



# Effects of vegetation succession on soil organic carbon fractions and stability in a karst valley area, Southwest China

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**Abstract** A series of complex organic fractions with different physical and chemical properties make up soil organic carbon (SOC), which plays a vital role in climate change and the global carbon cycle. Different SOC fractions have different stability and respond differently to vegetation succession. This research was carried out to assess the impacts of vegetation succession on SOC dynamics in the Qingmuguan karst valley area, southwest China. Soil samples were collected from four typical vegetation succession stages, including farmland, grassland, shrubland, and forest. The total SOC content and four oxidizable SOC fractions were measured. Results showed that the total SOC content and storage under farmland were highest, followed by forest and shrubland, and the grassland had the lowest total SOC content and storage. The SOC sequestration potential under different vegetation types in the study area was grassland ( $26.32 \text{ Mg C ha}^{-1}$ ) > shrubland ( $9.64 \text{ Mg C ha}^{-1}$ ). All SOC content, storage, and fractions showed a decrease with the increase of soil depth over the

0–50 cm in the study area. The four SOC fractions under forest at topsoil (0–10 cm) were higher than that under the other vegetation types. Compared with the other land uses, the farmland had the highest stable oxidizable SOC fractions (F3 and F4) at the 10–50-cm depth, while the shrubland had the highest active oxidizable SOC fractions (F1 and F2). In terms of the lability index of SOC, shrubland was the largest, followed by grassland and forest, and farmland was the smallest. These results provide essential information about SOC fractions and stability changes resulting from changes of vegetation types in a karst valley area of southwest China. It also supplements our understanding of soil carbon sequestration in vegetation succession.

**Keywords** Land-use change · SOC storage · Oxidizable carbon fractions · Lability index · Carbon sequestration potential

## Introduction

It is estimated that the soil carbon pool accounts for more than 50% of the terrestrial ecosystem carbon pool, which is about 3–4 times of vegetation carbon pool and 2–3 times of atmospheric carbon pool (Scharlemann et al., 2014; Lal, 2004). SOC serves as the material basis of soil fertility and is one of the cores for studying the global carbon cycle. Specifically, it not only provides a source of carbon for

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vegetation growth and maintains better soil physical structure, but also, at the same time, changes in its carbon storage and release can cause significant changes in atmospheric CO<sub>2</sub> concentration (Schuur et al., 2015). Consequently, SOC sequestration is a great way to achieve sustainable agriculture and mitigate global warming.

SOC consists of a series of plant, animal and microbial remains, excreta, secretions, and some decomposition products. The study of its fraction is necessary to detect the change of SOC under different management and utilization measures. Compared to the study of the total SOC, understanding the changes in SOC fractions can help us better evaluate the SOC responses to disturbances and the SOC protection mechanisms (Gabarron-Galeote et al., 2015; Yu et al., 2017). SOC grouping methods are diverse, such as physical classification and chemical classification. According to the differences of SOC stability, SOC can be divided into active organic carbon and stable organic carbon (Rabbi et al., 2014; Lehmann & Kleber, 2015). The sensitivity of soil active SOC fractions to land-use change is high, reflecting small changes in SOC content. In contrast, the stable SOC fraction determines the SOC storage, which is an important indicator of soil carbon reservoir (Lorenz et al., 2019; Soucemarianadin et al., 2018). In recent years, many studies have measured the SOC fractions and discussed the effects of management practices on active carbon fractions (Pal et al., 2020; Wang et al., 2014a, b). However, few studies focus on the size and responses of stable carbon fractions to different management practices (Liu et al., 2018c; Luo et al., 2021).

Due to the differences in separation techniques and practical means, the SOC fractions obtained are different. Appropriate SOC fractions should be measured for research according to various research purposes (Zhang et al., 2021). A recent study reported that SOC is a continuum of progressively decomposing organic compounds ranging from intact plant material to highly oxidized carbon fractions (Lehmann & Kleber, 2015). The modified Walkley–Black method is used to divide SOC into four continuous fractions along with decreasing order of oxidizability more recently, and this fractionation method has shown promise in distinguishing differences in the complete SOC stability continuum (Chan et al., 2001; Liu et al., 2018c). The SOC fractions (F1, F2, F3, and F4) measured by this method are very sensitive indexes

to study the dynamics of SOC (Batista et al., 2018; Zhang et al., 2021). In addition, the lability index of SOC (the percentage of active carbon to total SOC) could be calculated through these fractions to represent the activity of the SOC and then assess the SOC stability (Liu et al., 2018c; Yu et al., 2017). For example, Yu et al. (2022) evaluated the effect of vegetation degradation on SOC stability using the lability index and found that grassland degradation did not change the SOC stability in the Songnen grassland.

Many factors could influence the SOC content, for example, vegetation, climate, human activities, and soil physical and chemical characteristics. Among these factors, changes in land use and vegetation type have the most direct, crucial, and profound influence on SOC and terrestrial ecosystem carbon cycle (Wiesmeier et al., 2014). The changes in vegetation types intensely influence SOC by directly affecting the quantity and quality of above- and below-ground biomass and regulating the microbial activities (Deng et al., 2014; Li & Zhou, 2018). Natural vegetation succession can enhance the accumulation of SOC (Liu et al., 2018b). In recent years, under the context of global climate change, vegetation succession affects soil organic carbon storage, which is a meaningful way to realize soil carbon sink function, achieve carbon balance, and mitigate climate change (Chang et al., 2011).

China's karst area (3.44 million km<sup>2</sup>) accounts for about one-third of the land area, and it belongs to the distinct ecological vulnerable regions (Guo, 2002). Southwest China is one of China's main karst distribution areas, and it is very famous because of the most extensive distribution area, the complete development types, and the fragile ecological environment. SOC is the powerful medium of carbon transfer and the primary carbon circulation in the karst system (Pan & Cao, 1999). In the past two decades, southwest China has responded to the national policy of "returning farmland to forest and grassland" and achieved remarkable ecological restoration effects, making it the central area of returning farmland to grassland and forest in China (Huang et al., 2017). In the succession process, different vegetation types change the original structure and properties of the soil, leading to significant changes in the quantity and quality of SOC (Carolan & Fornara, 2016; Pringle et al., 2014). However, because the presence of SOC in soil ecosystems is very complex and it varies significantly under the intervention of human

activities, further studies are needed on the role of carbon cycling mechanisms in karst soil ecosystems.

In summary, although many scholars have studied the changes of SOC content and fractions, we still do not fully understand SOC because of the high heterogeneity, complexity of influencing factors, and dependence on the space–time scale of SOC (Liu et al., 2018a). Therefore, many vital scientific questions are still worthy of further exploration. Firstly, many studies focus on how vegetation type change affects SOC content and storage (Wiesmeier et al., 2014), while the information on how the soil's active and stable organic carbon fractions with different biochemical stabilities react to vegetation succession is still limited. Secondly, studies have shown that the stable SOC fractions in the soil can reflect the changes in external environmental conditions (Lehmann & Kleber, 2015). However, due to the extreme lack of relevant research, it is unclear how much the change in vegetation types can affect the change of stable SOC fractions. Thirdly, many studies have studied the changes in SOC after reforestation and grass restoration (Wang et al., 2014a, b), while relatively few studies have been conducted on the stability and sequestration potential of SOC. It is difficult to measure the great ecological benefits of the reforestation and grass restoration project. Given the significance of SOC and its fraction changes in the global climate change and the carbon cycling in terrestrial ecosystems, as well as the shortcomings of current studies. This study took four different vegetation types (farmland, grassland, shrubland, and forest land) in the small basin of Qingmuguan, a typical karst region in southwest China, as the research object. The vertical distribution characteristics of SOC content, storage, and fractions under four vegetation types were analyzed to reveal the effects of vegetation changes on SOC dynamics and its stability. Meanwhile, this study provided a theoretical basis for understanding the processes and mechanisms of soil carbon cycling in the karst region of southwest China.

## Materials and methods

### Study area

The research site is a typical karst valley area in Qingmuguan small watershed (29°40'N, 106°17'E) of

Jinyun Mountain, Southwest China, covering an area of 13.4 km<sup>2</sup>. It has a subtropical monsoon humid climate with warm winter and hot summer. The annual average temperature is 13.6 °C, the average temperature in the hottest month (August) is 24.3 °C, and the average temperature in the coldest month (January) is 3.1 °C. The annual average rainfall is 1783.8 mm, and the annual average evaporation is 777.1 mm. The soil in the area is yellow soil and yellow brown soil, with a small amount of scattered purple soil. The natural vegetation types are rich and diverse, mainly *Pinus massoniana*, *Cunninghamia lanceolata*, *Phyllotachys pubescens*, *Rubus corchorifolius*, etc.

Due to the fragile geological background, these karst valley areas tend to have unfertile soils and low soil-forming capacity of carbonate rocks by dissolution. Human activities are mainly distributed on both sides of the trough valley depression in the basin. A large area of forest is reclaimed as farmland, which impacts the natural ecological environment of the basin. Since the policy of returning farmland to forest and grassland in 2003, the farmland in this region has been gradually abandoned and restored, forming different vegetation types.

### Soil sampling

Soil samples from farmland, grassland, shrubland, and forest were collected during the growing season of 2020. In the sampling area of each vegetation type, four 1 m × 1 m replicated sampling plots were established along the random transects with intervals of 20 m. In each plot, five soil cores were randomly collected at 0–10-, 10–20-, 20–30-, 30–40-, and 40–50-cm depths with a hand-held drill after above-ground litter and biomass removal. Five soil samples were collected and mixed into the same soil sample for each soil layer range at each sampling point, and thus resulting in 100 composite soil samples. After the soil samples were divided and packed, the samples were transported to the laboratory in time. After removing the gravel and residual roots, some soil samples were air-dried in the natural state for reserve, and the other part was stored in the refrigerator for reserve.

### Soil analysis

SOC content is measured using the potassium dichromate-sulfuric acid elimination and ferrous sulfate titration

(Kalembasa & Jenkinson, 1973). SOC storage is measured using the equivalent soil mass method (Ellert & Bettany, 1995). The calculation formula of this method is as follows:  $\{S$  is the SOC storage ( $\text{Mg C ha}^{-1}$ );  $BD_i$  is the soil bulk density of layer  $i$  ( $\text{g cm}^{-3}$ );  $E_i$  is the SOC content in layer  $i$  ( $\text{g kg}^{-1}$ );  $T_i$  is the soil thickness of layer  $i$  (cm); and  $K$  is constant  $10^{-1}$ ; in this paper,  $n=5\}$ .

$$S = \sum_{i=1}^n BD_i \times E_i \times T_i \times K \quad (1)$$

where  $S$  is the SOC storage ( $\text{Mg C ha}^{-1}$ );  $BD_i$  is the soil bulk density of layer  $i$  ( $\text{g cm}^{-3}$ );  $E_i$  is the SOC content in layer  $i$  ( $\text{g kg}^{-1}$ );  $T_i$  is the soil thickness of layer  $i$  (cm); and  $K$  is constant ( $10^{-1}$ ); in this study,  $n=5$ .

Based on unchanged environmental conditions in a certain region, the storage potential of SOC refers to the increased amount of soil organic carbon storage when the current vegetation was changed to the vegetation type with the largest organic carbon storage in the future. The calculation formula is as follows:

$$SQ_i = S_m - S_i \quad (2)$$

where  $SQ_i$  is the sequestration potential of SOC of the  $i$ th vegetation type in the study;  $S_m$  is the maximum value of SOC storage in the research area; and  $S_i$  is the storage of SOC of the  $i$ th vegetation type in the research area.

The oxidizable SOC fractions were measured using a modified Walkley–Black method. This method used the principle that different reaction heats produced by different concentrations of concentrated sulfuric acid led to different oxidation degrees of SOC. Using concentrated sulfuric acid with acid–water solution ratio of 0.25:1, 0.5:1, and 1:1 (corresponding to  $\text{H}_2\text{SO}_4$  concentration of 6.0, 12.0, and 18.0 N), the SOC was divided into four parts with reduced oxidizability and defined as the following: Oxidizable organic carbon under 6.0 N  $\text{H}_2\text{SO}_4$  corresponds to the very labile carbon (F1); the difference of oxidizable organic carbon extracted between 6.0 and 12.0 N  $\text{H}_2\text{SO}_4$  was defined as labile carbon (F2); the difference in oxidizable organic carbon extracted between 12.0 and 18.0 N  $\text{H}_2\text{SO}_4$  was defined as less labile carbon (F3); and the difference between total SOC and oxidizable under organic carbon 18.0 N  $\text{H}_2\text{SO}_4$  was defined as recalcitrant carbon (F4).

## Statistical analysis

Chan et al. (2001) reported that F1 and F2 fractions represented the active carbon pool, whereas F3 and F4 fractions represented the stable carbon pool. The percentage of active carbon (F1 + F2) to total SOC was calculated to show the changes of the active carbon pool in the soils under different vegetation types. This value is the lability index of SOC ( $I_{\text{SOC}}$ ).

Statistical analyses were conducted using the SPSS 19.0 for windows (Chicago, IL, USA). One-way ANOVA and the least significant difference tests (LSD) were used to analyze the differences of SOC content, storage, fraction, and  $I_{\text{SOC}}$  under different vegetation types and to assess the impacts of different vegetation types on SOC dynamics and stability.

## Results

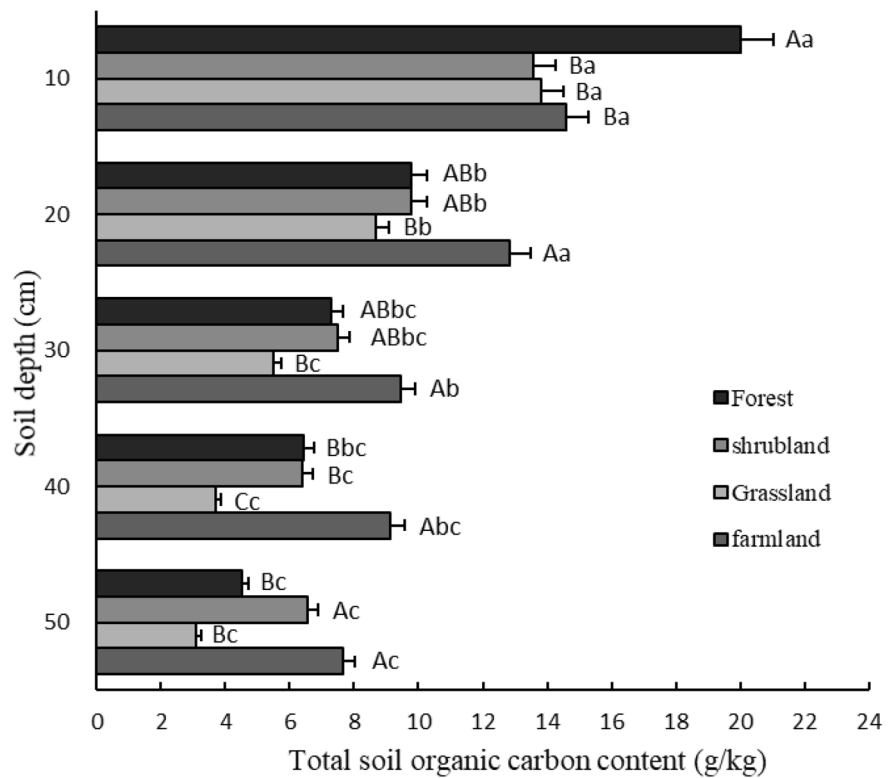
### Total SOC content

Different vegetation types and soil depths significantly impacted total SOC content in various degrees. The average total SOC content under the farmland, grassland, shrubland, and forest was 10.72, 6.94, 8.76, and 9.61  $\text{g kg}^{-1}$ , respectively. The total SOC content in farmland was the highest, followed by forest and shrubland, and the grassland had the lowest total SOC value. The total SOC contents under all vegetation types significantly decreased from surface soil to subsoil (Fig. 1). The range of the total SOC content among the vegetation types was 15.51, 10.27, 7.42, 6.40, and 5.44  $\text{g kg}^{-1}$  for 0–10-, 10–20-, 20–30-, 30–40-, and 40–50-cm depths, respectively. Higher SOC content at 0–10 cm was observed under forest compared to other vegetation types (shrubland, grassland, farmland). However, SOC content under the forest, shrubland, and grassland at the 10–50-cm depth was lower than that under the farmland. The content of SOC in farmland was significantly higher than that of grassland ( $P < 0.05$ ).

### Total SOC storage and carbon sequestration potential

The SOC storage varied from 4.43 to 32.41  $\text{Mg C ha}^{-1}$  in all soil layers (Table 1) and it was significantly influenced by vegetation types and soil depths. Result

**Fig. 1** Mean values of content of soil organic carbon at five depths under different vegetation types ( $\pm$  standard error). Values with the same uppercase letters (vegetation types) and the lowercase letters (soil depths) are not significantly different at  $P < 0.05$



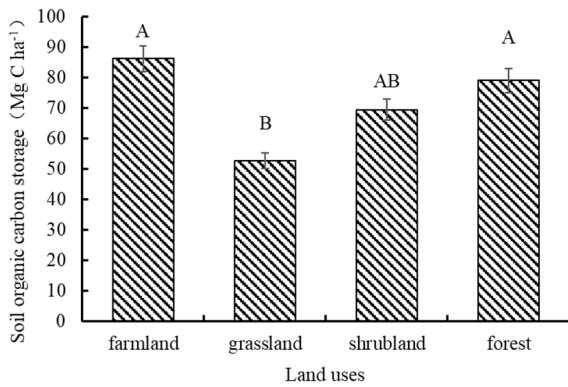
showed that SOC storage in 0–50-cm soil depth under the farmland, grassland, shrubland, and forest was 86.15, 52.67, 69.35, and 78.99 Mg C ha<sup>-1</sup>, respectively (Fig. 2). Under different vegetation types, the SOC in the farmland was largest, while grassland had the lowest SOC storage. The change trend of vertical distribution of SOC storage was the same as that of SOC content, both of which showed a significant decreasing trend from surface soil to subsoil under each vegetation type. The SOC storage in the 0–10-cm layer was the highest, followed by the 10–20-cm layer, while no significant difference in SOC storage were found among the 20–30-cm layer, 30–40-cm

layer, and 40–50-cm layer. In addition, the distribution of SOC storage in the upper 0–10-cm depth was significantly influenced by vegetation succession. The SOC storage under the farmland was higher in the 10–50-cm depth than other vegetation types, while it was larger under the forest in the 0–10-cm layer.

From Fig. 2, the SOC storage in the forest is higher than of shrubland and grassland. In this study, the SOC storage (78.99 Mg C ha<sup>-1</sup>) in the stable state under forest was the most saturated value of SOC in the study area to measure the carbon sequestration potential of SOC under other vegetation types. Therefore, the carbon sequestration potential in grassland

**Table 1** Distribution characteristics of mean values of soil organic carbon storage under different vegetation types ( $\pm$  standard error)

Soil depth (cm)	Farmland Mg C ha <sup>-1</sup>	Grassland	Shrubland	Forest
0–10	22.07 (± 1.42) Ba	20.48 (± 1.08) Ba	20.28 (± 1.38) Ba	32.41 (± 4.07) Aa
10–20	19.6 (± 0.74) Aa	13.48 (± 2.2) Bb	15.19 (± 1.94) ABb	15.93 (± 1.46) ABb
20–30	16.02 (± 1.21) Ab	7.59 (± 2.32) Bc	12.59 (± 0.95) Abc	12.09 (± 0.7) Abc
30–40	15.56 (± 0.46) Ab	6.69 (± 2.07) Bc	9.7 (± 1.17) Bc	10.7 (± 0.99) Bbc
40–50	12.9 (± 1.21) Ab	4.43 (± 0.11) Cc	11.59 (± 0.86) Abc	7.86 (± 0.87) Bc



**Fig. 2** Mean values of total soil organic carbon storage under different vegetation types ( $\pm$  standard error)

was the highest, with the value of  $26.32 \text{ Mg C ha}^{-1}$ , while the shrubland was the second with the value of  $9.64 \text{ Mg C ha}^{-1}$  in the study area.

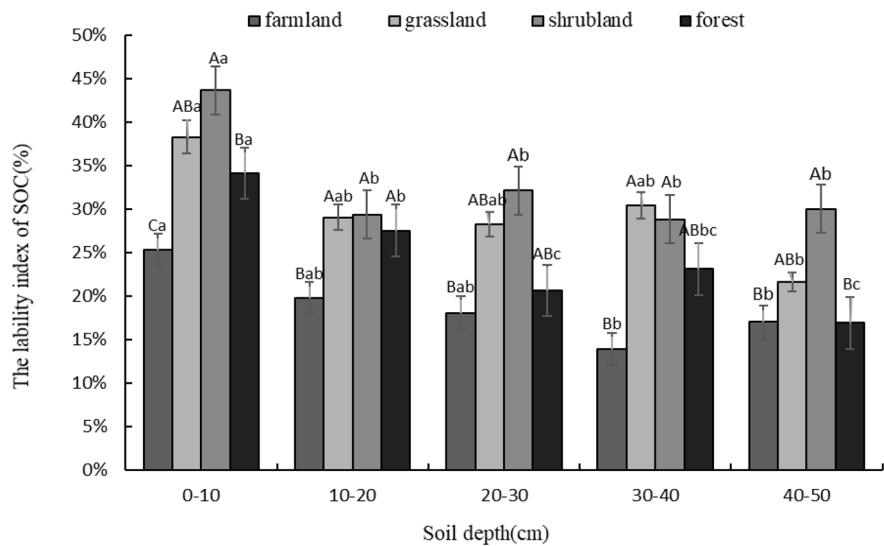
**Table 2** Mean values of contents of SOC fractions at five depths under different vegetation types ( $\pm$  standard error). Values with the same uppercase letters within rows (vegetation types), lowercase letters within columns (soil depths), and Roman letters within SOC fractions are not significantly different at  $P < 0.05$

Soil depth (cm)	Vegetation types			
	Farmland	Grassland	Shrubland	Forest
<b>F1</b>				
0–10	2.57 ( $\pm 0.39$ ) Ba	3.55 ( $\pm 0.24$ ) ABa	3.92 ( $\pm 0.61$ ) ABa	4.54 ( $\pm 0.77$ ) Aa
10–20	1.68 ( $\pm 0.38$ ) Ab	1.66 ( $\pm 0.25$ ) Ab	1.8 ( $\pm 0.39$ ) Ab	1.66 ( $\pm 0.26$ ) Ab
20–30	0.92 ( $\pm 0.06$ ) Bc	0.87 ( $\pm 0.27$ ) Bc	1.57 ( $\pm 0.1$ ) Ab	1.13 ( $\pm 0.2$ ) ABb
30–40	0.81 ( $\pm 0.03$ ) ABc	0.54 ( $\pm 0.16$ ) Bc	1.07 ( $\pm 0.13$ ) Ab	0.8 ( $\pm 0.13$ ) ABb
40–50	0.73 ( $\pm 0.07$ ) ABc	0.35 ( $\pm 0.13$ ) Bc	1.02 ( $\pm 0.05$ ) Ab	0.52 ( $\pm 0.2$ ) Bb
<b>F2</b>				
0–10	1.15 ( $\pm 0.39$ ) Ba	1.75 ( $\pm 0.14$ ) ABa	2.08 ( $\pm 0.28$ ) ABa	2.3 ( $\pm 0.4$ ) Aa
10–20	0.89 ( $\pm 0.26$ ) Aa	0.82 ( $\pm 0.2$ ) Ab	1.1 ( $\pm 0.27$ ) Ab	1.07 ( $\pm 0.28$ ) Ab
20–30	0.78 ( $\pm 0.16$ ) Aa	0.84 ( $\pm 0.37$ ) Ab	0.76 ( $\pm 0.22$ ) Ab	0.39 ( $\pm 0.06$ ) Abc
30–40	0.47 ( $\pm 0.21$ ) Aa	0.62 ( $\pm 0.2$ ) Ab	0.78 ( $\pm 0.23$ ) Ab	0.65 ( $\pm 0.22$ ) Abc
40–50	0.52 ( $\pm 0.1$ ) ABa	0.36 ( $\pm 0.2$ ) Bb	0.9 ( $\pm 0.15$ ) Ab	0.26 ( $\pm 0.09$ ) Bc
<b>F3</b>				
0–10	5.41 ( $\pm 0.73$ ) ABa	4.52 ( $\pm 0.23$ ) Ba	4.19 ( $\pm 0.63$ ) Ba	6.71 ( $\pm 0.95$ ) Aa
10–20	3.8 ( $\pm 0.49$ ) Ab	3.19 ( $\pm 0.58$ ) Ab	2.54 ( $\pm 0.3$ ) Ab	3.03 ( $\pm 0.5$ ) Ab
20–30	3.38 ( $\pm 0.17$ ) Ab	1.65 ( $\pm 0.44$ ) Bc	1.89 ( $\pm 0.41$ ) Bb	2.54 ( $\pm 0.39$ ) ABb
30–40	3.24 ( $\pm 0.34$ ) Ab	1.01 ( $\pm 0.27$ ) Cc	1.81 ( $\pm 0.2$ ) Bb	2.23 ( $\pm 0.16$ ) Bb
40–50	2.54 ( $\pm 0.62$ ) Ab	0.91 ( $\pm 0.11$ ) Bc	1.98 ( $\pm 0.37$ ) ABb	1.85 ( $\pm 0.39$ ) ABb
<b>F4</b>				
0–10	5.44 ( $\pm 0.57$ ) ABab	4.01 ( $\pm 0.57$ ) BCa	3.39 ( $\pm 0.55$ ) Ca	6.49 ( $\pm 0.89$ ) Aa
10–20	6.46 ( $\pm 0.72$ ) Aa	3 ( $\pm 0.56$ ) Bab	4.33 ( $\pm 1.01$ ) Ba	4.04 ( $\pm 0.22$ ) Bb
10–20	4.36 ( $\pm 0.51$ ) Abc	2.11 ( $\pm 0.36$ ) Bbc	3.27 ( $\pm 0.36$ ) ABa	3.23 ( $\pm 0.29$ ) ABbc
30–40	4.6 ( $\pm 0.12$ ) Abc	1.51 ( $\pm 0.3$ ) Cc	2.74 ( $\pm 0.35$ ) Ba	2.74 ( $\pm 0.57$ ) Bbc
40–50	3.84 ( $\pm 0.22$ ) Ac	1.46 ( $\pm 0.07$ ) Cc	2.65 ( $\pm 0.43$ ) Ba	1.88 ( $\pm 0.24$ ) BCc

### The oxidizable SOC fractions and the lability index of SOC

The vegetation type and soil depth considerably impact the SOC fractions (Table 2). In general, the contents of SOC fractions (F1 to F4) decreased significantly from surface to subsoil (Table 2). The oxidizable SOC fractions (F1 to F3) under the 0–10-cm soil depth were considerably higher than that in the 20–50-cm soil layer. As for F4 under farmland and shrubland treatments, the content at the 10–20 depth was significantly higher than that at the 0–10- and 20–50-cm soil layer. However, there was no significant difference among the depths of 20–30, 30–40, and 40–50 cm for all the four SOC fractions, irrespective of the vegetation types (Table 2). The content of all oxidizable SOC fractions under the forest in topsoil (0–10 cm) was higher than that under the other vegetation types. The content of F1 and F2 under

**Fig. 3** Mean values of the lability index of SOC under different vegetation types ( $\pm$  standard error). Values with the same uppercase letters (vegetation types) and the lowercase letters (soil depths) are not significantly different at  $P < 0.05$



shrubland at 20–50-cm depth was higher than that under farmland, grassland, and forest, except the F2 at 20–40-cm depth. On the other hand, the farmland had the highest stable oxidizable fractions (F3 and F4) at 10–50-cm depth among the four vegetation types.

Significant differences in the lability index of SOC ( $I_{SOC}$ ) were found among the four vegetation types and the five soil depths (Fig. 3).  $I_{SOC}$  values under farmland, grassland, shrubland, and forest varied from 13.90 to 25.32%, 21.64 to 38.32%, 28.85 to 43.68%, and 16.93 to 34.13%, respectively. The lability index of SOC under shrubland in soil was the largest in all soil layers. The  $I_{SOC}$  under farmland was the lowest in all soil layers except the forest at 40–50-cm depth. Under forest,  $I_{SOC}$  value at 0–10- and 10–20-cm depth was considerably higher than that at 20–30-, 30–40-, and 40–50-cm depth.

### Discussion

#### Impacts of vegetation succession on SOC content

SOC content was a balance between the inputs of plant residues into the soil and the loss of decomposition by the soil microorganisms. Vegetation succession affects the soil’s chemical and physical properties and many soil ecological processes, and thus changing the SOC content. The total SOC content increased with the vegetation succession sequence

from 34.72 in grassland to 43.80  $g\ kg^{-1}$  in shrubland and 48.04  $g\ kg^{-1}$  in forest. Previous studies also reported that the SOC content significantly increased along the vegetation succession sequence from grassland to forest (Liu et al., 2015). Therefore, the vegetation succession process is conducive to the management and protection of ecological environment in the karst areas.

However, the total SOC content at 0–50-cm depth under farmland was 35.2% (18.87  $g\ kg^{-1}$ ), 18.3% (9.78  $g\ kg^{-1}$ ), and 10.3% (5.54  $g\ kg^{-1}$ ) higher than that under grassland, shrubland, and forest, respectively (Fig. 1). There are many reasons as follows: The research area is located in the typical karst area in southwest China, which is mainly mountainous and has less farmland. Local farmers apply a large amount of organic fertilizer into the soil every year, thus increasing the organic carbon content in the soil (Li & Delvaux, 2019; Tian et al., 2015). In addition, almost all of the farmland in the study area is in the lower part of the mountain. The slope runoff formed during the rainy season will also bring soluble organic carbon from the upper grassland and shrubland to the lower farmland which will lead to an increase in the SOC under the farmland (Herbrich et al., 2017).

The SOC content under the four vegetations was relatively rich in the topsoil and then decreased significantly. The total SOC content under grassland, shrubland, and forest was 5.16, 3.81, and 10.25  $g\ kg^{-1}$  at 0–20-cm depth and was 2.40, 0.93, and 2.78  $g\ kg^{-1}$

at 20–50-cm depth, respectively (Fig. 1). The higher total SOC content at 0–20 cm soil layer than that of 20–50 cm layer in the present study might be explained by many reasons, such as the above-ground and below-ground biomass allocation patterns and the root distribution pattern in shallow and deep soil (Yu et al., 2017; Santos et al., 2019).

#### Impacts of vegetation succession on SOC storage and carbon sequestration potential

The SOC storage and carbon sequestration potential varied widely with the vegetation types and soil depths. Under the four vegetation types, the topsoil had the highest carbon storage, and with increasing of soil depth, the carbon storage was gradually reduced. This is mainly because the roots of plants in karst areas are mainly distributed in the surface soil, and the humus formed by their decomposition is mostly enriched in the surface soil. Moreover, the storage of SOC in each soil layer of 10–50 cm under farmland was higher than that in the corresponding soil layer of other vegetation types such as grassland (Fig. 1). However, SOC storage under forest topsoil at 0–10-cm depth was higher than that under the farmland. Probably because of the long-term plowing, the SOC under the farmland translocates into the deeper soil depth (Poeplau & Don, 2013), and the cessation of plowing after vegetation succession resulted in the accumulation of SOC near the ground surface (Yuan et al., 2021).

The optimal allocation and protection of forest and grass vegetation and the reduction of unreasonable anthropogenic activities are essential for the management of carbon in rocky desertification soils. In this study, the average total SOC storage in this area to a depth of 50 cm was  $71.79 \text{ Mg C ha}^{-1}$ . From grassland to shrubland and forest, soil carbon storage gradually increases, and the benefits of improving soil carbon storage through vegetation succession have been initially shown. The results for total carbon storage reported here verify data from other studies (Choudhury et al., 2016; Deng & Shangguan, 2017). Therefore, promoting the vegetation succession process is beneficial to the ecological protection in the ecologically fragile karst areas of southwest China. It was worth mentioning that farmland had the highest SOC storage in this study area, which may be because of a large amount of farm manure input from farmland and the increase of

SOC storage in farmland in the lower part of the mountain due to the migration of soluble organic carbon in local slope runoff and surface soil rich in SOC. Some studies also indicate that the SOC storage in farmland is still more significant than the vegetation types in the post-replacement stage of other vegetation (Vos et al., 2019; Zhang et al., 2010).

When the environmental conditions are stable, the organic carbon storage of soil in a certain period is a critical evaluation index to characterize soil carbon sequestration potential. The SOC storage value under the forest is higher than that of shrubland and grassland, and the climax community in this study area is also forest. Therefore, forest can be used as the saturation value of SOC storage in this study area. The results indicated that the SOC sequestration potential under different vegetation types in this study area was grassland ( $26.32 \text{ Mg C ha}^{-1}$ ) > shrubland ( $9.64 \text{ Mg C ha}^{-1}$ ), according to the current distribution of SOC storage. In other words, grassland soil had the highest carbon sequestration potential, while shrubland had the lowest carbon sequestration potential. These results may be because ecosystem productivity gradually tends to mature and stabilize in replacing abandoned farmland with succession. When the ecological series reaches the climax forest land, the biomass in the community is basically at its maximum. At the same time, the ecosystem is basically in a stable state. Therefore, the SOC content and storage will gradually reach saturation point and stabilize with vegetation succession. SOC fixation in the karst area can improve SOC, providing a suitable material basis for vegetation growth and development, and increasing the soil and water conservation. More importantly, it can also reduce atmospheric  $\text{CO}_2$  concentration and alleviate global warming.

#### Impacts of vegetation succession on the oxidizable SOC fractions and stability of SOC

This study assessed the impacts of different vegetation types and soil depths on the distribution of the four oxidizable SOC fractions extracted under a gradient of oxidation in the karst trough valley. Similar to the total SOC content and storage, the four oxidizable SOC fractions (F1 to F4) decreased with the increase of the soil depth irrespective of the vegetation types because of the higher supply of below- and above-ground biomass in the topsoil (Sprunger



& Robertson, 2018). With the deepening of the soil layer, the decreasing trend of SOC fractions slowed down. The downwards movement of each SOC fraction remains similar under different vegetation types (Liu et al., 2017).

The study revealed that the forest had more fractions in topsoil (0–10 cm) than other vegetation types. The main reason is the well-developed plant roots and many litters in autumn and winter. Maia et al. (2007) and Barreto et al. (2011) also showed higher levels of organic carbon fractions in the forest cover at the topsoil. Except for the topsoil, the contents of F1 and F2 in shrubland were considerably higher than those in other vegetation types. Mclauchlan and Hobbie (2004) illustrated that F1 and F2 were quickly mineralized, had a fast turnover, and profoundly impacted global carbon cycling. While in farmland, the contribution of F3 and F4 to SOC was considerably higher than those in other vegetation types, which was supported by Qin et al. (2021). These results indicated that the distribution of SOC fractions depended on the difference in SOC sources. In addition, soil factors also controlled these SOC pools.

As mentioned above,  $I_{SOC}$  can determine the loss of carbon and the stability of SOC (Wang et al., 2014a, b). In this study, the value of  $I_{SOC}$  under shrubland was the largest, followed by grassland, and forest was the third, and the farmland had the smallest value. The lowest value of  $I_{SOC}$  indicated that the SOC in shrubland was more labile than other vegetation types, while the highest value of  $I_{SOC}$  indicated that the SOC in farmland was more stable than other vegetation types. Although the shrubland was a huge C sink, its SOC was more sensitive and unstable than other vegetation types. Angst et al. (2019) in Poland reported that the stability of SOC varied substantially among tree species, and this variability was independent of the amount of organic carbon in soils. These inconsistent results in different studies are primarily related to differences in the environmental conditions, soil management practices, soil-sampling depths, and vegetation types (Bhattacharyya et al., 2015; Soucemarianadin et al., 2018).

## Conclusion

Our study indicated that vegetation types significantly influenced the total SOC content, storage, and four oxidizable SOC fractions with varying magnitude in

the karst trough valley. The total SOC content and storage under all vegetation types had similar change trends. The order of their size was as follows: forest > shrubland > grassland, indicating that SOC content and storage all had a significant upward trend with the vegetation succession. It was worth mentioning that farmland had the highest SOC content and storage in this study area, which may be because of the unique topography in this karst valley area and organic fertilization by farmers. In terms of soil carbon sequestration potential, the potential of grassland in this research area was the highest, and the shrubland was the smallest. Vegetation succession in karst trough areas is conducive to soil organic carbon accumulation and local ecological conservation. All SOC content, storage, and four fractions showed a significant downward trend with the increase of soil depth. The study revealed that forests had more SOC fractions in topsoil (0–10 cm) than other vegetation types. The farmland had the highest stable oxidizable SOC fractions (F3 and F4), while the shrubland had the highest active oxidizable SOC fractions (F1 and F2) at 10–50-cm depth. Regarding  $I_{SOC}$ , the value under the shrubland was the largest, followed by grassland and forest, and the farmland had the smallest value.

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**Availability of data and materials** The corresponding author will provide the data supporting the study's findings upon reasonable request.

**Code availability** The software application used for statistical data analysis was SPSS 19.0 and Microsoft Excel 2019.

## Declarations

**Conflict of interest** The authors declare no competing interests.

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