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Soil organic carbon stock and its changes in a typical karst area from 1983 to 2015

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Abstract

Purpose Changes in soil organic carbon (SOC) stock have major impacts on global terrestrial carbon cycling. However, their responses to land use conversions are poorly characterized for karst areas with extremely fragile geology and intensive human disturbance.

Methods To investigate the effects of soil type and land use on SOC stock in a typical karst region of southwestern China, 0–15 cm topsoil samples were randomly collected in 2015. Furthermore, in the same locations as the sites in 1983, 0–100 cm stratified profile soil samples (0–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm) were collected to evaluate the changes in SOC stock as affected by land use conversions from 1983 to 2015.

Results The current SOC stock in 0–15 cm differed significantly between Calcisols and Ferralsols, and was highest in the secondary forest, followed by shrubland, grassland, plantation forest, and cropland. Changes in the stratified SOC stock (both recalculated to 0–20, 20–40, 40–60, 60–80, and 80–100 cm intervals in 1983 and 2015) varied among different land use conversions. Average stratified SOC stock decreased after forest degradation and reclamation, except in 80–100 cm. After reforestation, it had decreases in 0–20 and 20–40 cm, whereas it increased in subsoil (40–60, 60–80, and 80–100 cm). However, compared with the cropland in which soil was exposed to continuous conventional tillage, average stratified SOC stock increased in all soil layers after reforestation.

Conclusion The increases in SOC stock after reforestation and re-cultivation (short-term reuse in abandoned croplands) indicated the positive role of agricultural abandonment in increasing terrestrial SOC stock.

Keywords Land use conversion · Reclamation · Reforestation · Degradation · Karst ecosystems

1 Introduction

Soil organic carbon (SOC) stock is an important component of the global carbon cycle. It comprises roughly two-thirds of the total carbon in terrestrial ecosystems, which is approximately three times more than the current total atmospheric carbon (Yousaf et al. 2017). Therefore, even slight changes in the SOC stock could have major impacts on global terrestrial carbon cycling (Johnson et al. 2007). Currently, land management such as land use and tillage management is considered to be one of the main factors influencing SOC stock (Chatterjee et al. 2017; Gao et al. 2014). It has been estimated that agriculture accounts for 10–12% of the total global anthropogenic emissions of greenhouse gases, 63% of which was attributed to SOC loss caused by land management (Xu et al. 2013). Thus, accurate estimations of changes in SOC stock can provide instructive feedback for human activities and a theoretical basis for the assessment of global climate change.

Many studies have estimated the dynamic changes in SOC stock (Li et al. 2019; Liu et al. 2018; Ramírez et al. 2019); however, the change patterns vary depending on the sampling

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site or study region. For example, Ramírez et al. (2019) evaluated the changes in SOC stock from 1972–1994 to 2014–2016 in central Chile, and showed that the cultivated soils in semiarid regions and Mollisols were more vulnerable to SOC losses. Li et al. (2019) studied the SOC stock changes along a chronosequence of Caragana intermedia plantations in alpine sandy land, and found that the SOC stock significantly increased with the increase in plantation age. Liu et al. (2018) examined the SOC stock changes in the upper 30 cm of the grasslands in northern China between the 1980s and 2000s, and suggested that the overall SOC stock did not show significant changes during the study period. The above differences may be caused by its unique soil environment (e.g., soil depth, plant species, temperature, soil moisture, parent material, and soil type) and land management. Among which, land use conversion has been demonstrated to have significant effects on the SOC stock owing to its key role in hydrological and biogeochemical processes (McLauchlan et al. 2014; Meglioli et al. 2017). Additionally, the restoration age after the conversion of croplands to forests or grasslands was found to affect the changes in SOC stock (Deng et al. 2014). In agricultural soils, cropping duration has also been recognized as an important factor affecting the SOC stock (Huang et al. 2012). SOC stocks have been shown to increase significantly with the increase in restoration age after agricultural abandonment (Deng et al. 2014), whereas cropland SOC stocks have been shown to decrease after years of conventional tillage (Chatterjee et al. 2017).

The karst area in southwestern China is one of the largest continuous karst areas in the world (Zhang et al. 2017). Karst ecosystems are susceptible to serious damage by intensive human activities. Furthermore, the soil in these systems is shallow and discontinuous (Jiang et al. 2014). Over the past few decades, forests in karst areas have been undergoing varying degrees of degradation due to deforestation, agricultural expansion, livestock overgrazing, and fire (Liu 2009; Liu et al. 2013; Zhu 2003). Meanwhile, ecological restoration efforts such as China's Grain to Green Program (GTGP) have been implemented to improve ecosystem services, mitigate human pressures on natural ecosystems, and restore the deteriorating ecological environment (Feng et al. 2013; Zhang et al. 2015). Conversions from natural ecosystems such as forests or grasslands to croplands usually lead to declines in SOC stock (Lal et al. 2018; Wang et al. 2017). Meanwhile, conversions from croplands to grasslands or forests are likely to increase the SOC stock (Deng et al. 2014; Zhang et al. 2014). However, some studies have reported negligible changes in SOC stock after agricultural abandonment. For example, Li et al. (2012) found that SOC stock did not change significantly after forestation with softwoods such as pine. Previous studies on the dynamic changes in SOC stock have mainly focused on northern, northeastern, and northwestern areas or a single ecosystem in China (Ding et al. 2017; Gao et al. 2015; Yang et al. 2010); therefore, knowledge regarding the SOC stock changes in southwestern karst areas remains limited.

Moreover, studies involving the dynamic changes in SOC stock as affected by land use conversions in southwestern karst areas have mostly been based on the space-for-time substitution approach (Hu et al. 2018; Li et al. 2012). And few accurate point-by-point analyses have been conducted to determine the SOC stock changes over the past three decades. In the present study, the typical southwestern karst area in northwest of Guangxi Province was selected as the study site. Current SOC stock data were calculated from soil samples collected in 2015 and compared with data from the second national soil survey in 1983. The aims of the study were to (1) estimate the current SOC stock as affected by soil type and land use; and (2) identify the effects of soil type and land use conversion on SOC stock changes over the past three decades from 1983 to 2015.

2 Materials and methods

2.1 Study area

The study was conducted in the northwest of Guangxi Province, southwest China (23° 40′–25° 25′ N, 107° 35′–108° 30′ E) (Fig. 1). The region includes Huanjiang County, Luocheng County, Hechi District, Yizhou District, Du'an County, and Dahua County, and is a typical karst landform comprised of gentle valleys flanked by steep hills. The region is characterized by subtropical monsoon climate with a mean annual air temperature of 17.8–22.2 °C and a mean annual precipitation of 1346–1640 mm. The soils of the region are Calcisols over dolomite or limestone in karst areas, and Ferralsols over clasolite in non-karst areas (WRB 2015). Additionally, according to the degree of human disturbance, the soil could be classified as disturbed soil or natural (undisturbed) soil (Wei 1986). Disturbed soil is considered to have developed from a variety of natural soils after long-term cultivation activities and it is typically found in croplands. Natural soil is native soil that has been less affected by human disturbance and it is typically found in forests, shrublands, and grasslands. In order to evaluate the combined effects of human disturbance and soil type on SOC stock, the two soil types (Calcisols and Ferralsols) were reclassified into these two groups, viz., disturbed soil and natural soil.

The vegetation of this region was diverse and mainly comprised secondary and non-native species. The secondary forests were dominated by macrophanerophytes such as *Sinoadina racemosa* and *Radermachera sinica*. The plantation forests included *Zenia insignis* Chun and other economic species. The shrublands were mainly inhabited by *Vitex negundo* L. and *Pterolobium punctatum* Hemsl. The grasslands were dominated by Gramineae such as *Imperata cylindrica* and *Miscanthus*

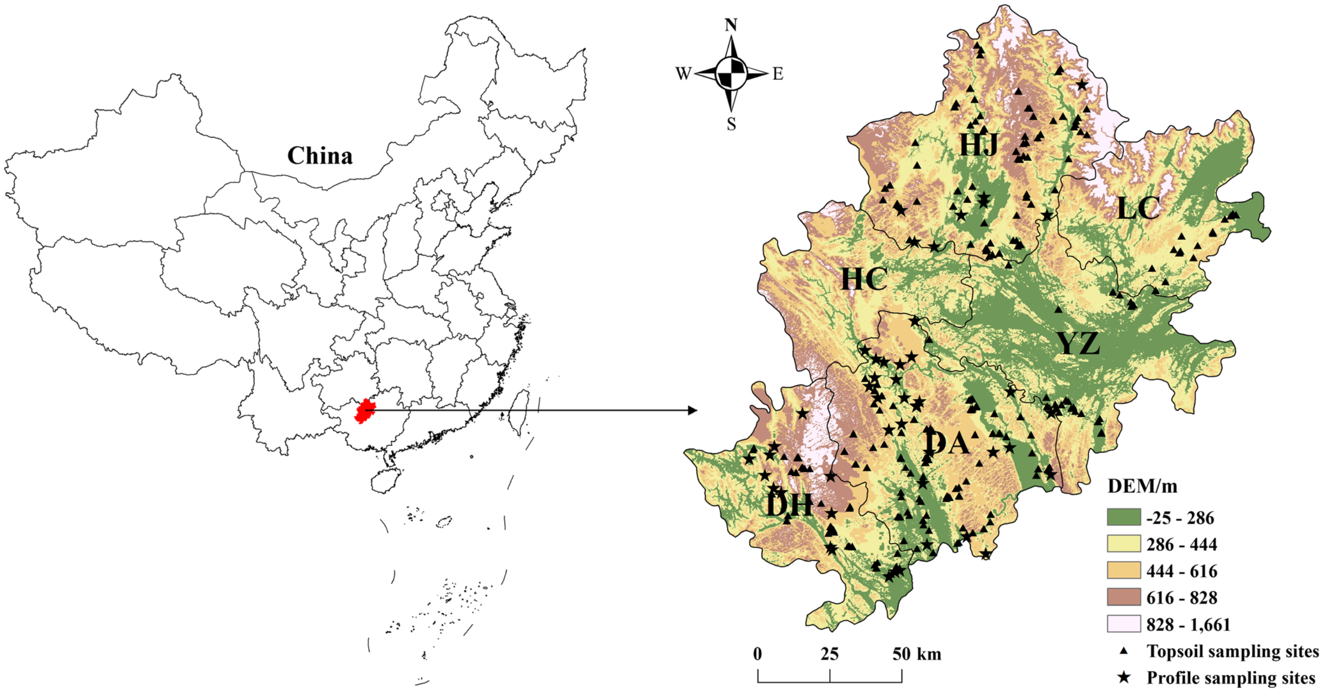


Fig. 1 Location of the study area and sampling sites in northwest of Guangxi, southwest China. *HJ* Huanjiang County, *LC* Luocheng County, *HC* Hechi District, *YZ* Yizhou District, *DA* Du'an County, *DH* Dahua County

floridulus. The croplands were typically managed under a corn-soybean rotation. The duration of agricultural abandonment was normally 5 to 15 years for grasslands and plantation forests, 10 to 20 years for shrublands, and 30 to 50 years for secondary forests. Additionally, GTGP, an ecological restoration program, has been implemented in the region since 2001. Based on the land-use types of each site in 1983, 2000, 2010, and 2015, five transformation modes (cropland, re-cultivation, reclamation, reforestation, and forest degradation) were mainly studied (Table 1).

2.2 Soil sampling and analysis

Soil data in 1983 were obtained from the second national soil survey, recorded in the soil annals of Du'an County (Wei 1986). It described SOC contents across genetic layers of soil, the deepest of which were up to 100 cm. Additionally, it provided details on the geographic locations of sampling sites.

From the end of March to early June 2015, topsoil samples (0–15 cm) were collected using random sampling methods of distinguishing lithologies (dolomite, limestone, and clasolite) and land-use types (cropland, plantation forest, grassland, shrubland, and secondary forest), to estimate the current SOC stock. At each site, a 20 × 20 m grid was set, and at least nine sub-soil samples were collected and thoroughly mixed. Furthermore, stratified soil samples were collected in the same positions as the sampling sites in 1983 to estimate the specific changes and identify the effect of land use conversion on changes in SOC stock. Considering the inconsistency in soil depth at each stratified sampling site, if the soil depth was ≥ 100 cm, samples were collected hierarchically (0–10, 10–20, 20–30, 30–50, 50–70, and 70–100 cm); otherwise, samples were collected to the deepest depth of the site. In total, 707

Table 1 Detailed information of the five transformation modes

Mode	Description	Land-use type			
		1983	2000	2010	2015
Cropland	Croplands under long-term conventional tillage	Cropland	Cropland	Cropland	Cropland
Re-cultivation	Conversion from cropland through plantation forest or grassland to cropland	Cropland	Plantation forest or grassland		Cropland
Reclamation	Conversion from forest or grassland to cropland	Secondary forest, plantation forest, or grassland			Cropland
Reforestation	Conversion from cropland to grassland or forest	Cropland	Grassland, plantation forest, or secondary forest		
Forest degradation	Conversion from secondary forest to grassland or plantation forest	Secondary forest	Plantation forest or grassland		

topsoil samples were collected and 48 paired soil profiles were excavated (a total of 273 stratified soil samples, and less than 288 due to the inconsistency of soil depth at each profile site). Soil samples were air-dried and sieved (2 mm mesh) prior to soil physicochemical analysis.

SOC in 1983 and 2015 was measured by wet oxidation using the dichromate redox colorimetric method (Wang et al. 2019). Bulk density (BD) was measured using the cutting ring method (Liu et al. 2017). Topographic indexes (elevation, slope, and aspect) were obtained from the digital elevation model with a spatial resolution of 30 × 30 m using Arcgis software (ESRI Inc., USA). Land-use types in 2015 were recorded during sampling, whereas those in 1983 were obtained from the soil annals of Du'an County (Wei 1986). Land-use types in 2000 and 2010 referred to the global land cover data sets (GlobeLand30–2000 and GlobeLand30–2010, respectively), with the precision of 83% (Chen et al. 2015).

Descriptive statistical analysis was used to present the mean, standard deviation, and 95% confidence interval of the data. One-way ANOVA with least significant difference (LSD) test was used to assess the differences in SOC stock among different soil types and land-use types. Linear regression was used to test the correlation between two sets of data. SPSS 21.0 (SPSS Inc., USA) was used to analyze the data and OriginPro 8.0 (Originlab Inc., USA) was used to prepare the figures. P values < 0.05 were considered statistically significant.

2.3 Determination and calculation of SOC stock

Soil BD data were not recorded in 1983; therefore, we estimated these data based on their relationship with SOC using a logarithmic model (Huang et al. 2012; Yang et al. 2010). Notably, as shown in Eq. 1, the model parameters were fitted with the measured SOC and BD data of the soil samples from the study area collected in 2015, with $R^2 = 0.45$ and $P < 0.01$. SOC stock was calculated using Eq. 2 (Lozano-García et al. 2017; Yang et al. 2010).

$$\mathrm{BD} = -0.156 \times \ln(\mathrm{SOCC}) + 1.7047 \tag{1}$$

$$\mathrm{SOCS} = \mathrm{SOCC} \times \mathrm{BD} \times \mathrm{SD} \times 10^{-2} \tag{2}$$

where SOCS is SOC stock (kg m^{-2}), SOCC is SOC content (g kg^{-1}), BD is bulk density (g cm^{-3}), and SD is soil depth (cm).

In order to improve the comparability of data obtained in 1983 and 2015, the inconsistency in soil depth at each site was addressed using the methodology adopted by Yang et al. (2011). The original SOCS data at each soil depth were converted to SOCS in the upper 100 cm of soil using the depth functions developed by Jobbágy and Jackson (2000, 2001), as follows:

$$Y = 1-\beta^{\mathrm{d}} \tag{3}$$

$$X_{100} = \frac{1-\beta^{100}}{1-\beta^{d_0}} \times X_{d_0} \tag{4}$$

where Y denotes the cumulative proportion of SOCS from the soil surface to depth d (cm), β is the relative rate of decrease in SOCS with increasing soil depth, X_{100} denotes the SOCS in the upper 100 cm of soil, d_0 denotes the original soil depth in individual sites (cm), and X_{d0} is the original SOCS at the soil depth of d_0. The average global depth distribution of carbon was used to calculate the β value ($\beta = 0.9786$) (Li et al. 2012; Yang et al. 2011). Finally, the stratified samples from 1983 and 2015 were both transformed to 20 cm intervals (0–20, 20–40, 40–60, 60–80, and 80–100 cm) from initial sampling intervals according to the above-mentioned formula.

3 Results

3.1 Current 0–15 cm SOC stock in 2015

In the 0–15 cm horizon, SOC stock was significantly ($P < 0.05$) higher in Calcisols than in Ferralsols. And it was highest in secondary forest, followed by shrubland, grassland, plantation forest, and cropland successively, but it was not significantly different between secondary forest and shrubland. Regarding the SOC stock based on actual soil depth, there was no significant difference between Calcisols and Ferralsols, and it only differed significantly between secondary forest and the other land-use types (Table 2).

3.2 Stratified SOC stock and its changes from 1983 to 2015

Overall, average SOC stock in the upper 100 cm of soil was estimated to be 11.81 kg m^{-2} in 1983 and 9.11 kg m^{-2} in 2015, with 95% confidence intervals of 9.50–14.11 and 7.87–10.36 kg m^{-2}, respectively. It decreased by 2.69 kg m^{-2} from 1983 to 2015, with 95% confidence interval of − 4.91 to − 0.48 kg m^{-2} (Table 3). SOC stocks in 1983 and 2015 both decreased with the increase in soil depth. In 0–20 cm, average SOC stock was 4.69 and 3.04 kg m^{-2} in 1983 and 2015, representing 39.71% and 33.37% of the total SOC stock in the upper 100 cm, respectively. It was lowest in 80–100 cm, with average values of 0.83 and 1.11 kg m^{-2} in 1983 and 2015, representing only 7.03% and 12.18% of the total SOC stock in the upper 100 cm, respectively. SOC stock change in 0–20 cm was the highest among all soil layers, decreasing by 1.64 kg m^{-2}, with 95% confidence interval of − 2.49 to − 0.80 kg m^{-2}. In addition, average SOC stock in 20–60 cm also decreased, whereas that in 60–100 cm increased.

Table 2 Distributions of 0–15 cm SOC stock and SOC stock based on actual soil depth among different soil types and land-use types in 2015

Index	Soil type		Land-use type				
	Calcisols	Ferralsols	Secondary forest	Shrubland	Grassland	Cropland	Plantation forest
N	588	119	117	118	122	185	165
$SOCS_{0-15}$	5.05/2.22a	3.24/0.98b	6.33/1.96 a	5.89/2.15a	5.32/2.43b	3.30/1.17d	3.98/1.56c
SD (cm)	42.4/25.5b	81.9/20.3a	34.7/19.1 cd	28.1/16.8d	40.2/27.4c	71.2/25.9a	55.5/25.3b
$SOCS_{SD}$	9.42/4.30a	9.56/2.85a	11.06/4.43a	9.05/3.65b	9.38/5.30b	8.99/3.35b	8.99/3.57b

SOCS is SOC stock (kg m^{-2}); *N* is the sample number; data is mean/standard deviation; different letters mean statistical differences ($P < 0.05$) among different soil types or land-use types

3.3 Soil type-related changes in stratified SOC stock from 1983 to 2015

Differences in stratified SOC stock changes were identified between disturbed soil and natural soil, in both Calcisols and Ferralsols (Table 4). SOC stock in disturbed soil decreased only in the upper soil (0–40 cm for Calcisols and 0–60 cm for Ferralsols), whereas that in natural soil decreased in all soil layers from 1983 to 2015. Average SOC stock in upper 100 cm of Calcisols increased by 0.02 kg m^{-2} in disturbed soil, whereas that in natural soil decreased by 12.64 kg m^{-2}; average SOC stock in upper 100 cm of Ferralsols decreased in both disturbed soil and natural soil.

3.4 Stratified SOC stock changes following land use conversion

The changes in stratified SOC stock following land use conversions are shown in Fig. 2. The croplands, which were under long-term conventional tillage, could be used as control, in which SOC stock changes were relatively small and considered stable. In re-cultivation mode, average SOC stock increased in all soil layers. In reclamation mode, it decreased in 0–20, 20–40, 40–60, and 60–80 cm, but increased by 0.15 kg m^{-2} in 80–100 cm. In reforestation mode, the average overall (0–100 cm) SOC stock decreased by 0.60 kg m^{-2}. Among the soil strata, average SOC stock decreased in 0–20 and 20–40 cm but increased in 40–60, 60–80, and 80–100 cm. However, compared to the control, average SOC stock increased in all soil layers in reforestation mode. Among all land use conversions, average SOC stock changes in forest degradation were the largest, with an overall decrease of 13.74 kg m^{-2} in 0–100 cm. Moreover, average SOC stocks of forest degradation decreased in all soil layers.

4 Discussion

4.1 SOC stock changes during the past three decades

SOC stocks are affected by various factors such as climate, land use, parent material, soil type, topography, plant species, and human activities (Li et al. 2012, 2019; Lozano-García et al. 2017; Nitsch et al. 2018; Ramírez et al. 2019). Many

Table 3 95% confidence intervals of stratified SOC stock and changes in SOC stock between 1983 and 2015

Soil depth (cm)	1983			2015			SOCS Change (1983–2015)		
	Mean	95% confidence interval of the mean		Mean	95% confidence interval of the mean		Mean	95% confidence interval of the mean	
		Lower	Upper		Lower	Upper		Lower	Upper
0–20	4.69	3.77	5.60	3.04	2.70	3.38	− 1.64	− 2.49	− 0.80
20–40	3.04	2.45	3.63	2.01	1.71	2.31	− 1.03	− 1.59	− 0.47
40–60	1.97	1.59	2.36	1.52	1.24	1.81	− 0.45	− 0.86	− 0.03
60–80	1.28	1.03	1.53	1.43	1.16	1.69	0.15	− 0.16	0.46
80–100	0.83	0.67	0.99	1.11	0.89	1.33	0.28	0.03	0.52
0–100	11.81	9.50	14.11	9.11	7.87	10.36	− 2.69	− 4.91	− 0.48

SOCS is SOC stock (kg m^{-2}); sample number $N = 48$; for the SOCS Change (1983–2015), positive values represent an increase and negative values represent a decrease from 1983 to 2015

Table 4 SOC stock and changes in SOC stock between 1983 and 2015 among different soil types

Soil type		Soil depth (cm)	1983 SOCS	2015 SOCS	SOCS change (1983–2015)	Soil type		Soil depth (cm)	1983 SOCS	2015 SOCS	SOCS change (1983–2015)
Disturbed soil	Calcisols	*N*	15	14	12	Natural soil (undisturbed soil)	Calcisols	*N*	3	4	2
		0–20	3.76/2.35	3.01/1.48	− 0.82/2.26			0–20	7.64/7.96	3.45/0.83	− 6.18/9.19
		20–40	2.44/1.52	2.09/1.51	− 0.38/1.86			20–40	4.96/5.17	2.26/1.08	− 3.78/4.81
		40–60	1.58/0.99	1.64/1.42	0.08/1.58			40–60	3.22/3.35	1.92/0.98	− 1.95/2.70
		60–80	1.03/0.64	1.49/1.34	0.53/1.47			60–80	2.09/2.17	1.67/0.87	− 0.63/1.60
		80–100	0.67/0.42	1.16/1.12	0.57/1.19			80–100	1.35/1.41	1.26/0.66	− 0.11/1.05
		0–100	9.48/5.92	9.38/6.37	0.02/7.63			0–100	19.25/20.07	10.55/4.01	− 12.64/19.35
	Ferralsols	N	16	19	15		Ferralsols	N	14	11	9
		0–20	3.96/1.54	2.96/1.16	− 0.83/1.25			0–20	5.88/3.50	3.08/0.90	− 3.46/3.61
		20–40	2.57/1.00	1.91/0.64	− 0.60/1.06			20–40	3.81/2.27	2.01/0.96	− 2.31/2.34
		40–60	1.67/0.65	1.32/0.60	− 0.27/0.96			40–60	2.47/1.47	1.59/0.84	− 1.26/1.51
		60–80	1.08/0.42	1.39/0.56	0.37/0.60			60–80	1.60/0.95	1.34/0.88	− 0.60/1.10
		80–100	0.70/0.27	1.05/0.47	0.37/0.59			80–100	1.04/0.62	1.09/0.67	− 0.21/0.76
		0–100	9.97/3.89	8.61/2.55	− 0.97/3.97			0–100	14.80/8.81	9.11/3.98	− 7.83/9.03

SOCS is SOC stock (kg m^{-2}); *N* is the sample number; data is mean/standard deviation; for the SOCS Change (1983–2015), positive values represent an increase and negative values represent a decrease from 1983 to 2015

studies have been conducted to estimate the dynamic changes in SOC stock using data obtained from the Chinese second national soil survey in 1980s. For example, Yang et al. (2010) showed that grassland SOC stock remained relatively constant from 1980s to 2000s in northern China. Gao et al. (2015) found that SOC stock decreased in three counties (Hailun, Shuangcheng, and Gongzhuling) in the northeastern black soil areas from 1980 to 2011. In the present study, SOC stock decreased overall (0–100 cm) and in 0–60 cm, whereas SOC stock in 60–100 cm increased from 1983 to 2015. Moreover, as shown in Table 3, SOC stock and its changes both varied with soil depth, demonstrating that to some extent, soil depth determined the response of SOC stock to environmental changes (e.g., land use conversion) (Poeplau et al. 2011; Shi et al. 2013). In the present study, tillage practices and land use conversions were found to be the main causes of the increases or decreases in SOC stock in different soil layers. Moreover, some previous studies found that the direction and magnitude of the changes in SOC stock were related to the original SOC content (Holmes et al. 2006; Yang et al. 2010). Similarly, the present study found that the changes in SOC stock were closely related to the initial total (0–100 cm) SOC stocks in 1983 (Fig. 3). Overall, the SOC stock change in 0–100 cm showed a significant ($P < 0.01$) correlation with the initial total SOC stock in 1983 ($r = 0.85$). In addition, soil strata analyses indicated that the correlation coefficient decreased with increasing soil depth, and the strongest correlation was observed in 0–20 cm ($r = 0.93$).

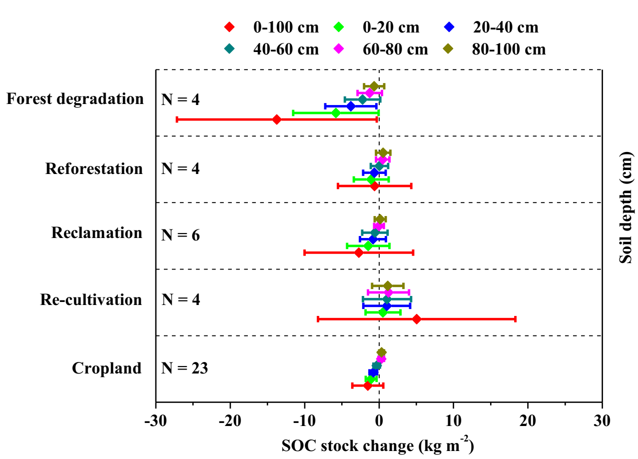


Fig. 2 Effect of land use conversion on SOC stock change from 1983 to 2015. Bars represent the mean and 95% confidence interval

4.2 Combined effects of human disturbance and soil type on SOC stock

Soil type influences the storage capacity of resistant plant components, and the accumulation and retention of humic substances (Aranda et al. 2011; Parfitt et al. 1997); these features determine the potential for SOC sequestration (Celerier et al. 2009). In the present study, current SOC stock in 0–15 cm differed significantly among different soil types (Table 2), which demonstrated the effect of soil type. In addition, the different degrees of human disturbance can lead to differences in SOC stock changes among soils of the same type. The present study identified the differences in two soil

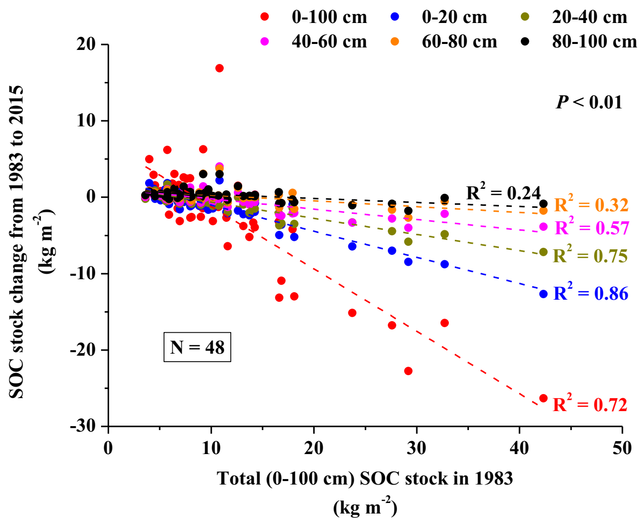


Fig. 3 Relationships between SOC stock change from 1983 to 2015 and total (0–100 cm) SOC stock in 1983

types (Calcisols and Ferralsols) between disturbed soil and natural soil (Table 4). These differences reflected the variation in soil development mechanisms related to human disturbance (Wei 1986), or possibly the inconsistency in sampling numbers between disturbed soil ($N = 31$) and natural soil ($N = 17$). The directions and magnitudes of SOC stock changes in stratified layers (0–20, 20–40, 40–60, 60–80, and 80–100 cm) in different soil types differed with those in 0–100 cm, which may be due to the single consideration of the influence of soil type and the neglect of the effects of tillage practices or land use conversions.

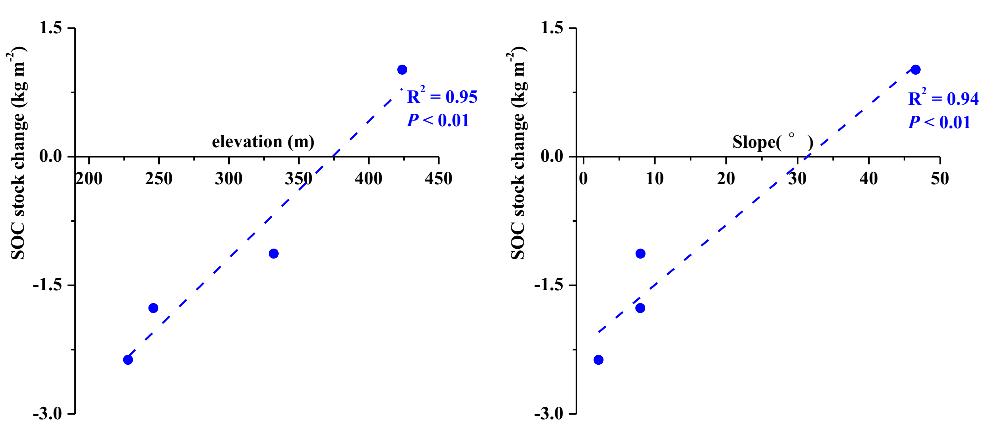
4.3 Effect of land use conversion on SOC stock

Previous studies demonstrated that SOC stock was closely related to the land-use type (Gao et al. 2014; Li et al. 2017; Rolando et al. 2017). Similarly, in the present study, current SOC stock in 0–15 cm differed among different land-use types (Table 2). The different responses of SOC to different land-use types may be attributed to the difference in the amounts and forms of organic material added to the soils from different vegetation types (Li et al. 2017).

Tillage is considered to potentially affect SOC accumulation in agricultural soils (Chatterjee et al. 2017; Obour et al. 2017; Zhang et al. 2016). Karst regions are affected by intensive human activities, among which intensive tillage is the most degradative system because plant residues are physically split and mixed with soil, aggregates are disrupted (releasing physically protected organic materials), and temperature, aeration, and biological activity increase (Roscoe and Buurman 2003). In the present study, the croplands were used as the control and considered stable; however, overall (0–100 cm) SOC stock decreased by 1.52 kg m^{-2} actually, indicating that long-term tillage also accelerated the loss of SOC. Moreover, tillage practices are limited to the plow layer (or topsoil), and may therefore exert less effects on the subsoil (Roscoe and Buurman 2003). In the present study, the topsoil (0–20 cm) SOC stock showed the greatest change, whereby the decrease (1.06 kg m^{-2}) accounted for 69.7% of the overall reduction in 0–100 cm (1.52 kg m^{-2}).

Land use conversions are known to affect the distribution and supply of soil nutrients (Fraterrigo et al. 2005; Gamboa and Galicia 2011). Generally, conversions from natural vegetation types (e.g., forest and grassland) to croplands lead to a decline in SOC stock, whereas conversions from croplands to grasslands or forests are likely to increase SOC stock sequestration. Similarly, in the present study, SOC stock in 0–80 cm decreased after forest degradation and reclamation (Fig. 2). In contrast to previous studies (Deng et al. 2014; Zhang et al. 2014), in the present study, SOC stock decreased overall (0–100 cm) and in 0–40 cm after reforestation. However, if compared with the control (croplands), average SOC stock increased after both re-cultivation and reforestation (Fig. 2), which indicated the positive role of agricultural abandonment in increasing terrestrial SOC stock in karst regions (Hu et al. 2018; Li et al. 2012). Therefore, with the premise of the increase in SOC during 2001–2015 after agricultural abandonment, we can infer that the decrease in SOC stock over the past three decades (1983–2015) may be caused by the deterioration

Fig. 4 Relationships between SOC stock change in 0–20 cm from 1983 to 2015 and topography (elevation and slope) in reforestation mode



in soil quality (e.g., rocky desertification and land erosion) during 1983–2000 (Jiang et al. 2014; Yang et al. 2014), indicating that the destruction of karst areas with fragile ecological environments is difficult to be repaired and requires more time to be restored. Thus, ecological restorations are still urgently required in these areas. In addition, topsoil is more susceptible to land use conversions (Liu et al. 2017). In the present study, with the exception of re-cultivation mode, the greatest changes in SOC stock occurred in 0–20 cm, compared with deeper soil layers.

4.4 Effect of topographic factors on SOC stock

The influences of topography on SOC stock have been intensively studied (Bangroo et al. 2017; Wang et al. 2017). However, the responses of SOC stock to different topographic conditions under different land use conversions are still not fully understood. For example, Wang et al. (2017) studied the combined effects of land-use type and topographic position on SOC stock in the Chinese Loess Plateau, and found that variations in SOC stock across different topographic positions were dependent on land-use types. Similarly, in the present study, SOC stock changes in 0–20 cm after reforestation were closely related to elevation and slope (Fig. 4), whereas those in the other soil layers had no significant correlation with topographic factors (elevation, slope, and aspect). Therefore, we concluded that, in addition to land-use type and topography, soil depth played a key role in SOC stock changes (Poeplau et al. 2011; Shi et al. 2013). These findings indicated that all factors affecting SOC stock (e.g., soil depth, soil type, land use, and topography) should be considered in land management practices.

5 Conclusions

Current SOC stock in 0–15 cm varied among different soil types and land-use types; however, the SOC stock based on actual soil depth did not follow the same pattern owing to the inconsistency in soil depth. Average SOC stock in 0–100 cm decreased by 2.69 kg m^{-2} from 1983 to 2015, but the extent of this change varied among different soil layers, with the greatest change observed in 0–20 cm. Moreover, SOC stock changes in all soil layers were correlated with the initial total (0–100 cm) SOC stocks in 1983. Due to the different degrees of human disturbance, SOC stocks in Calcisols and Ferralsols and their changes from 1983 to 2015 both differed between disturbed soil and natural soil. Average SOC stock decreased after forest degradation and reclamation, except in 80–100 cm. In addition, average SOC stock in 0–40 cm decreased, whereas that in subsoil (40–100 cm) increased after reforestation. However, when compared with the long-term cultivated croplands, average SOC stock increased in all soil layers after both reforestation and re-cultivation (short-term reuse of abandoned croplands), which indicated the positive role of agricultural abandonment. Therefore, ecological restoration in karst areas is still considered to be an effective way to ameliorate the effects of human disturbance on these extremely fragile ecological environments.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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