

Estimation of soil organic carbon storage and its fractions in a small karst watershed

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Received: 17 October 2016/Revised: 1 March 2017/Accepted: 19 April 2017/Published online: 13 May 2017
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Abstract With few available soil organic carbon (SOC) profiles and the heterogeneity of those that do exist, the estimation of SOC pools in karst areas is highly uncertain. Based on the spatial heterogeneity of SOC content of 23,536 samples in a karst watershed, a modified estimation method was determined for SOC storage that exclusively applies to karst areas. The method is a “soil-type method” based on revised calculation indexes for SOC storage. In the present study, the organic carbon contents of different soil types varied greatly, but generally decreased with increasing soil depth. The organic carbon content decreased nearly linearly to a depth of 0–50 cm and then varied at depths of 50–100 cm. Because of the large spatial variability in the karst area, we were able to determine that influences of the different indexes on the estimation of SOC storage decreased as follows: soil thickness > boulder content > rock fragment content > SOC content > bulk density. Using the modified formula, the SOC content in the Houzhai watershed in Puding was estimated to range from 3.53 to 5.44 kg m⁻², with an average value of 1.24 kg m⁻² to a depth of 20 cm, and from 4.44 to

14.50 kg m⁻², with an average value of 12.12 kg m⁻² to a depth of 100 cm. The total SOC content was estimated at 5.39×10^5 t.

Keywords Bare rock rate · Estimation method · Soil organic carbon storage · Small watershed · Karst

1 Introduction

As the largest carbon pool on earth, the terrestrial ecosystem has a total carbon storage of approximately 2500 Pg, of which nearly two thirds (approximately 1550 Pg) is soil organic carbon (SOC). Due to global warming, any subtle changes in the terrestrial carbon pool greatly influence the global climate (Schlesinger 1982; Lal 2004). Many methods for estimating SOC storage have been proposed by the academic community (Bohn 1982; Wang et al. 2011; Wei et al. 2014a, b; Zhang et al. 2015; Zheng et al. 2016). Evaluations of soil type, ecological methods, and geostatistical methods are commonly used in these types of studies. In both geostatistical and ecological methods, the entire study area is represented by a sample area, which can result in large errors depending on the number of sampling points and the sampling method. However, in the more widely used soil-type method, SOC storage in small or medium-sized areas is estimated by summing SOC values that have been calculated for each soil type, weighted by the corresponding acreage (Rodriguez-Murillo 2001). Because it is unclear which factors influence SOC storage, large differences exist between the values estimated by different people, and it is difficult to determine which estimates are the most accurate (Wang et al. 2003; Mao et al. 2015; Zhao et al. 2015). In the 1950s, Bolin used a summary of the SOC contents

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published by nine researchers in the United States to calculate the global organic carbon stock and obtained a value of 710 Pg (Bolin 1977). Using a soil distribution map and the organic carbon content of the related soil groups, Bohn estimated that the global SOC storage equals 2946 Pg. In 1982, Post and others (Batjes 1996) used 2696 soil profile datasets from around the world to estimate the global SOC storage reserves in the top 1 m of soil and obtained a value of approximately 1395 Pg (Bohn 1982). Estimates of the soil C stock of the top 1 m of soil in China ranges from 50 to 185.6 Pg according to Fang et al. (1996), and Pan et al. (2005), who used a soil-type method in which the average C density and soil acreage of each soil type were calculated from the soil C contents provided in general soil surveys of China (particularly soil survey maps with scales of 1:4 million and 1:10 million). Due to the spatial distribution of SOC, some errors exist in estimated global SOC storage (Jie et al. 2004). Using the same method and considering the same study area, different researchers have arrived at different conclusions. Incorrect estimates have mainly occurred because of the large variability in soil type, the spatial distribution of organic C, and the weak representativeness of the sampled soil profiles. Highly representative soil profiles and accurate ranges for the related soil indexes are important for obtaining reliable estimates.

Karst areas are different from non-karst areas in terms of terrain and landform conditions, hydrothermal conditions, site conditions for vegetation, and soil development conditions (Lu et al. 2014), all of which cause the soil C cycle in karst areas to differ from that in other areas (Chen et al. 2014; Heilman et al. 2014). The study of soil C storage in karst areas is necessary to evaluate the C sink capacities of terrestrial soil ecosystems in China (Gifford 1994; VandenBygaart et al. 2004; Jones et al. 2005). Due to their unique geology and climate conditions, karst areas have low environmental C storage capacities, weak resilience against disturbance, low stabilities, and poor self-adjusting abilities. In addition, the basic characteristics of karst areas, such as bedrock outcrops, small soil C stocks, discontinuity, and complex microrelief, make it more difficult to calculate SOC storage in these areas (Zhang et al. 2016). In recent studies, some indexes, such as boulder content and soil thickness, have been used in estimating SOC storage in karst areas (Zhou et al. 2010; Zheng et al. 2012; Chen et al. 2014). However, some areas, such as large desertified rocky areas, have not been considered when estimating SOC storage in karst areas. In 2010, a 36,500 km² rocky area undergoing desertification was observed in Guizhou Province; the area accounted for 19% of the land area in the province (Ying et al. 2012). Large areas of bare rock, which do not contain SOC, should be removed from formulas used to estimate SOC storage. In this study, we considered the spatial variability of related indexes,

including soil distribution and acreage, occurrence rate of bare rock, rock fragment content, soil thickness, soil bulk density, and SOC content, in a plateau-type karst area in a small watershed. By revising the formulas used for obtaining SOC density and storage data, we propose a calculation method based on the soil-type method to improve the reliability of C storage estimations.

The primary objective of this research is a comprehensive analysis of the factors that impact organic carbon storage in the Houzhai River Basin. By exploring the factors that control organic carbon storage and correcting the formulas used to calculate SOC storage, a more reasonable calculation model can be put forward. Our in-depth study of a karst area informed a more accurate method for estimating the carbon pool in karst areas. This new method can be used as a reference for regional sustainable development and the accurate estimation of the global soil carbon pool.

2 Samples and methods

2.1 The study area

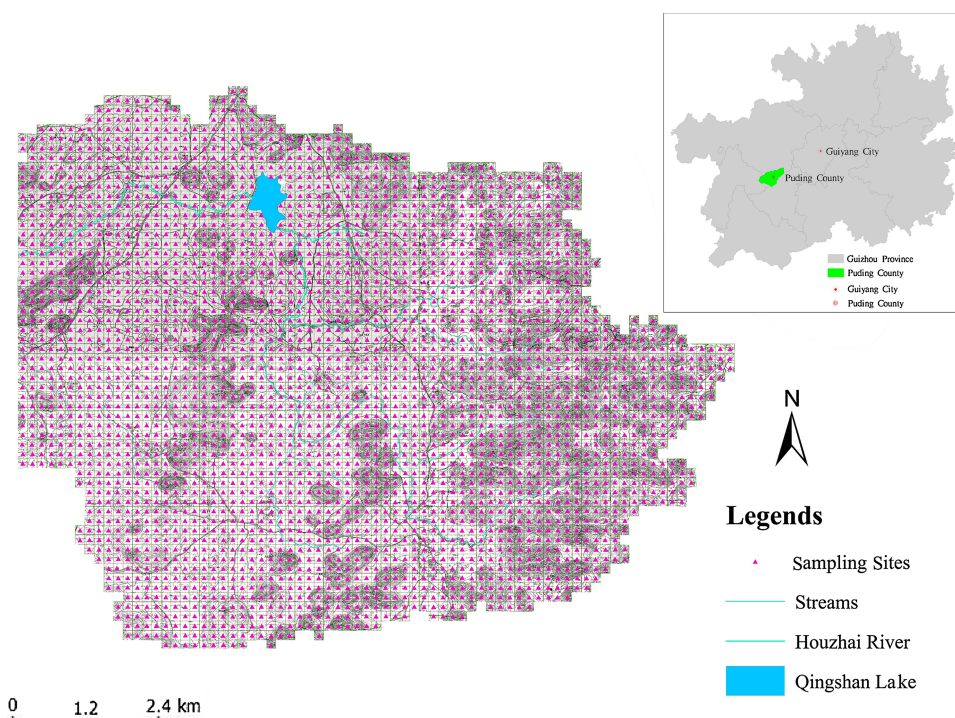
The study site (105°40′43″–105°48′2″E, 26°12′29″–26°17′15″N) is located in the towns of Chengguan, Maguan, and Baiyan in Puding County, Guizhou Province, and covers an area of 75 km². The elevation at the study site is between 1223 and 1567 m above sea level, and the air pressure is between 806.1 and 883.8 hPa. Three major categories of soil were studied: limestone soil, paddy soil, and yellow soil. The vegetation in the area includes Chinese weeping cypress (*Cupressus funebris* Endl.), *Populus adenopoda* Maxim, *Toona sinensis* (A. Juss.) Roem., and Chinese pear (*Pyrus pyrifolia* Burm Nakai), among others. The main crops in the study area include paddy rice (*Oryza sativa*, *Oryza glaberrima*), corn (*Zea mays* Linn. sp.), soybeans (*Glycine max* (Linn.) Merr), and sunflowers (*Helianthus annuus*) (Fig. 1).

2.2 Experimental design

2.2.1 Layout of sampling points

Grids were laid out on a 1:10,000 topographic map of the study area in accordance with the principles of the grid method using ArcGIS 9.3. A sampling point was placed at the center of each cell, and each cell represented an area of 150 m × 150 m. Although 3333 sampling points were generated, only 2755 points were considered because the remainder was located in rivers, on roads, under houses, or in other inaccessible areas.

Fig. 1 Location of the Houzhai river small watershed and distribution of sample sites



During soil sampling and when conducting a survey for local information, a portable GPS, a box compass, and a topographic map showing the point distribution were used to locate the sampling points in the field.

2.2.2 Sample collection

Soil samples were collected from the bottom to the top and layer by layer along the soil profile, which was always ≤ 100 cm deep. When the bedrock or parent material layer was at a depth of less than 100 cm, the soil profile depth was the soil and rock interface. The soil profile was divided into up to 12 depth increments (0–5, 5–10, 10–15, 15–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, 80–90, and 90–100 cm). Local information for each sampling point and the soil bulk density, soil thickness, rock coverage, and other indexes were measured and recorded.

2.3 Test methods

First, the soil samples were air-dried, ground, and prepared according to the requirements of the laboratory. Then, the SOC contents of the samples were determined using the potassium dichromate method.

Soil acreage was calculated using GIS information and field survey data. Bulk density was measured layer by

layer from the top to the bottom of the soil profile using the cutting-ring method. Soil thickness was recorded according to the type of ecological niche using an iron measuring rod that was 60 or 120 cm long, based on the soil mass at different depths. The boulder content was surveyed using a linear transect. Due to the existence of complex landscapes in the karst area, the length of the linear transect was set at 10 m. Although more accurate information could be obtained from a longer transect, establishing a longer transect would have required excessive effort. Grid cells with rock coverage were surveyed using a tape measure.

2.4 Data analysis

The soils were divided into several types as follows: 457 samples of Xanthi-udic ferralsols, 613 samples of Black Lithomorphie Isohumisols, 397 samples of yellow limestone soil, 129 samples of Cab High fertility Orthic Anthrosols, 439 samples of Cab Low fertility Orthic Anthrosols, 125 samples of white Cab High fertility Orthic Anthrosols, 106 samples of Cab Medium fertility Orthic Anthrosols, 185 samples of large mud field loam, and 304 samples of Fec Hydragric Anthrosols. The data from these 2755 soil samples were analyzed using Excel 2013 and ArcGIS 9.3.

2.5 Computation of soil organic carbon storage and formula modification

2.5.1 Commonly used equations

$$A: \quad \bar{C} = \frac{\sum_{i=1}^n C_i \times H_i}{\sum H_i},$$

$$C = \sum_{j=1}^n \bar{C}_j \times 10 \div 1.724 \times \rho \times S \times \frac{2000}{3} \times \sum H_j \times 10^{-2}$$

(Pan et al. 2005)

where C_i is the SOC content in the i layer of the soil, H_i is the thickness of the i layer of the soil (cm), \bar{C}_j is the weighted average organic matter content for the first j soil species (%), C is the carbon pool, ρ is the soil bulk density (g cm^{-3}), S is the acreage of soil j (mu), $\frac{2000}{3}$ is used to convert the resulting value to meters in the coefficient, and 10^{-2} is a conversion coefficient.

$$B: \quad C_j = 0.58S_jH_jO_jW_j \quad (\text{Wang et al. 2003})$$

where j is the soil type, C_j is the total SOC stock in an area of soil j (t), S_j is the acreage of soil j (km^2), H_j is the thickness of the i layer of soil j (cm), O_j is the SOC content of soil j (%), and W_j is the bulk density of the i layer of soil j (g cm^{-3}).

$$C: \quad \text{socd}_j = c_j \times h_j \times w_j \div 10, \quad \text{soc}_j = \text{socd}_j \times s_j$$

(Zhang et al. 2015)

where j is the soil type, socd_j is the SOC density in the i layer of soil j (kg m^{-2}), c_j is the SOC content of soil j (%), h_j is the thickness of the i layer of soil j (cm), W_j is the bulk density of soil j (g cm^{-3}), soc_j is the total stock of SOC in the study area (t), and s_j is the acreage of soil j (km^2).

Although the three equations used above for estimating the SOC stock are expressed in different forms, they share the same theory and involve the use of the same four major parameters: SOC content, soil bulk density, soil thickness, and soil acreage. Equation A accounts for soil type and indicates a bulk density value of 1.4 g cm^{-3} . By taking the mean values of all indexes, Equation B represents the SOC stock of one soil type. Equation C, in which SOC content is considered by soil layer, also represents the SOC stock of one soil type. Because the SOC content, soil bulk density, soil thickness, and other parameters vary widely among the soil types in the karst area, the equations above should be modified before they are used for estimating the SOC stock when using the soil-type method.

2.5.2 First modified equation

Due to the variety of soil types in the karst area, the soil-type method was adopted. Because of the large variability in the

indexes, such as the SOC content, bulk density, and soil thickness, the SOC density was calculated layer by layer. The soil profile was divided into twelve layers. The SOC density in each layer was computed based on its corresponding SOC content, bulk density, and thickness. In addition, the spatial eigenvalue of the SOC density of the Houzhai River watershed in Puding was estimated based on the SOC density in each soil layer. Next, the SOC density and soil acreage of each soil type were used to determine the SOC stock layer by layer, which was then used to determine the total SOC storage in the study area. Thus, the equations for SOC density and storage can be modified as follows:

$$\text{SOCD}_{i,j} = C_{\text{soc}_{i,j}} \times \rho_{i,j} \times T_{i,j} \times 10^{-2},$$

$$\text{SOCS} = \sum_{j=1}^m \sum_{i=1}^n \text{SOCD}_{i,j} \times S_j \times 10^3 \quad (2)$$

where $\text{SOCD}_{i,j}$ is the SOC density in the i layer of soil j (kg m^{-2}), $C_{\text{soc}_{i,j}}$ is the SOC content in the i layer of soil j (g kg^{-1}), $\rho_{i,j}$ is the bulk density of layer i of soil j (g cm^{-3}), $T_{i,j}$ is the thickness of layer i of soil j (cm), 10^{-2} is a conversion coefficient, SOCS is the total stock of SOC in the study area (t), S_j is the acreage of soil j (km^2), and 10^3 is a unit conversion factor.

2.5.3 Second modified equation

To minimize the difference between the estimated SOC stock and the actual SOC stock, the error caused by rock coverage in the karst area was reduced by revising the bare rock rate. Equation 2 can be modified to generate Eq. 3 as follows:

$$\text{SOCD}_{i,j} = C_{\text{soc}_{i,j}} \times \rho_{i,j} \times T_{i,j} \times 10^{-2},$$

$$\text{SOCS} = \sum_{j=1}^m \sum_{i=1}^n \text{SOCD}_{i,j} \times S_j \times (1 - \delta_j) \times (1 - G_j) \times 10^3 \quad (3)$$

where δ_j is the boulder content in the sampling area of soil j (%), G_j is the volume percentage of gravel that is larger than 2 mm in soil j , and the other indexes are the same as those described in Eq. 2.

After the second modification, Eq. 3 can be used to estimate SOC storage in the karst area while considering the large variability in the related indexes.

3 Results

3.1 Statistical analysis of the related soil indexes

3.1.1 Characteristics of soil acreage, boulder content, and soil thickness

In accordance with the survey and statistics, three soil groups were identified in the basin: limestone soil, paddy

soil, and yellow soil. These soils include the following nine soil types: Xan Udic Fernalisols, Black Lithomorphc Isohumisols, yellow limestone soil, Cab High fertility Orthic Anthrosols, Cab Low fertility Orthic Anthrosols, Cab Medium fertility Orthic Anthrosols, Cab Medium fertility Orthic Anthrosols, large mud field loam, and Fec Hydragric Anthrosols. Using GIS and field surveys, the study area was divided into different sampling units based on soil type. The units, quite different in size, were interlaced in the basin. Coverages are listed in Table 1. The Black Lithomorphc Isohumisols and yellow limestone soils covered small areas and usually occurred in clusters. These soils were generally mixed together and difficult to separate using GIS technology. Based on the number of sampling points for these two soil genera, the soil coverages of Black Lithomorphc Isohumisols and yellow limestone soils were 13.79 and 8.93 km², respectively.

Because limestone, paddy, and yellow soils are interwoven, the soil in the watershed is very heterogeneous. The limestone soil areas suffer from severe stony desertification and scattered rock exposure. When rock coverage is not considered, soil coverage is overestimated. Therefore, the value of soil acreage was revised by considering the area covered by rocks. The boulder content differed substantially for different soil units; for instance, 43.34% of the area containing Black Lithomorphc Isohumisols was covered by rocks (the highest percentage), as was 29.22% of the area with tilled Cab High fertility Orthic Anthrosols (the lowest non-zero percentage). Rock exposure was rare in the three major tillage areas consisting of Xan Udic Fernalisols, large mud field loam, and Fec Hydragric Anthrosols; therefore, the rate of rock coverage in these areas was recorded as zero. The particle size distribution and rock exposure rate in the Cab Medium fertility Orthic Anthrosols and Fec Hydragric Anthrosols were nearly the same, with no rock fragments. However, the sizes of the rock fragments in the other soil types decreased as follows: Black Lithomorphc Isohumisols > Cab Udi Orthic Entisols > Cab Medium fertility Orthic Anthrosols > white Cab High fertility Orthic Anthrosols > Cab Low fertility Orthic Anthrosols > Cab High fertility Orthic Anthrosols > Xan Udic Fernalisols.

Because limestone soils develop slowly from carbonate rock and severe water and soil losses occur in lithic areas, the soils in the peak clusters were very thin, and bare rock was sometimes observed. However, the soil in the low-lying lands was relatively thick. The soil thicknesses in the sampling areas of different soil units were very different. For instance, the Xan Udic Fernalisols were deeper than 100 cm, while the Black Lithomorphc Isohumisols were only a few centimeters to 20 cm deep. The Xan Udic Fernalisols that developed on dry land from yellow soils were deep. However, the small amount of yellow soil that

Table 1 Description of related indexes of different soils

	YC	RD	YLS	LL	SC	WLL	WS	LMFS	YCS
Soil area (km ²)	12.88	13.79	8.93	3.39	9.87	2.81	2.38	12.59	7.53
Rate of rock coverage (%)	0	43.34 ± 23.62	37.83 ± 21.51	29.22 ± 13.06	33.09 ± 17.65	37.82 ± 15.26	35.42 ± 19.67	0	0
rock fragment content (%)	1.02 ± 0.13	21.56 ± 10.56	19.68 ± 7.07	9.26 ± 5.06	12.32 ± 4.29	15.42 ± 7.21	17.01 ± 9.43	0	0
Soil thickness (cm)	100 ± 13	20 ± 11	32 ± 16	85 ± 27	58 ± 33	64 ± 33	33 ± 25	87 ± 23	93 ± 17

YC, Xan Udic Fernalisols; RD, Black Lithomorphc Isohumisols; YLS, Cab Udi Orthic Entisols; LL, Cab High fertility Orthic Anthrosols; SC, Cab Low fertility Orthic Anthrosols; WLL, Cab Medium fertility Orthic Anthrosols; WS, Cab Medium fertility Orthic Anthrosols; LMFS, Cab Medium fertility Orthic Anthrosols; YCS, Fec Hydragric Anthrosols

developed from sandy shale was rather thin and included Xan Udic Fernalisols, which were deeper than 100 cm. The Cab High fertility Orthic Anthrosols, Cab Low fertility Orthic Anthrosols, Cab Medium fertility Orthic Anthrosols, and Cab Medium fertility Orthic Anthrosols with different soil thicknesses were located in dry areas. The Cab Medium fertility Orthic Anthrosols were shallow. The areas of large mud field loam and Fec Hydragric Anthrosols were paddy fields. The Cab High fertility Orthic Anthrosols were thin in the upstream area but relatively thick downstream. Most of the Fec Hydragric Anthrosols were deeper than 100 cm, and the Black Lithomorphic Isohumisols and yellow limestone soils were relatively thin and scattered in peak clusters.

3.1.2 Soil bulk density

The soil bulk densities of the Black Lithomorphic Isohumisols, yellow limestone soil, and Cab Low fertility Orthic Anthrosols gradually increase with increasing soil depth. The bulk densities of Xan Udic Fernalisols, Cab High fertility Orthic Anthrosols, Cab Medium fertility Orthic Anthrosols, and Fec Hydragric Anthrosols increase and then decrease as the thicknesses of the soil layers increase. Meanwhile, the bulk densities of the Cab High fertility Orthic Anthrosols and Cab Medium fertility Orthic Anthrosols tend to remain stable in the deep layers, but the bulk density of Xan Udic Fernalisols tends to increase with depth. The bulk density of Cab Medium fertility Orthic Anthrosols first decreases and then increases with increasing soil depth. The bulk densities in the bottom layers of the Black Lithomorphic Isohumisols, yellow limestone soil, and Cab Low fertility Orthic Anthrosols reached a plateau, while the bulk densities of the Cab High fertility Orthic Anthrosols and Fec Hydragric Anthrosols were greatest in the plow pan. The bulk densities of the other soils were greatest in the transitional zone between the A and B horizons. The same layers of different soil units have very different bulk densities. For example, the bulk density at a depth of 15–20 cm in the mud field loam was 0.32 g cm^{-3} greater than the bulk density at the same depth in the Black Lithomorphic Isohumisols. The maximum bulk plow pan was observed in the large area containing mud field loam and was 1.44 g cm^{-3} . The minimum bulk density was in the surface layer of the Black Lithomorphic Isohumisols at 0.94 g cm^{-3} (Fig. 2).

3.1.3 Soil organic carbon content

The SOC contents in the different soils decreased with increasing soil depth at different rates. The SOC content decreased gradually at a depth of 0–50 cm, and no large

differences were observed at depths of 50–100 cm. The SOC contents of the different soil genera in corresponding layers were very different. For example, the SOC content of the Black Lithomorphic Isohumisols in the surface layer was 2.61 times greater than that in the Xan Udic Fernalisols. Overall, the Black Lithomorphic Isohumisols had the highest SOC content, and the Xan Udic Fernalisols the lowest SOC content. In all soil samples, the SOC content was higher at the surface than in the deeper soil layers. Black Lithomorphic Isohumisols and yellow limestone soils located in peak clusters and in natural woodlands soils had higher SOC than the other seven units of cultivated soil. Moreover, the SOC content of the Black Lithomorphic Isohumisols in the upper part of the peak cluster was greater than that of the yellow limestone soil in the lower part of the peak cluster (Fig. 3).

3.2 Index values of SOC storage

The interval values of the indexes, including the SOC content, bulk density, soil thickness, soil acreage, and bare rock rate, in the Houzhai River Basin in Puding were obtained by analyzing data from 2755 sampling points (Table 2).

In the study area, the SOC density at 5-cm intervals at depths of 0–20 cm ranged from 0.21 to 3.43 kg m^{-2} , and the SOC density at 10-cm intervals at depths of 20–100 cm ranged from 0.16 to 4.21 kg m^{-2} . The SOC density at a depth of 20–100 cm in the different soils ranges from 5.14 to 19.32 kg m^{-2} . The bulk density at a depth of 0–100 cm ranged from 0.94 to 1.44 g cm^{-3} . The soil thickness ranged from 20 to 100 cm (soil deeper than 100 cm was labeled 100 cm). The average soil thickness in the study area was 64 cm. The boulder content in the karst area ranged from 29.22% to 43.34%, and the particle rock content ranged from 0% to 75.71%, which was used to revise the soil acreage. The total area of the watershed is 75 km^2 , of which the area of water is 0.83 km^2 and the area of land is 74.17 km^2 . The total area of land includes both soil and bare rock. The SOC contents, bulk densities, thicknesses, and acreages of the soils were very different, particularly in the large area containing limestone soils. Therefore, SOC stocks in each soil type and in each soil layer were calculated individually and then used to calculate total SOC storage of the area.

3.3 Estimates of soil organic carbon density

The SOC density at intervals of 5 cm at depths of 0–20 cm in the sampling area of each soil genus decreased as the depth of the soil layer increased. Black Lithomorphic Isohumisols were observed to have the highest SOC density, while yellow limestone soil was observed to have the

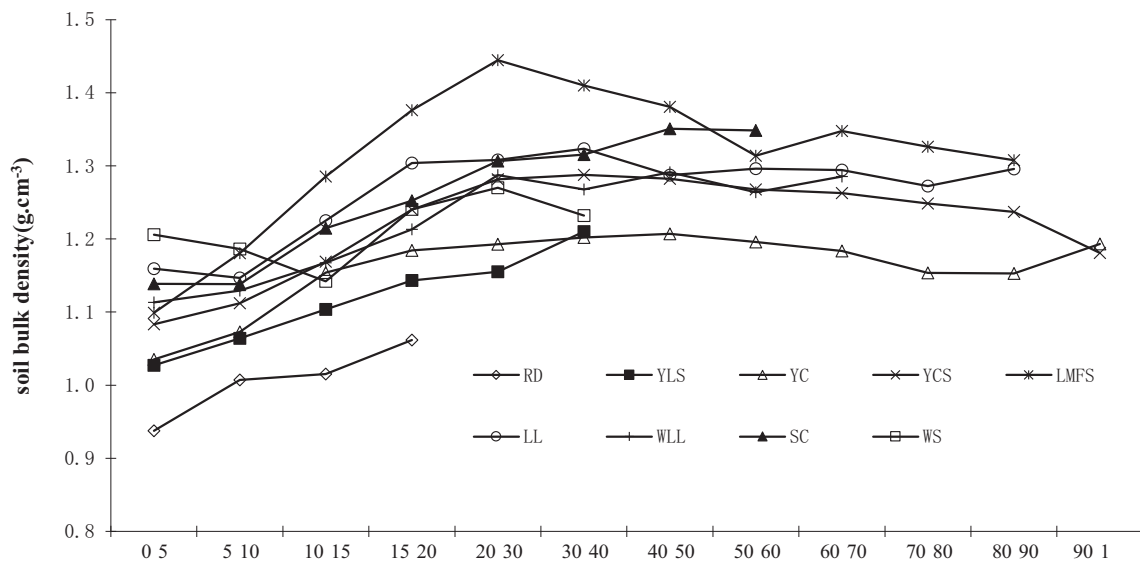


Fig. 2 Soil bulk density of different soils. YC, Xan Udic Ferralsols; RD, Black Lithomorphie Isohumisols; YLS, Cab Udi Orthic Entisols; LL, Cab High fertility Orthic Anthrosols; SC, Cab Low fertility Orthic Anthrosols; WLL, Cab Medium fertility Orthic Anthrosols; WS, Cab Medium fertility Orthic Anthrosols; LMFS, Cab Medium fertility Orthic Anthrosols; YCS, Fec Hydragric Anthrosols

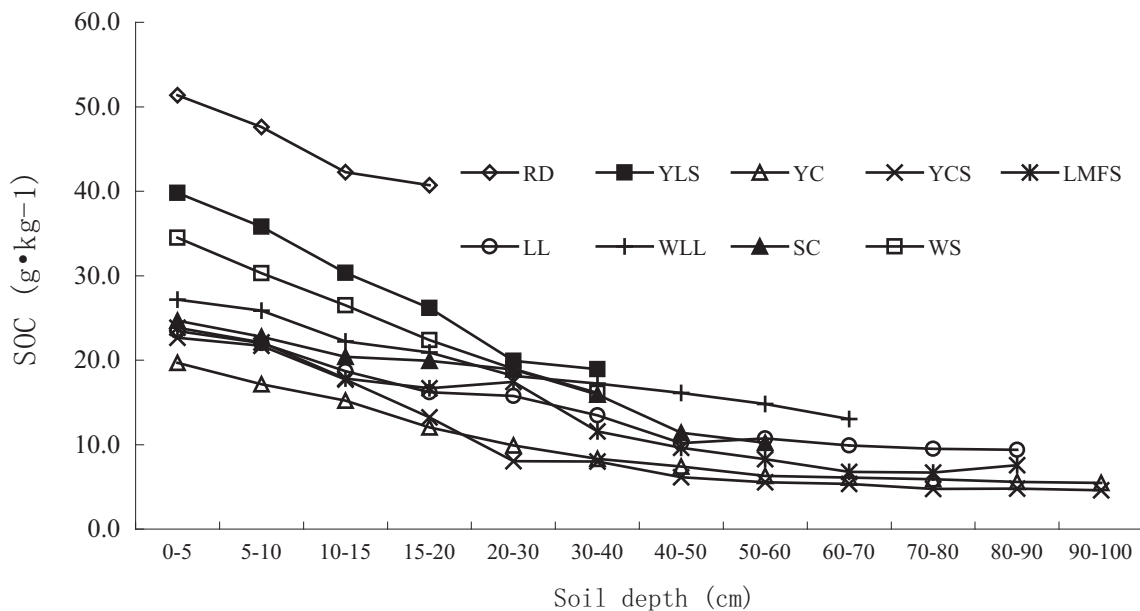


Fig. 3 SOC content of different soils

lowest SOC density. The SOC density at intervals of 10 cm at depths of 20–100 cm in the sampling area of each soil type gradually decreased as the depth of the soil layer increased, and generally became stable near the bottom of the soil profile. The largest SOC density to a depth of 10 cm was 1.58 times the smallest value. The SOC density to a depth of 20 cm ranged from 3.29 to 5.44 kg m⁻², and the SOC density to a depth of 100 cm ranged from 4.44 to 14.50 kg m⁻² (Table 3). Meanwhile, the national average SOC density to a depth of 87 cm in China is 10.53 kg m⁻²

(Wang et al. 2011). The average SOC density to a depth of 10 cm in the karst area of the Houzhai River watershed was 2.39 kg m⁻², 1.95 times that of the 1.21 kg m⁻² observed in China.

3.4 Comparisons of the methods used to calculate soil organic carbon storage

The estimated SOC storage in the Houzhai River watershed is $\text{SOC}_7 = 9.37 \times 10^5 \text{ t}$ when the variability of the SOC

Table 2 Interval value of different indexes

Index	Unit	Min.	Max.	Mean	Notes
C_{soc}	kg m^{-2}	0.21	3.43	1.24	5-cm thickness(0–20 cm)
		0.16	4.21	1.36	10-cm thickness(20–100 cm)
		5.14	19.32	12.12	20- to 100-cm thickness total
ρ	g cm^{-3}	0.94	1.44	1.20	
T	cm	20	100	64	100 cm, >100 cm
δ	%	29.22	43.34	36.12	Volume percentage (%) of gravel that is larger than 2 mm
	%	0	75.71	7.71	
S	km^2	0.83 (water)	74.17 (land)	75.00 (total)	Rock coverage included

Table 3 Spatial distribution eigenvalue of soil organic carbon density of different soils in basin (unit kg m^{-2})

Soil layer/cm	YC	RD	YLS	LL	SC	WLL	WS	LMFS	YCS
0–5	0.97	1.35	1.32	1.19	1.19	1.14	1.30	1.46	1.34
5–10	0.88	1.22	1.15	1.12	1.07	1.03	1.12	1.45	1.29
10–15	0.77	1.04	1.01	1.04	0.99	0.97	0.92	1.38	1.23
15–20	0.67	0.83	0.83	0.89	0.85	0.79	0.74	1.15	1.10
20–30	1.06	–	1.22	1.48	1.30	1.19	0.86	2.52	1.57
30–40	0.86	–	0.80	1.05	0.88	0.85	0.46	1.63	1.03
40–50	0.78	–	–	0.85	0.62	0.56	–	1.33	0.78
50–60	0.67	–	–	0.65	0.44	0.35	–	1.09	0.66
60–70	0.59	–	–	0.54	–	0.30	–	0.91	0.56
70–80	0.53	–	–	0.42	–	–	–	0.89	0.45
80–90	0.41	–	–	0.33	–	–	–	0.69	0.43
90–100	0.35	–	–	–	–	–	–	–	0.36
Total	8.54	4.44	6.33	9.56	7.34	7.18	5.4	14.5	10.8

SOC density is in line with soil thickness

content, bulk density and soil thickness is considered and the influence of rock coverage is ignored. If the SOC content, bulk density, and soil thickness are given as average values and the variabilities of the remaining indexes are considered, the corresponding estimates of SOC storage in the Houzhai River watershed are $\text{SOCS}_4 = 9.61 \times 10^5 \text{ t}$, $\text{SOCS}_5 = 9.28 \times 10^5 \text{ t}$, and $\text{SOCS}_6 = 8.53 \times 10^5 \text{ t}$, respectively, and $\text{SOCS}_6 < \text{SOCS}_5 < \text{SOCS}_4$ (Table 4). This indicates that SOC content, bulk density, and soil thickness have different degrees of influence on the estimation of SOC storage.

When assuming that the soil is uniform to a depth of 100 cm and that the average soil bulk density is 1.20 g cm^{-3} , the estimated SOC storage decreases as follows: $\text{SOCS}_1 > \text{SOCS}_2 > \text{SOCS}_3 = 1.8(\text{SOCS}_7)$. In other words, SOC storage decreases as the average SOC content decreases, and the SOCS_3 content is 1.8 times the SOCS_7 content. When rock coverage is ignored, the SOC storage in the Houzhai River watershed is $\text{SOCS}_7 = 9.37 \times 10^5 \text{ t}$; taking rock coverage into account, the SOC storage is $\text{SOCS}_8 (\text{CK}) = 5.39 \times 10^5 \text{ t}$ —a difference of $3.98 \times 10^5 \text{ t}$

(Table 4), which is very large considering that the area of the watershed is 75 km^2 . This indicates that the boulder content is a significant factor that must be considered to improve the reliability of SOC storage estimates in karst areas. Different correction indicators should be compared to estimate the error in organic carbon storage estimates. If it is assumed that the soil is homogeneous to a depth of 100 cm, with an average bulk density of 1.20 g cm^{-3} , and if other variation factors are not considered, the error range is 216.33% to 287.01%. However, when mean SOC content, soil bulk density, soil thickness, and the variability of other indicators are considered, the error range is reduced to 58.26% to 78.29%.

4 Discussion

4.1 Spatial heterogeneity of the soil in the karst area

The extraordinary spatial heterogeneity of the Houzhai River watershed in Puding forms a dual structure; the

Table 4 Soil organic carbon storage with different calculation modes

Modes	Variable factor	Invariable factor	Solution	SOCS/ 10 ⁵ t	Error percentage difference between SOCS ₈ (CK)
SOCS ₁	–	<i>C</i> _{soc} (mean of 0–30 cm), $\rho = 1.20 \text{ g cm}^{-3}$, $T = 100 \text{ cm}$, S	Acreage priority	20.86	287.01
SOCS ₂	–	<i>C</i> _{soc} (mean of 0–50 cm), $\rho = 1.20 \text{ g cm}^{-3}$, $T = 100 \text{ cm}$, S	Acreage priority	19.32	258.44
SOCS ₃	–	<i>C</i> _{soc} (mean of 0–100 cm), $\rho = 1.20 \text{ g cm}^{-3}$, $T = 100 \text{ cm}$, S	Acreage priority	17.05	216.33
SOCS ₄	ρ , T	<i>C</i> _{soc} (mean of 0–100 cm), S	Acreage and layer priority	9.61	78.29
SOCS ₅	<i>C</i> _{soc} , T	$\rho = 1.20 \text{ g cm}^{-3}$ (mean), S	Acreage and layer priority	9.28	72.17
SOCS ₆	<i>C</i> _{soc} , ρ	$T = 64 \text{ cm}$ (mean), S	Acreage and layer priority	8.53	58.26
SOCS ₇	<i>C</i> _{soc} , ρ , T	S	Acreage and layer priority	9.37	73.84
SOCS ₈ (CK)	<i>C</i> _{soc} , ρ , G , T , S	–	Layer, acreage priority and revised acreage by δ	5.39	–

landscape elevation increases and decreases for various soil types that are interwoven with one another and with scattered bare rocks. In the vertical direction, soil depths differ substantially among the soil types, and related indexes at different soil depths within the same soil type are very different. The related indexes in this complex area with high spatial heterogeneity are widely variable. The spatial distribution of soil mass in this area is complex, various soil genera are interwoven with one another, and there is a discontinuous regolith caused by exposed rock and non-uniform soil thickness. The spatial heterogeneity in the karst area is responsible for the variability in the related indexes, including the SOC content, bulk density, soil thickness, soil distribution, soil coverage, and bare rock rate, all of which play important roles in estimating SOC storage. In the process of estimating SOC storage and density, the boulder content and soil thickness should be considered in order to reduce error. These factors should be revised further to estimate the SOC stock and density in areas with high bare rock rates. Simultaneously, the variability in the spatial distribution of soil mass, SOC content, and bulk density should be considered important factors for sampling and for calculating SOC storage (Bohn 1982; Wei et al. 2014a). The large spatial heterogeneity of the soil should play a significant role in estimating the SOC storage in the karst area when using the soil-type method.

The accuracy of SOC storage estimates in karst areas are related not only to the estimate modes but also to the accuracy of the indexes, such as the SOC content, bulk density, soil thickness, and soil acreage, which are important factors for estimating the SOC stock. However, due to the exposed rock in the karst area, the actual soil acreage must be revised by using boulder content and rock fragment content. This study was conducted using a high-quality database containing information from 2755 samples that represent 23,536 soil samples. With the basic data

detailed above, accurate estimates of SOC density and storage can be obtained. Meanwhile, the formula used for determining C storage can be revised. All of these factors can contribute to the accurate calculation of C storage in small karst areas (Fig. 4).

4.2 Influencing factors of soil organic carbon density in karst areas

Although some researchers have previously considered boulder content and soil thickness in karst areas (Li et al. 2015; Tang et al. 2016; Wen et al. 2016), this study considers related indexes such as SOC content, bulk density, soil thickness, soil coverage, and boulder content together. SOCS₄ is $0.24 \times 10^5 \text{ t}$ more than SOCS₇; SOCS₅ is $0.092 \times 10^5 \text{ t}$ less than SOCS₇; SOCS₆ is $0.84 \times 10^5 \text{ t}$ more than SOCS₇; and SOCS₈ is $3.98 \times 10^5 \text{ t}$ less than SOCS₇ (Table 4). These results show that the influences of the indexes on SOC storage estimates decrease as follows: soil thickness > boulder content > SOC content > bulk density. Hence, to estimate SOC storage in karst areas, the impacts of soil thickness and boulder content should be prioritized, followed by SOC content and soil bulk density. This study presents a detailed survey of soil types, SOC, bulk density, boulder content, and soil thickness by using a detailed survey and soil-type method. Using this method resulted in more accurate SOC content and density estimates for this basin. When using an average soil bulk density of 1.20 g cm^{-3} , the SOC storage in the Houzhai River watershed was estimated at $7.33 \times 10^5 \text{ t}$ using Equation A— $1.94 \times 10^5 \text{ t}$ greater than the SOC storage estimated using Eq. 3; the SOC storage estimated using Equation B was $7.63 \times 10^5 \text{ t}$, which was $2.24 \times 10^5 \text{ t}$ greater than the result based on Eq. 3. Equations A, B, and C all ignore the influence of rock coverage and have large errors because the indexes, such as SOC content and bulk

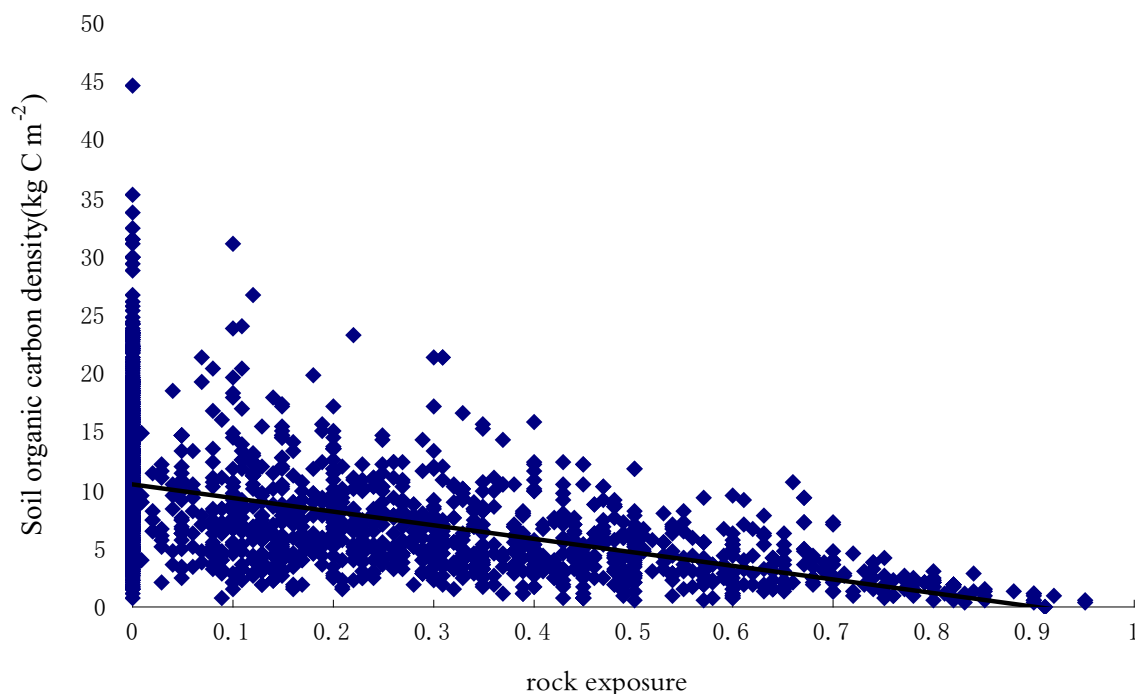


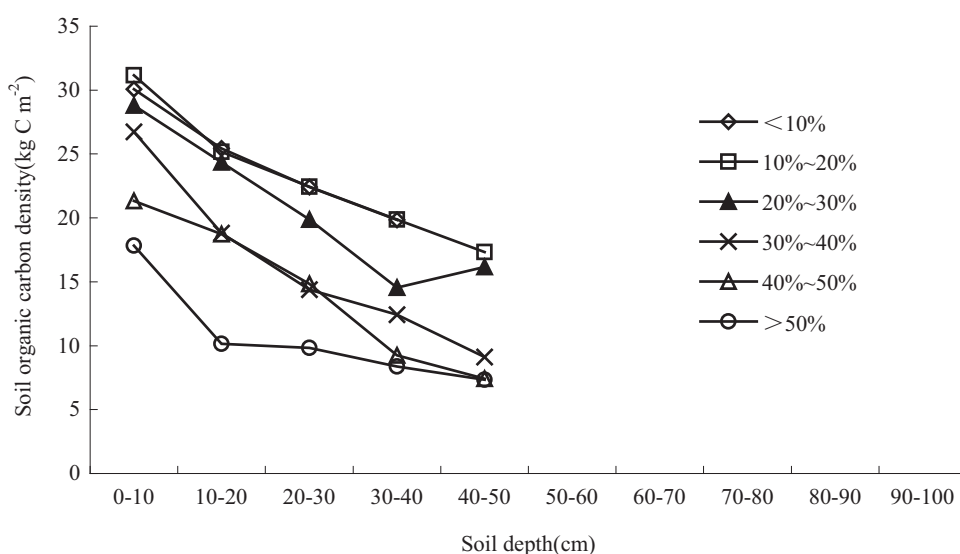
Fig. 4 Correlation between exposed rock rate and soil organic carbon density

density, contained variability. If mean SOC content, soil bulk density, and soil thickness are considered in addition to the variabilities of other indicators, the error is very large. The error of SOC storage in the small watershed in the post-walled river basin was 73.84% when the bare rock ratio was not considered.

Soil thickness and rock exposure are both important factors that directly and indirectly affect SOC storage in karst areas. In the Houzhai River basin, soil thickness and rock exposure ranged from 0 to >100 cm and from 0% to 95%, respectively, and were used in the equations to

calculate the SOC density and SOC storage. The karst soils developed from limestone, dolomite, and widely exposed laminated bedrock. These soils are unique and complicated, resulting from the weathering of rock around fissures and accumulating dissolved oxygen. In addition, these soils form discontinuous shallow deposits with a scattered distribution and variable thickness. The organic carbon density of the soil was negatively correlated with boulder content, meaning that the boulder content was high when the SOC density was lower and vice versa (Zhang et al. 2003). These results are consistent with

Fig. 5 Soil organic carbon density by soil depth and gravel content (series)



those of (Zhang et al. 2007), who showed that bedrock around sampled soil layers (similar to the stone throughout the soil) is generally shallow; that organic carbon is concentrated in a small amount of soil; and that exposed bedrock with litter debris, soil particles, and nutrients has stone surface erosion that reallocates the litter and soil nutrients, resulting in a lower SOC density (Zhang et al. 2016).

Generally, SOC densities decreased with increasing soil depth and with increased gravel content (Fig. 5). This decrease occurred because less soil was present when the proportion of gravel was greater and the unit area with a certain thickness of SOC decreased. The largest SOC density—33.59 tC hm⁻²—was observed at soil depths of 0–10 cm and gravel content of 10%–20%. The SOC density was the lowest when the gravel content was greater than 50%.

5 Conclusions

(1) Composite estimates of SOC must take into account the variability in SOC content, soil bulk density, soil thickness, and bare rock rate. In karst areas, the soil-type method should be used layer-by-layer in the vertical direction and type-by-type in the horizontal direction.

(2) Due to its impact on estimation accuracy, boulder content was used to revise the following formula. The revised equations of SOC density and storage in karst areas are $SOC D_{ij} = C_{socij} \times \rho_{ij} \times T_{ij} \times 10^{-2}$ and $SOC S = \sum_{j=1}^m \sum_{i=1}^n SOC D_{ij} \times S_j \times (1 - \delta_j) \times (1 - G_j) \times 10^3$, respectively.

(3) The influences of the different indexes on the accuracy of SOC storage estimation decrease as follows: soil thickness > boulder content > SOC content > bulk density. Using the equations revised by the bare rock rate, the estimated SOC storage in the small watershed of the Houzhai River in Puding is 5.39×10^5 t; SOC content to a depth of 20 cm ranges from 3.53 to 5.44 kg m⁻², with an average value of 1.24 kg m⁻², and the range of the SOC content to a depth of 100 cm is from 4.44 to 14.50 kg m⁻², with an average value of 12.12 kg m⁻².

Acknowledgements Funding was provided by National Key Basic Research Development Program (Grant No. 2013CB956702).

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