 0.27d	26.91 ± 1.21a

Note: different small letters in the same row indicate significant difference at 0.05 level among different sizes.

different size fractions (Fig. 1). In the BL, the contents of SOC associated with aggregates were relatively high in aggregates with 0.5–1 and 0.25–0.5 mm sizes in both 0–20 and 20–40 cm soil layer; the SOC of the aggregates < 0.25 mm was the highest at a soil depth of 40–60 cm. In the GL, SL, and WL, the contents of SOC associated with aggregates < 0.25 mm were the highest. The contents of SOC associated with aggregates of all the four kinds of land cover decreased as the decrease of particle sizes. In addition, the contents of SOC associated with aggregates > 5 mm were the lowest on the whole of all the four land cover types and have significant differences with other particle sizes especially in WL.

The contents of SOC associated with aggregates were the highest in 0–20 cm soil layer. In the BL, contents of SOC associated with aggregates decreased with the increase of soil depth except aggregates with > 5, 2–1, and 0.5–0.25 mm sizes. In the SL, SOC associated with aggregates with 0.5–0.2 and < 0.25 mm decreased with the increase of soil depth, and SOC associated with the other aggregate sizes have no obvious regularity with the increase of soil depth. When it comes to GL and WL, the contents of SOC associated with aggregates with various size fractions decreased as the soil depth increased.

As shown in Table 2, in all of the types of land cover, the contribution of the organic carbon in the WSAs < 0.25 mm to the total organic carbon content of the soil was the highest, ranging from 18.85 to 41.08 %, with an average of 25.95 %. In the BL, GL, and SL, the contribution of the organic carbon contents of the aggregates > 5 mm was the lowest with values of less than 10 %. In the WL, the contribution of the organic carbon contents of the WSAs with sizes of 0.25–0.5 mm was the lowest. At different soil depths, the contributions of the organic carbon contents of the WSAs with various sizes to the total organic carbon contents of the aggregates varied insignificantly.

3.2 Effects of vegetation restoration on distribution of soil aggregate sizes

The constituent size fractions of the dry-sieved aggregates in the different types of land cover were shown in Fig. 2. The dry-sieved aggregates in the different layers of soil predominantly consisted of aggregates ≥ 2 mm, accounting for greater than 60 % of the total aggregates. The aggregates > 5 mm also comprised a large amount of the soil aggregates, accounting for 35.56–60.98 % of the total aggregates. The aggregates < 0.25 mm comprised the smallest proportion of aggregates, accounting for 3.52–8.49 % of the total aggregates. The contents of aggregates from bigger sizes to smaller sizes were gradually diminishing on the whole in each soil depth of different land cover types. Contents of aggregates greater than 5 mm were showing as WL > GL > SL > BL in the same soil layer of different land cover, while the other aggregates sizes had no obvious regularity and difference.

For all four land cover types, contents of aggregates > 5 mm decreased as soil depth increase and aggregates < 0.25 mm increased as soil depth increase, but the other aggregate sizes had no obvious regularity. Compared with BL, WL, and GL significantly increased the contents of aggregates > 5 mm and significantly decreased the contents of aggregates < 0.25 mm.Within the different layers of soil, the contents of the aggregates > 5 mm were ranked, in descending order, as WL > GL > SL > BL, and the contents of the aggregates ranging from 2 to 5 mm were ranked, in descending order, as SL > BL > GL > WL. The contents of the aggregates < 0.25 mm in the top soil decreased in the vegetation succession from bare land to grassland, shrub land and woodland.

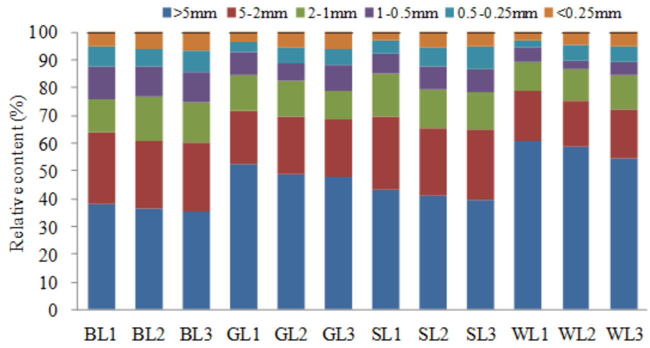

Figure 2. Relative distribution of soil dry aggregates with different sizes under different vegetation types. (BL1, BL2, BL3, GL1, GL2, GL3, SL1, SL2, SL3, WL1, WL2, and WL3 represent 0–20 (1), 20–40 (2), and 40–60 cm (3) soil layers of bare land (BL), grassland (GL), shrubland (SL), and woodland (WL), respectively.)

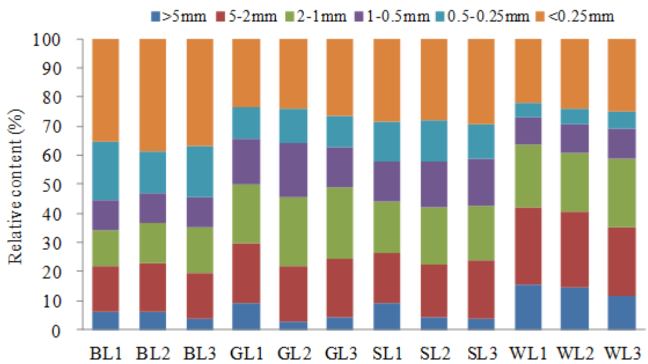

Figure 3. Relative distribution of soil water-stable aggregates with different sizes under different vegetation types (BL1, BL2, BL3, GL1, GL2, GL3, SL1, SL2, SL3, WL1, WL2, and WL3 represent 0–20 (1), 20–40 (2), and 40–60 cm (3) soil layers of bare land (BL), grassland (GL), shrubland (SL), and woodland (WL), respectively).

The water-stable aggregates of the different types of land cover predominantly consisted of particles with sizes < 0.25, 1–2, and 2–5 mm, accounting for 59.01–71.31 % of the total WSAs (Fig. 3). Water-stable aggregate contents in BL, GL and SL were minimum in aggregates > 5mm and maximum in aggregates < 0.25 mm. When it comes to WL, aggregates content was minimum in aggregates of 0.5–0.25 mm and maximum in aggregates of 5–2 mm. The WSAs < 0.25 mm comprised the majority of the total WSAs, accounting for 23.64–35.93 % of the total WSAs. Within the various layers of soil, the content of aggregates < 0.25 mm in the different types of land use increased as the soil depth increased according to the ranking BL > SL > GL > WL, while the contents of the larger aggregates decreased as the soil depth increased. The BL exhibited the highest content of aggregates < 0.25 mm in the various layers of soil. The contents of aggregates < 0.25 mm in the other vegetation types were less than 30 %.

Table 3. The soil aggregate stability based on dry–wet sieving method.

Vegetation types	Layer cm^{-1}	$WSA_{>0.25}$ (%)	PAD (%)	MWD (mm) Dry	MWD (mm) Wet	GMD (mm) Dry	GMD (mm) Wet	*D* Dry	*D* Wet
BL	0–20	71.68Ab	21.5Cb	4.183Ad	1.588Ac	3.181Ac	0.699Ac	2.163Aa	2.649Ba
	20–40	68.21ABb	28.34Ba	4.085Ad	1.304ABc	2.627Bd	0.626Bc	2.192Aa	2.690ABa
	40–60	64.07Bb	31.87Aa	3.243Bd	1.169Bc	1.966Cd	0.535Cc	2.227Aa	2.725Aa
GL	0–20	83.36Aa	13.59Cc	5.335Ab	1.966Ab	3.882Ab	1.061Ab	2.037Aa	2.487Bc
	20–40	80.81Ba	16.33Bb	5.011ABb	1.642Bb	3.605ABb	0.913Ab	2.091Aa	2.505ABc
	40–60	74.31Ca	19.43Ac	4.883Bb	1.498Bb	3.384Bb	0.881Ab	2.121Aa	2.580Ac
SL	0–20	73.86Ab	23.13Ca	4.655Ac	1.697Ac	3.35Ac	0.71Ac	2.112Aa	2.603Ab
	20–40	68.69Bb	26.87Ba	4.467Ac	1.473ABbc	3.107ABc	0.638ABc	2.187Aa	2.623Ab
	40–60	66.5Bb	28.26Ab	4.415Ac	1.252Bc	2.842Bc	0.588Bc	2.224Aa	2.678Ab
WL	0–20	86.72Aa	10.68Bd	6.101Aa	3.618Aa	4.934Aa	1.981Aa	1.994Aa	2.425Bc
	20–40	81.03Ba	17.02Bb	5.882Aa	3.027Ba	4.534Ba	1.503Ba	2.045Aa	2.522ABc
	40–60	76.36Ca	21.1Ac	5.41Ba	2.505Ba	4.087Ca	1.151Ca	2.074Aa	2.556Ac

Note: different small letters in the same column mean significant differences in same layer of different land cover types at 0.05 level; different capital letters in the same column mean significant differences in different soil layer of same land cover types at 0.05 level, the same in the Table 4.

3.3 Effects of vegetation restoration on soil aggregate stability

The stability of the soil aggregates differed significantly based on the type of vegetation (Table 3). The soil depth also affected the stability of the soil aggregates. The contents of the aggregates > 0.25 mm in the WL, GL, SL, and BL, were equal to 81.37, 79.49, 69.02, and 68.65 %, respectively. The PAD of the aggregates > 0.25 mm in the BL (27.24 %) was the highest, and the PAD of the aggregates > 0.25 mm in the WL (16.27 %) was the lowest. The MWD and GMD values of the dry-sieving and wet-sieving aggregates were both ranked, in descending order, as WL > GL > SL > BL. The fractal dimensions of the dry-sieved aggregates in the four types of land cover ranged from 1.994 to 2.227, and the fractal dimensions of the WSAs ranged from 2.425 to 2.725, ranking, in descending order, as BL > SL > GL > WL in studied soil profile.

In all four types of land cover, the contents of the aggregates > 0.25 mm, MWD, and GMD decreased with the increase of soil depth. Contrarily, the PAD and D values increased as the soil depth increased. The MWD and GMD of the dry-sieved and wet-sieved aggregates were ranked, in descending order, as WL > GL > SL > BL, while the D values of the dry-sieving and wet-sieving aggregates were ranked, in descending order, as BL > SL > GL > WL. The PAD of the aggregates obtained at a soil depth of 0–20 cm were ranked, in descending order, as SL > BL > GL > WL, while the PAD of the aggregates obtained at soil depths of 20–40 and 40–60 cm were ranked, in descending order, as BL > SL > WL > GL. The stability of the soil aggregates in the same soil layers of the different types of vegetation was significantly different. Other indicators changed not significantly as the soil depth changed.

The probabilities of the soil aggregates in the different types of land cover remaining unchanged are shown in Table 4. In the BL, GL, and SL, dry-sieving and wet-sieving destroyed the aggregates with particle sizes greater than 5 mm and ranging from 1 to 5 mm and a have small impact on the aggregates with sizes ranging from 0.25 to 1 mm. The probability of the soil aggregates with sizes ranging from 0.25 to 1 mm remaining unchanged ranged from 0.26 and 0.51. In the WL soil, the probability of the soil aggregates > 5 mm remaining unchanged was the highest (0.39–0.55), and the probability of the soil aggregates with sizes ranging from 0.25 to 0.5 mm only ranged from 0.23 to 0.31. The ASI values ranged from 2.19 to 3.32. The average ASI values of the WL, GL, SL, and BL were, in descending order, equal to 2.85, 2.65, 2.39, and 2.31, respectively. The ASI values of the aggregates in the topsoil were the highest, and the ASI values decreased as the soil depth increased. The ASI values of the different types of land cover at different soil depths were ranked, in descending order, as WL > GL > SL > BL. The difference of the ASI values between WL and GL, as well as BL and SL were not significant at the same soil layer. However, except at soil depths of 20–40 and 40–60 cm, the differences in the ASI values of the GL and BL and the values of WL and SL at the same soil depths were significant.

3.4 Relationships between water-stable aggregates and organic carbon

The correlations among the parameters of the WSAs are shown in Table 5. Fractal dimension was significantly and negatively associated with the MWD, GMD, and SOC ($P < 0.01$), and the MWD was significantly and positively associated with the GMD ($P < 0.01$). The SOC was significantly and positively associated with both the MWD and GMD ($P < 0.01$). The contents of the aggregates with par-

Table 4. Conservation ratio of aggregates and aggregate stability index.

Vegetation types	Layer cm^{-1}	Conservation ratio of aggregates (%)						Aggregate stability index (ASI)
		> 5 mm	5–2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	< 0.25 mm	
BL	0–20	0.22	0.25	0.28	0.3	0.42	1	2.47Ab
	20–40	0.15	0.28	0.23	0.28	0.38	1	2.30Bb
	40–60	0.10	0.23	0.21	0.26	0.39	1	2.19Bb
GL	0–20	0.18	0.34	0.44	0.46	0.49	1	2.91Aa
	20–40	0.05	0.24	0.38	0.42	0.51	1	2.60Ba
	40–60	0.07	0.31	0.32	0.36	0.39	1	2.45Ba
SL	0–20	0.19	0.28	0.26	0.34	0.44	1	2.51Ab
	20–40	0.09	0.21	0.25	0.34	0.45	1	2.34Bb
	40–60	0.07	0.22	0.22	0.35	0.46	1	2.32Bb
WL	0–20	0.55	0.51	0.52	0.43	0.31	1	3.32Aa
	20–40	0.48	0.35	0.30	0.31	0.25	1	2.69Ba
	40–60	0.39	0.23	0.38	0.30	0.23	1	2.53Ba

ticle sizes of greater than 5, 2–5, and 1–2 mm were significantly and negatively correlated with D ($P < 0.05$), and the contents of the aggregates with particle sizes of 0.25–0.5 mm and less than 0.25 mm were significantly and positively correlated with D ($P < 0.05$). The MWD and GMD were significantly and positively correlated with the contents of the aggregates > 2 mm and significantly and negatively correlated with the contents of the aggregates < 0.5 mm. The SOC was positively correlated with the contents of aggregates with various size fractions and significantly correlated with the contents of aggregates greater than 5 mm.

4 Discussion

4.1 Effects of vegetation restoration types on distribution of SOC associated with water-stable aggregates

The SOC contents of soil aggregates with various particle sizes can be used to micro-characterize the balance between organic matter and the mineralization rate of organic carbon. The organic carbon contents of aggregates affect the nutrient holding capacity and carbon sequestration in soil significantly (Wu et al., 2004). The soil organic matters of different land use types differed based on the quantity and quality of the litter and the environment, affecting the organic carbon contents of the soil and the stability and contents of the organic carbon in the aggregates (Novara et al., 2015). In all four types of land cover, the SOC contents associated with aggregates with various particle sizes were the highest at a soil depth of 0–20 cm, which were consistent with the results of Li et al. (2002). This was because the large amount of plant residue that had accumulated in the topsoil and the amount of organic matter that had been input into the soil improved the biological activity of the microorganisms, animals, and roots in the topsoil and, thus, facilitated the formation of particulate organic carbon (Wei et al., 2011).

Vegetation restoration have great impact on the contents of total SOC and SOC associated with different aggregate sizes. The organic carbon contents of the aggregates were the highest in the WL and the lowest in the SL and BL, primarily due to the amount of vegetative coverage and the quantity and decomposition of litter. Due to their high amounts of vegetative coverage, the WL and GL exhibited large amounts of litter and a considerable amount of input SOC. The BL and SL exhibited significantly smaller amounts of litter and input SOC and accelerated levels of organic carbon decomposition due to artificial disturbances. In general, the organic carbon contents of the soil aggregates decreased as the soil depth increased; in these types of land cover, artificial disturbances accelerated the decomposition of organic carbon.

In previous studies, De Jonge (1999), Christensen (1986), and Li et al. (2006) determined that organic carbon is primarily distributed in microaggregates (< 0.25 mm) and that organic carbon contents increase as aggregate particle sizes decrease. Puget (1998, 2000) found that large aggregates are a source of organic carbon enrichment. In another study, Li et al. (2000) found that organic carbon is distributed in a "*V*" shape in aggregates and that the organic carbon contents of aggregates > 2 mm and < 0. 25 mm are high. In a study by Li et al. (2000), as the particle sizes increased the SOC contents decreased, but the organic carbon contents of the aggregates exhibited no significant differences, possibly due to the high calcium carbonate and clay contents of the lime soil in the karst region (Wei et al., 2011). In this study, the organic carbon contents of the aggregates < 0.25 mm in the GL, SL, and WL increased by 5.28–95.37, 1.46–106.25, and 6.02–85.43 % compared to the aggregates with other particle sizes. These results corresponded with the theory that organic carbon initially accumulates in aggregates with small size frac-

Table 5. Correlation between parameters of water-stable aggregation.

						WSA sizes (mm)					
		D	MWD	GMD	SOC	> 5	5–2	2–1	1–0.5	0.5–0.25	< 0.25
D		1									
MWD		−0.544**	1								
GMD		−0.608**	0.963**	1							
SOC		−0.454**	0.701**	0.756**	1						
	> 5	−0.203	0.409*	0.265	0.588**	1					
	5–2	−0.346*	0.168	0.203	0.348*	0.798**	1				
WSA	2–1	−0.202	0.224	0.121	0.418*	0.871**	0.808**	1			
sizes	1–0.5	−0.215	0.194	0.172	0.410*	0.882**	0.817**	0.951***	1		
(mm)	0.5–0.25	0.312*	0.114	0.237	0.338*	0.822**	0.678**	0.947**	0.926**	1	
	< 0.25	0.633**	0.074	0.112	0.368*	0.865**	0.835**	0.960**	0.922**	0.951**	1

* $P < 0.05$; ** $P < 0.01$.

tions (Hassink, 1997) as well as the results of other studies concerning the karst region (Lu et al., 2012; Luo et al., 2011).

4.2 Effects of vegetation restoration on the distribution and stability of soil aggregates

The size fractions of aggregates affect the storage and supply of soil nutrients, the pore structure and hydraulic properties of soil, and the movement of organisms in soil. Therefore, the size distributions of aggregates are closely related to soil quality (Dexter, 1988; Nimmo and Perkins, 2002). SOC is a binding substance imperative for the formation of aggregate structures (Cerdà, 2000; Wu et al., 2004). Land cover significantly affects SOC contents by influencing the input and output of the organic matter in soil and, therefore, the distribution and stability of soil aggregates (Powers, 2004; Luo et al., 2011; Arjmand et al., 2015). After vegetation restoration, the organic carbon contents, MWD, and GMD of the WSAs > 0.25 mm increased, and the PAD and D values decreased. Thus, as a result of vegetation restoration, the SOC content increased, promoting the formation of soil aggregates and increasing the stability of the soil aggregates. The organic carbon contents, MWD, and GMD of the WSAs > 0.25 mm in the WL and GL were significantly higher than those of the WSAs > 0.25 mm in the BL and SL, while the PAD values of the WL and GL were significantly lower than those of the BL and SL, indicating that the WL and GL possessed good soil aggregate structures with strong resistance and high nutrient storage capacities. In the BL and SL, artificial disturbances led to the destruction of soil structures, accelerating the transformation of large WSAs to aggregates with small size fractions and exacerbating the low of soil and nutrients. The structural stability and erosion resistance of the soil in the GL were higher than those of the soil in the SL, primarily because the GL was subjected to less disturbances. Thus, the GL exhibited higher levels of vegetative coverage with considerable amounts of returned biomass, while the SL, due to felling, picking, and the forced compaction of wildlife, possessed fewer soil organic matter sources and disrupted soil structures. BL and SL were prone to erosion when they suffered strong rainfall splash due to low surface vegetation coverage, leading to aggregates dispersed into small ones and decomposition of unstable organic carbon, which result in a substantial decline in macroaggregates and organic carbon content (Gabarrón-Galeote et al., 2013).

The contents of the WSAs decreased as the soil depth increased. This was likely because the excess litter on the topsoil; the high organic matter contents; and the good water, heat, and air conditions of the soil contributed to the formation of large aggregates (Tisdall and Oades, 1982; Xiao et al., 2008). In addition, the organic matter contents of the deep soil were relatively low, a small number of large soil aggregates were formed, and the contents of the large WSAs were reduced. In the same types of land cover, the ASI of the WSAs decreased as the soil depth increased, just as the contents of the large WSAs decreased as the soil depth increased. Of the four typical types of land cover in the study area, the WL exhibited the highest aggregate stability and strongest erosion resistance, promoting the stability of the soil structure, the storage of nutrients, and the contents of organic carbon. The GL soil exhibited the second highest aggregate stability, and the BL and SL possessed relatively poor water stability.

The vegetation restoration process significantly affected the formation and distribution of large aggregates in that the BL, SL, GL, and WL exhibited significantly decreased levels of aggregates < 0.25 mm throughout the various soil layers and significantly increased levels of larger aggregates throughout the vegetation restoration process. Studies have shown that vegetation restoration would effectively improve the soil infiltration capacity, water holding capacity, and aeration of the lime soils and promote the formation of soil aggregates (Qi, 2007). Therefore, aggregate stability could be improved and soil erosion could be prevented by reducing soil disturbances, increasing the organic matter and nutrient contents of soil, and, therefore, facilitating the natural restoration of vegetation.

The fractal dimensions of the particle size distributions of soil granular structures reflect the influence of the contents of aggregates on the structure and stability of the soil (Dexter, 1988; Nimmo and Perkins, 2002). Thus, smaller fractal dimensions indicate better soil structures and stability and higher erosion resistance. Likewise, higher fractal dimensions indicate poorer soil structures and stability (Zhou et al., 2008; Barral et al., 1998).

The fractal dimensions of various soil particle sizes reflect the ability of the soil particles to fill spaces and could be used to evaluate soil structures (Tyler and Wheatcraft, 1989; Yang et al., 1993). According to the correlation analysis, D was significantly positively correlated with aggregates < 0.25 mm and had significantly negative correlations with MWD, GMD, and SOC. As the value of D increased, the contents of the aggregates > 0.25 mm decreased, and the soil density increased; this may result in poorer permeability as well as nutrient and moisture storage capacities. The results of this study indicated that as the vegetation was restored, the fractal dimensions of the WSAs decreased, and the stability of the soil structures and organic carbon contents improved.

5 Conclusions

Total SOC and SOC associated with water-stable aggregates increased with the restoration of vegetation. SOC was initially accumulated in aggregates with small size fractions and WSAs < 0.25 mm has the greatest contribution to soil total SOC. Contents of WSAs < 0.25 mm reduced while WSAs > 1 mm increased significantly in the process of vegetation succession from bare land to woodland. Vegetation restoration has promoted the accumulation of aggregates with small particle sizes into large sizes and, therefore, improved water stability of aggregates. The fractal dimension of water-stable aggregates was highly significantly and negatively correlated with the MWD, GMD, and SOC ($P < 0.01$), indicating that it could be used to objectively and comprehensively reflect the soil aggregate characteristics and stability. The woodland and grassland were more conducive to facilitate water-stable aggregate stability and SOC protection; thus, promoting natural vegetation restoration by reducing artificial disturbances could effectively restore the ecology and prevent soil erosion in karst regions.

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