Patterns and influencing factors of spatio-temporal variability of soil organic carbon in karst catchment

Zhenming Zhang

Institute for Forest Resources and Environment of Guizhou,
Guizhou University,
Guiyang, 550025, China
and
Guizhou Institute of Biology,
Guiyang, 550001, China
and
College of Forestry,
Guizhou University,
Guiyang, 550001, China
Email: zhang6653578@163.com

Yunchao Zhou*

Institute for Forest Resources and Environment of Guizhou
and
College of Forestry,
Guizhou University,
Guiyang, 550001, China
Email: yczhou@gzu.edu.cn
and
Puding Karst Ecosystem Research Station of Guizhou Province,
Anshun, 561000, China
*Corresponding author

Shijie Wang

State Key Laboratory of Environmental Geochemistry,
Institute of Geochemistry,
Chinese Academy of Science,
Guiyang, 550002, China
Email: wangshijie@vip.skleg.cn
and
Puding Karst Ecosystem Research Station of Guizhou Province,
Anshun, 561000, China

Xianfei Huang

Institute for Forest Resources and Environment of Guizhou
and
College of Forestry,
Guizhou University,
Guiyang, 550025, China
and
Guizhou Provincial Key Laboratory for Environment,
Guizhou Normal University,
Guiyang, 550001, China
Email: hxfswjs@gznu.edu.cn

Abstract: The patterns of spatio-temporal variability of the soil organic carbon (SOC) stored in karst catchment were investigated, to provide a scientific basis for estimating SOC storage in karst regions and selecting technical measures for soil carbon sequestration. In this paper, field sampling, laboratory measurement, geostatistics, and geographic information system (GIS) were combined, to investigate the patterns and influencing factors of SOC's spatio-temporal variability in Houzhai catchment from 1980 to 2015. The results showed that according to the soil samples of the entire catchment, the SOC content averaged 21.98 g/kg in 1980 and 25.07 g/kg in 2015, with an increase of 3.09 g.kg^{-1} (14.58%). Over the three and a half decades, SOC in this region showed weakened spatial structure, reduced correlation, and broken spatial distribution. Moreover, SOC in both periods presented a pattern of high values in the east and low values in the west, high in the periphery and low in the centre, and high in the south and low in the north. However, some local values were highly variable in embedded or block distribution. The key factors that could affect spatio-temporal variability of SOC in Houzhai catchment included the soil types, land utilisation, and major environmental factors.

Keywords: soil organic carbon; SOC; temporal and spatial distribution; influencing factors; small watershed; karst.

Reference to this paper should be made as follows: Zhang, Z., Zhou, Y., Wang, S. and Huang, X. (2019) 'Patterns and influencing factors of spatio-temporal variability of soil organic carbon in karst catchment', *Int. J. Global Warming*, Vol. 17, No. 1, pp.89–107.

Biographical notes: Zhenming Zhang is an Associate Professor at the Department of Plant Research Room, Guizhou Institute of Biology. He graduated in forest cultivation major and obtained his Agronomy PhD degree from the School of Guizhou University. His research interests are soil chemistry and low-carbon energy development. He has published a number of research papers at the national and international journals.

Yunchao Zhou graduated from graduated from Nanjing Agricultural University in 1981. He received his PhD from the Nanjing Agricultural University in 2002. He is a researcher at the Guizhou University, Institute for Forest Resources and Environment of Guizhou. His research interests include carbon sink, soil nutrients and soil chemistry.

Shijie Wang graduated from Chengdu College of Geology in 1985. He received his MSc and PhD from the Institute of Geochemistry of Chinese Academy of Sciences. He is a researcher at the Chinese Academy of Science, Deputy Director of the State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry. His research interests include environmental science, soil geochemistry and control of rocky desertification.

Xianfei Huang graduated from Guizhou Normal University in 2008. He received his MSc from Guizhou Normal University in 2008. He is currently a PhD candidate at the College of Forestry in Guizhou University. He is a researcher at Guizhou Normal University, Guizhou Provincial Key Laboratory for Environment. His research refers to soil nutrients, soil contamination and ecological risk.

1 Introduction

Not only is soil organic carbon (SOC) an important indicator for soil quality evaluation, but also, the level and change of its content have major impacts on the global climate (Bohn, 1982). Because of the complex natural pedogenetic processes and the impact of increasing human activities, SOC exhibits strong spatial variation, and temporal variation also exists to a certain degree (Bellamy et al., 2005). In particular, revealing the temporal variability of regional SOC is the prerequisite for assessing regional soil quality evolution and soil carbon sequestration. To date, researchers have extensively studied the spatial variation of regional SOC. Associated studies have been conducted not only on the regional scale but also on global, national, provincial, and county scales (Batjes, 1996; Li et al., 2007; Qi et al., 2009; Mao et al., 2015). However, these studies are mainly focused on large-scale non-karst areas, with little research on the catchment scale (Wang et al., 2003). In particular, there are few studies reporting the spatial and temporal variation of SOC on a catchment scale in karst areas, and the existing studies are mainly focused on a specific factor (e.g., different vegetation types, land use patterns, and human disturbance) (Liu et al., 2014; Hui et al., 2014). The SOC content and its dynamics mainly depend on the equilibrium between the input and degradation of organic carbon in the soil (Pan et al., 2010). As their dynamic variations result in a very uneven distribution of SOC, all the factors that affect the accumulation and decomposition of SOC may influence the distribution of organic carbon (Camilli et al., 2016). The effects of different factors vary across diverse regions, and the spatial and temporal changes of environmental factors, soil properties, human disturbances, and their comprehensive factors are especially different during karst rocky desertification (Lal, 2004). Therefore, it is necessary to systematically study the dynamic changes of SOC and its influencing factors in karst areas to thoroughly understand the mechanism of soil carbon sequestration in these areas.

The karst ecosystem, which is unique, differs from non-karst areas in terms of topographic and landform features, hydrothermal conditions, site conditions of vegetation, and soil development levels, which results in small environmental capacity, weak resistance to interference, low stability, and poor self-adjustment ability of the karst area (Jiang et al., 2014). Due to the special binary hydrological structure and complex geological and geomorphological conditions, SOC shows a high level of spatial heterogeneity (Xu and Zhang, 2014; Zhang et al., 2014). In recent years, with rapid population growth and socio-economic development, excessive human activities have accelerated the process of rocky desertification, leading to significant changes in the SOC content (Yan et al., 2007). This inevitably has major impacts on soil properties and even the global carbon cycle and causes great difficulty in evaluating the dynamics of SOC stock and the carbon source/sink in these areas. Moreover, the soil has special mechanisms for the carbon cycle in karst areas (Lu et al., 2014). It is necessary to study the spatial and temporal variations of SOC content and its influencing factors in karst soil. However, current studies of SOC dynamics in such areas have mainly focused on various single factors (Yu et al., 2010). In a karst area, there are fragmented terrains, complex landforms, and different soil types, with sporadic and staggered distributions. The regolith is discontinuous, and bare rocks divide the soil mass into patches of varying sizes (Yu et al., 2010). The soil thickness is uneven, and large amounts of rock are exposed. These conditions contribute to the high spatial heterogeneity of SOC and the extremely complex spatial distribution of soil masses (Xie et al., 2015). The main objectives of the present study were:

a to reveal the spatial and temporal distribution characteristics of SOC in the Houzhai River Catchment

b to study the primary influencing factors of SOC in the catchment

c to provide feasible technical measures for estimating the SOC storage in karst soil.

2 Materials and methods

2.1 Study region

The study region (105º40′43″ – 105º48′2″E, 26º12′29″ – 26º17′15″N) is located in Puding County in the central part of Guizhou Province in southwestern China, including the three towns of Chengguan (CG), Maguan (MG) and Baiyan (BY), and it covers an area of 72 km^2. The elevation is between 1,223.4 and 1,567.4 m above sea level, and the air pressure is between 806.1 and 883.8 hpa. There are three major categories of soil: limestone soil, paddy soil and yellow soil. The vegetation (Table 1) includes *Cupressus funebris Endl*., *Populus Adenopoda* Maxim, *Toona sinensis* (A. Juss.) Roem., *Pyrus pyrifolia* Burm Nakai., and so on. The main crops are *Oryzasativa Oryzaglaberrima*, *Zea mays* Linn. Sp., *Glycine max* (Linn.) Merr, Helianthus annuus, etc. There are seven soil types in the study area: Xan Udic Fernalisols, Black Lithomorphic Isohumisols, Cab Udi Orthic Entisols, Cab High fertility Orthic Anthrosol, Cab Low fertility Orthic Anthrosols, Cab Medium fertility Orthic Anthrosols, Fec Hydragric Anthrosols.

Table 1 Geographic information of study area

Items	*Chengguan town*	*Maguan town*	*Baiyan town*
Precipitation (mm)	1,170.9	1,178.8	1,396.9
Temperature (ºC)	15.3	15.2	15.1
Frostless season (days)	301	289	292
Soil thickness (cm)	6 –> 100 (70.14)[a]	6 –> 100 (57.36)	5 –> 100 (58.76)
Major vegetations	*Tree species: Cupressus funebris Endl*, *Broussonetia papyrifera*, *Populus Adenopoda Maxim*. *Shrub species: Pyracantha floruneana*, *Itea ilicifolia*	*Tree species: Cupressus funebris Endl*, *Broussonetia papyrifera*, *Toona sinensis* (*A.Juss*.) *Roem*., *Celtis sinensis*. Shrub species: *Rosa cymosa*, *Zanthoxylum bungeanumMaxim*.	*Tree species: Cupressus funebris Endl*, *Platycarya longipes*, *Pyrus pyrifolia Burm Nakai*. Shrub species: *Pyracantha floruneana*, *Rosa cymosa*
Land uses (%)	Forestland: 11.84; bush forest: 15.67; cultivated land: 56.75; unused land: 5.85; construction land: 9.92	Forestland: 14.67; bush forest: 22.54; cultivated land: 49.84; unused land: 7.13; construction land: 5.82	Forestland: 16.24% bush forest: 18.33; cultivated land: 54.38; unused land: 4.91; construction land: 6.14

Note: ‘a’, the mean value of soil thickness.

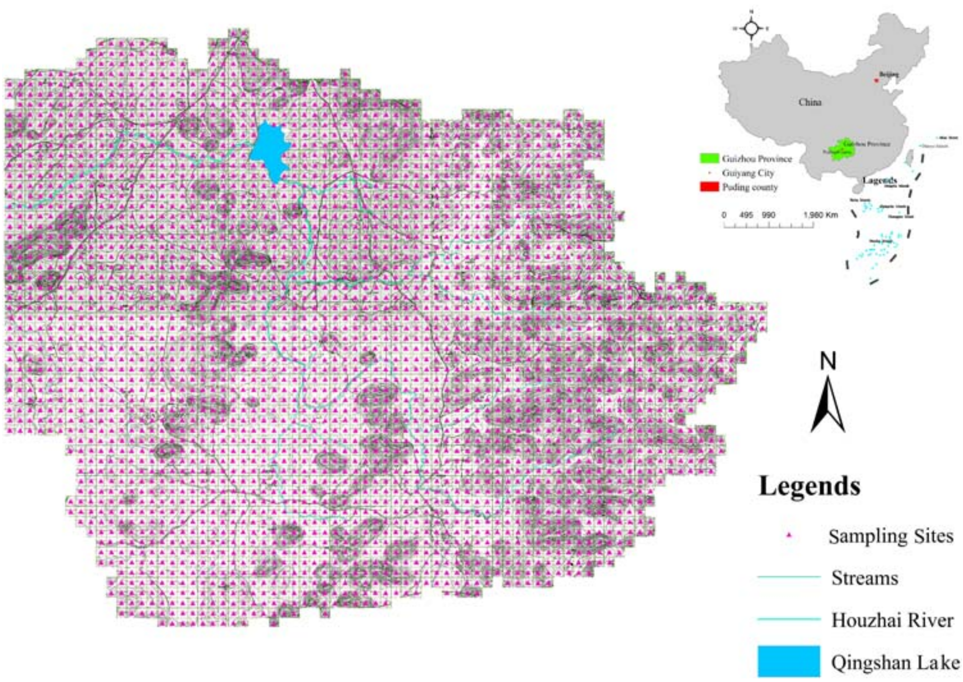
2.2 Data source

In this study, the basic data about the soil surface (0 to 20cm) in 1980 was mainly obtained from the results of the Second Soil Survey in Puding County. The spatial locations were determined according to the survey’s description on the sample locations, including the major landmarks and environmental actors surrounding the sampling points. Based on the principle of consistency and approximation, a total of 76 surface (0 to 20 cm) sampling points were selected to determine the spatial location. Data from the project team measured data in 2015; sampling plots were designed with a grid-based sampling method and a total of 3,180 sampling grids (150 m ×150 m). The sampling sites were defined as the centre of each sampling grid (shown in Figure 1). From March 2013 to January 2015, 2,755 soil profiles, consisting of 22,057 soil samples, were sampled in the designed sampling grids. The detailed information of sampling method could be found in literature (Zhang et al., 2018a, 2018b).

2.3 Sample treatment and determination analysis

Both of the soil samples collected in 1980 and 2015 were air dried, ground and prepared for the specimen as required by the laboratory. The SOC was determined via a potassium dichromate method. The soil acreage was calculated using GIS technology and surveying in the field. The bulk density was measured layer by layer from the top to the bottom of the soil profile via a cutting-ring method. The soil thickness was recorded in accordance with the type of ecological niche with an iron stick that was 60 or 120 cm long, depending on the soil mass at different depths. The bare rock rate was surveyed with a line-transect method. Due to the complex landscape in a karst area, it would be more accurate but less operable if the line transect was too long. Therefore, the length of the line transect was set at 10 m, and the grid cells with rock coverage were surveyed via tape measure.

Figure 1 The location of Houzhai catchment and the distribution of sample sites (see online version for colours)



2.4 Geostatistical analysis

A semi-variance function (h) was used to describe the spatial heterogeneity of the soil properties. The semi-variance function was used to obtain the variation of the semi-variance function value with an increase in the distance of the sample; the scatter plots were fitted with a Gaussian model and other theoretical models. When the soil properties met a two-order stationary assumption and the intrinsic hypothesis and when the sample size was large enough, the semi-variance theory variation function (h) formula was used. The semi-variance ($r(h)$) is as follows (Bergstrom et al., 1998):

$$r(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[Z(x_i) - Z(x_i + h) \right]^2 \tag{1}$$

where Z is the measured soil property, x is the sample location, and $N(h)$ is the number of pairs of locations separated by a lag distance h. The semi-variogram expresses the relationship between the semi-variance and the lag distance (*h*). It typically increases from a value at $h = 0$ (identified as the nugget) to a maximum value (identified as the sill). The SOCD of the spatial distribution pattern was determined using a kriging interpolation method with a spatial interpolation grid.

2.5 Data analysis

First, with different levels of SOC density data values for quality control, the numerical calculations of the distribution with the four percentile method was used to determine the extreme limit and extreme limit values to calculate the maximum and minimum value, mean value, standard deviation, and coefficient of variation. Second, a spatial autocorrelation analysis was conducted using the semi-variance function variables, which must meet the normal distribution data of non-normal distribution; this will cause proportional effects on the variance function and reduce the estimation precision.

Using CANOCO 5.0 statistical software for a single factor analysis of variance (ANOVA), a Pearson correlation analysis and stepwise regression analysis were conducted. A semi-variogram model, fitted with GS+ software, was used for ordinary kriging interpolation in ArcGIS 9.3 software, rendering an organic carbon density spatial distribution map.

3 Results and analysis

3.1 Statistical analysis of SOC content

As suggested by the statistical analysis of SOC contents in Houzhai catchmen (Table 2), the SOC content averaged 21.98 $g.kg^{-1}$ in 1980; the amplitude was 1.28 to 86.28 $g.kg^{-1}$, and the range was 85.00 $g.kg^{-1}$, with the maximum being 67.41 times greater than the minimum. The SOC content averaged 25.07 $g.kg^{-1}$ in 2015, with the maximum (119.11 $g.kg^{-1}$) being 73.98 times greater than the minimum (1.61 $g.kg^{-1}$), spanning a huge range of 117.50 $g.kg^{-1}$. The degree of variability was extremely high. From 1980 to 2015, the variation coefficient of SOC content ranged from 55.56 to 67.79%, which fell between 10% and 100%, showing a moderate degree of variation. Due to the small sample size in 1980, the coefficient in that year was large. There were significant differences in soil nutrient content between the two periods ($p < 0.05$). The three and a half decades saw a 3.09 g/kg (14.58%) increase in the average SOC content, indicating that human activities had a great impact on the SOC content in the catchment.

Table 2 Descriptive statistics characteristics of SOC content

Time	*Sample number*	*Range (g/kg)*	*Mean (g/kg)*	*Standard deviation (g/kg)*	*Variance (%)*	*Skewness*	*Kurtosis*	*ΔSOC (g/kg)*
1980	76	1.28~86.28	21.98a	14.90	67.79	1.09	2.04	-
2015	2,755	1.61~119.11	25.07b	13.93	55.56	1.85	4.94	3.09

Notes: Different letters in the same column mean significant difference ($p < 0.05$). ΔSOC is changes of SOC content from 1980 to 2015.

3.2 Spatio-temporal variability of SOC

The optimal semi-variance functions and their parameters of SOC in Houzhai catchment during the two periods were shown in Table 3. For the fitting accuracy, the residual standard deviation RSS was close to 0, and the determination coefficient R^2 was close to 1, suggesting that the semi-variance functions fitted in this study could truly reflect the spatial structure of SOC. The optimal theoretical model of the semi-variance functions for SOC in 1980 and 2015 was an exponential model. The soil available phosphorus and SOC nugget coefficient in both periods ranged from 0.50 to 0.75, indicating a moderate degree of spatial correlation. The nugget coefficient of in 2015 was higher than that in 1980, with the spatially correlated distance narrowing while the fractal dimension increasing. This implied that over the 35 years, the spatial structure and correlation of SOC in this region was reduced, the spatial distribution tended to be broken, and the spatial variation increasingly took place on smaller scales. Meanwhile, all the standardised Z values of the global Morans' I of each nutrient were greater than 2.58, indicating a significant spatial autocorrelation ($p < 0.01$). The features of spatial clustering were obvious, and the standardised Z values in 2015 were lower than those in 1980, showing that the spatial autocorrelation of SOC had been weakened over 35 years, which was consistent with the analysis of semi-variance function.

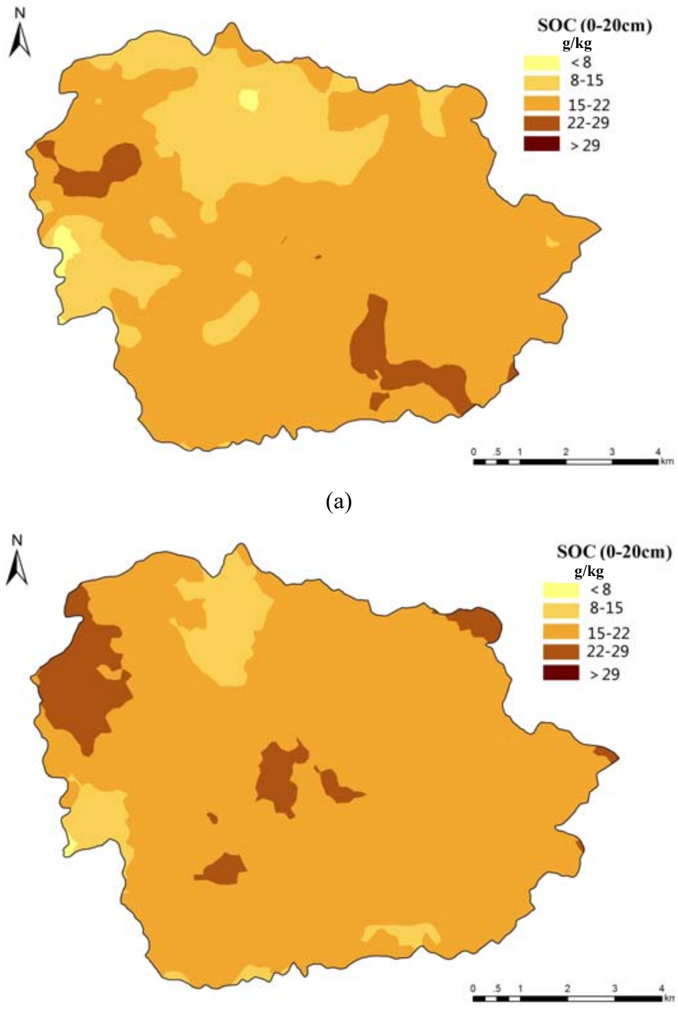
Table 3 Semi-variogram model of SOC and its parameter values

Time	*Model type*	*Nugget* (C_0)	*Sill* ($C_0 + C_1$)	$C_0/C_0 + C$	*Partial base value* (C_1)	*Range* (*m*)
1980	Index	0.127	0.231	0.549	0.04	2711.6
2015	Index	0.031	0.045	0.688	0.04	2126.3
Time	R^2	*RSS*	*Fractal dimension* (*FD*)		*Morans'I*	*Z*
1980	0.96	3.55×10^{-5}	1.74		0.11	6.27
2015	0.83	5.51×10^{-5}	1.96		0.15	5.85

3.3 Patterns of spatio-temporal variation of SOC

The maps of SOC spatial distribution in 1980 and 2015 (Figure 2) were plotted by using Kriging interpolation, to visually present the differences in spatio-temporal distribution of SOC between different times. Since SOC density is jointly affected by multiple factors, including geographical locations, climatic conditions, soil types, vegetation types, and land use modes, there can be a complex spatial variability. According to Figure 2, SOC in the studied region in both periods presented a pattern of high values in the east and low values in the west, high in the periphery and low in the centre, and high in the south and low in the north. In 1980, embedded or block distribution of SOC could be found, gradually decreasing from east to west, with small regions of high values in the east and low in the west, respectively. In 2015, the distribution of SOC became uniform, with small blocks of high value in the centre and west and a few embedded in the northeast. Thirty-five years ago, land reclamation seriously damaged the woodlands, leading to deteriorated ecosystem, severe rocky desertification, and huge loss of SOC. During 1980s and 90s, Guizhou provincial government began to control the desertification, by implementing ecological restoration projects, such as returning farmland to forest, artificial grass plantation, and artificial afforestation. Meanwhile, farmland management policies, such as conservation tillage, straw returning, and organic fertilisation, were adopted to maximise the SOC content. The joint effects of these initiatives tremendously changed the spatial distribution of SOC in the desertification regions. The overall trend demonstrated that through 35 years of development, the overall SOC content was significantly improved, except that only a few regions in the southeast saw a decline. Through field survey, it was found that industrial parks had been established near this area in the recent decades, and a large number of forests were cut down, leading to a huge loss of soil and a sharp drop of SOC content.

Figure 2 Temporal and spatial distribution of soc in the Houzai catchment, (a) the SOC spatial distribution of 1980 (b) the SOC spatial distribution of 2015 (see online version for colours)



(a)

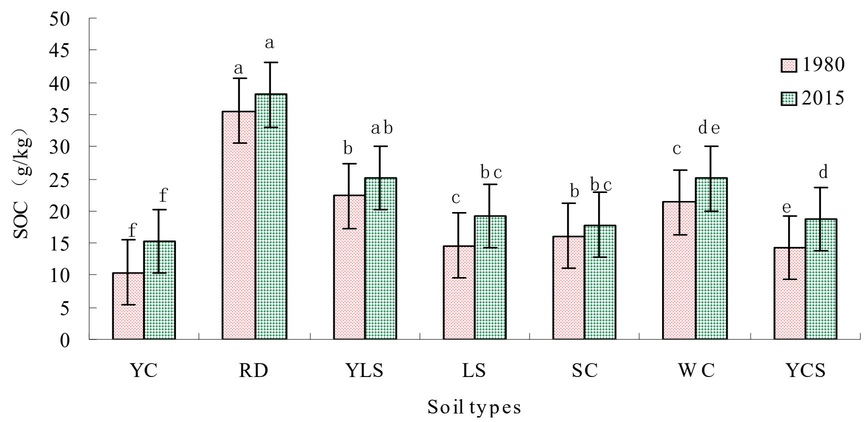
(b)

3.4 Influencing factors of SOC content

3.4.1 Soil type

Soil type is one of the key factors that influence the spatial variability of SOC content. The differences in farmland management measures, as well as soil formation and development, primarily constituted the differences in organic carbon content between different soil types. The results of variance analysis showed significantly difference in SOC content between different soil types ($p < 0.01$), so multiple comparisons were made with results as shown in Figure 3. The SOC contents in 1980 could be ranked as follows: Black Lithomorphic Isohumisols > Cab Udi Orthic Entisols > Cab Medium fertility Orthic Anthrosols > Cab Low fertility Orthic Anthrosols > Cab High fertility Orthic Anthrosols > Fec Hydragric Anthrosols > Xan Udic Fernalisols. Among them, the SOC content of Black Lithomorphic Isohumisolswas 35.58g.kg^{-1}, significantly higher than those of the other six types. The contents of the following Cab Udi Orthic Entisols (22.32 g.kg^{-1}) and Cab Medium fertility Orthic Anthrosols (21.32 g.kg^{-1}) were significantly lower. The content of Xan Udic Fernalisols (10.43 g.kg^{-1}) was the minimum, and Black Lithomorphic Isohumisolswas 3.41 times higher than it. According to SOC contents in 2015, Black Lithomorphic Isohumisolswas significantly higher than the other types; Cab Udi Orthic Entisols and Cab Low fertility Orthic Anthrosols were close to each other but still higher than the remaining four types; Xan Udic Fernalisols was evidently the lowest one. The SOC contents in 2015 could be ranked as follows: Black Lithomorphic Isohumisols > Cab Udi Orthic Entisols > Cab Medium fertility Orthic Anthrosols > Cab High fertility Orthic Anthrosols > Fec Hydragric Anthrosols > Cab Low fertility Orthic Anthrosols > Xan Udic Fernalisols. Among them, the content of Black Lithomorphic Isohumisols (38.07 g.kg^{-1}) was the highest, while that of Xan Udic Fernalisols (15.23 g.kg^{-1}) was the lowest, with the former being 2.50 times higher than the latter. The difference in average SOC contents between 2015 and 1980 was 1.70 to 4.80 g.kg^{-1}, and the SOC contents in 2015 were generally higher than those in 1980.

Figure 3 Difference of soc content under different soil types (see online version for colours)

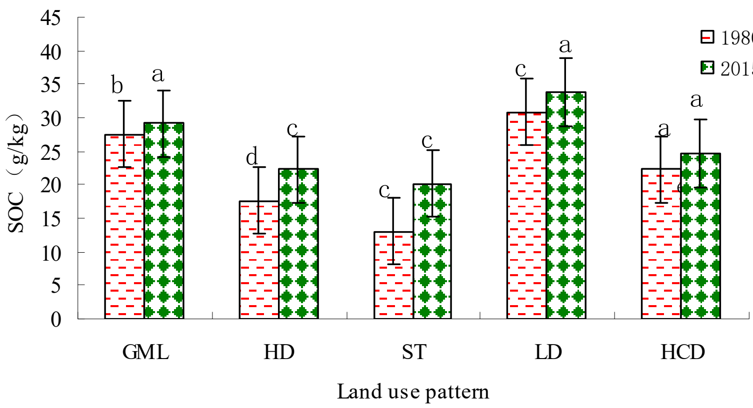


Note: YC = Xan Udic Fernalisols; RD = Black Lithomorphic Isohumisols; YLS = Cab Udi Orthic Entisols; LS = Cab high fertility Orthic Anthrosols; SC = Cab low fertility Orthic Anthrosols; WC = Cab medium fertility Orthic Anthrosols; YCS = Fec Hydragric Anthrosols.

3.4.2 Land utilisation

Under different land use modes, the SOC contents in 2015 were higher than those in 1980 (Figure 4). SOC contents in both periods could be similarly ranked as follows: woodland > shrubbery > unused grassland > dry field > paddy field. Among SOC contents in 1980, the maximum 30.80 $g.kg^{-1}$ was in woodland, while the minimum of 13.03 $g.kg^{-1}$ was in paddy field, with the former being 2.31 times higher than the latter. In both periods, paddy field had the maximum difference of 7.92 $g.kg^{-1}$ in SOC content, while shrubbery had the minimum of 1.62 $g.kg^{-1}$. In particular, woodland and shrubbery featured good vegetation coverage, abundant plant litter, minimal human disturbance, and thus the highest SOC contents. The second highest SOC content belonged to the unused land due to its relatively worse vegetation structure. For the dry and paddy fields grown with crops, the frequent human disturbances during farming would disturb the soil structure, resulting in larger soil permeability, stronger soil respiration, and accelerated decomposition rate of SOC. Combined with the loss of organic materials during crop harvest, SOC contents in these two types were low. Specifically, since some dry fields were located in mountains, while SOC content could be higher in mountains than in depressions, the SOC content of dry fields was higher than those of paddy fields.

Figure 4 Difference of soil organic carbon content under different land use patterns (see online version for colours)



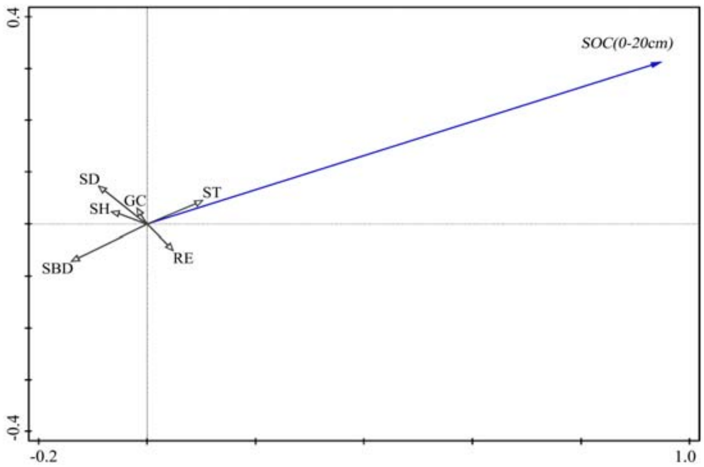
Note: GML = shrubbery; HD = dry field; ST = paddy field; LD = woodland; HCD = unused grassland.

3.4.3 Other environmental factors

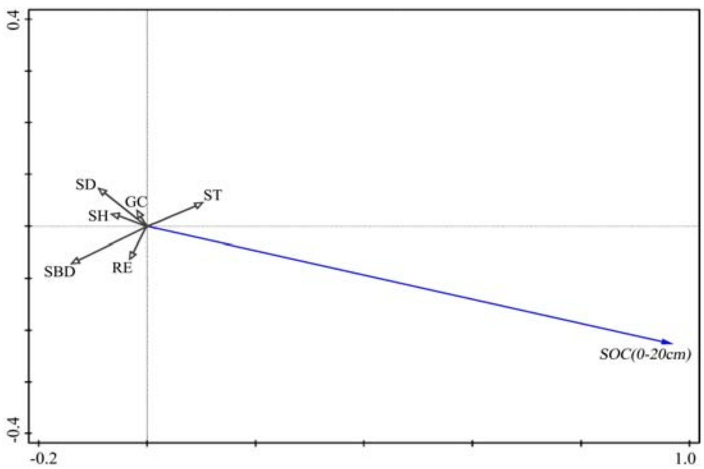
To reveal the interrelationship between SOC content and environmental factors during different periods, redundancy analysis (RDA) was performed on the major environmental factors, including soil depth, gravel content, slope orientation, slope gradient, soil bulk density, and rock exposure rate, of Houzhai catchment in 1980. As suggested by Table 4, the explanations of the first two axes were 82.3% and 11.1%, respectively, contributing to a cumulative rate of 93.4%. The SOC content and environmental coefficient of the first two axes were 0.912 and 0.418, respectively, indicating that the first two order axes could adequately reflect the correlation between SOC content and environmental factors in the studied area.

To further illustrate the impact of environmental factors on SOC content over 35 years, RDA was performed on the SOC content and environmental factors of Houzhai catchment in 2015. As suggested by Table 5, the explanations of the first axes were 79.6% and 12.3%, respectively, contributing to a cumulative rate of 91.9%. The SOC content and environmental coefficient of the first two axes were 0.907 and 0.316, respectively, indicating that the first two order axes could adequately reflect the correlation between SOC content and environmental factors in the studied area.

Figure 5 Two dimensional ordination diagram of soil organic carbon content and environmental factors in the watershed of Houzhai catchment, (a) dimensional ordination diagram of soil organic carbon content and environmental factors in the watershed of 1980 (b) dimensional ordination diagram of soil organic carbon content and environmental factors in the watershed of 2015 (see online version for colours)



(a)



(b)

Note: ST = soil thickness; GC = gravel content; SD = slope orientation; SH = slope gradient; SBD = soil bulk density; RE = rock exposure rate.

Table 4 The RDA results of SOC content and environmental factors in 1980 years

Sort axis	*Characteristic value*	*Cumulative contribution rate*	*Correlation coefficient*	*Canonical eigenvalue*	*Total eigenvalue*
Axis I	0.823	82.3	0.912	0.943	1.000
Axis II	0.111	93.4	0.418		
Axis III	0.042	97.6	0.113		
Axis IV	0.024	100.0	0.000		

Table 5 The RDA results of SOC content and environmental factors in 2015 years

Sort axis	*Characteristic value*	*Cumulative contribution rate*	*Correlation coefficient*	*Canonical eigenvalue*	*Total eigenvalue*
Axis I	0.796	79.6	0.907	0.913	1.000
Axis II	0.123	91.9	0.316		
Axis III	0.048	96.7	0.158		
Axis IV	0.033	100.0	0.000		

To visually present the impact of environmental factors on SOC content, the two were sorted and analysed (Figure 5). The length of the connected line of environmental factors denotes the correlation between SOC content and environmental factors. Longer connection means greater correlation, and smaller angle implies higher correlation. When the angle is less than 90º, it means that the environmental factors are positively correlated with the organic carbon density; otherwise, they are negatively correlated. The smaller angle in the same direction indicates higher correlation between the organic carbon density and environmental factors. As suggested by the figure, for 1980, the angle between SOC and soil depth was small in the same direction, indicating a strong positive correlation between the two. SOC content was positively correlated with soil depth and gravel content, while organic carbon density was negatively correlated with slope orientation, slope gradient, soil bulk density, and rock exposure rate. The influences of environmental factors on SOC content were ranked as follows: soil depth > gravel content > slope orientation > slope gradient > rock exposure rate > soil bulk density. This indicated that soil depth, gravel content, and slope orientation were the key factors that affect SOC content of Houzhai catchment in 1980. For 2015, SOC content was positively correlated with soil depth and rock exposure rate, but negatively correlated with gravel content, slope orientation, slope gradient, and soil bulk density. The influences of environmental factors on SOC content were ranked as follows: rock exposure rate > soil bulk density > soil depth > slope orientation > gravel content >slope gradient >. That is to say, rock exposure rate, soil bulk density and soil depth, were the key factors that affect SOC content of Houzhai catchment in 2015.

4 Discussions

4.1 Spatial and temporal variability of SOC in a small karst catchment

The variation of SOC content on a large regional scale is greatly influenced by climate, soil parent material, and hydrological conditions (Persson and Stadenberg, 2010). In the range of a small catchment, the variation of SOC content is affected not only by climate and parent material but also by other factors such as soil type and land use patterns (Wei et al., 2014). Together, the special physicochemical properties of carbonates and the landform features formed in them result in a shallow soil layer and high rock coverage in the karst area (Zheng et al., 2012). The regolith is often separated into discontinuous patches, and the soil physicochemical properties exhibit high spatial heterogeneity (Zhou et al., 2010). The Houzhai catchment is a typical small plateau karst catchment with complex and diverse topography and landforms; the spatial distribution patterns of various topography and landforms are extremely complicated. In this catchment, the SOC in the soil samples varies between 0.13 and 128.74 $g.kg^{-1}$, with a wide range of 128.61 $g.kg^{-1}$, and the maximum is 990.31 times the minimum. The range of SOC content in the surface layer is generally wide. The SOC content in different soil layers and the 10 cm SOC density have large coefficients of variation, showing high variability. These features reflect the high spatial heterogeneity of SOC in this catchment.

The spatial structure and hierarchical features are important attributes of the ecological system; if there is no spatial structure, the ecological system does not function (Wang et al., 2009). Regardless of the regional or middle and small scales, spatial variation of soil properties commonly exists (VandenBygaart et al., 2004). The geostatistical method is a powerful tool to quantitatively study the above problem. The spatial distribution of SOC content includes two aspects: one is the change with soil depth in the vertical direction, and the other is the change with different geological positions in the horizontal direction. In the Houzhai catchment, the SOC content overall shows a fragmented patchy spatial distribution pattern. This occurs because there is a staggered distribution of peak forests, peak clusters, and small depressions in the upper catchment. The SOC content is higher in the peak forests and peak clusters, while it is lower in the depressions with thick soil layers. The karst area has a shallow soil layer, a discontinuous regolith, and an irregular distribution of various soil types. As the thickness of the soil layer varies, the SOC content shows a fragmented patchy distribution. With increasing soil depth, the SOC content decreases, and there is no soil where the bedrock is reached in shallow soil areas; thus, the level of patch fragmentation increases with increasing soil depth. The soil layer is generally shallow and thin in the peak forests and peak clusters in the upper catchment, and there are few high SOC areas below 80 cm. The few high SOC areas are mainly concentrated in the middle and lower parts of the catchment.

The factors that affect SOC content are complex. In addition to spatial factors, temporal factors are also important for the SOC content and its changes (Rodriguez-Murillo, 2001). As large areas of forests had been reclaimed into slope cropland before the 1990s, the SOC content was greatly reduced. Since the 1990s, grain-for-green and forest conservation measures have been implemented (Xiong et al., 2007). Thus, in recent years, the vegetation cover has greatly increased, and a thick soil layer has developed in the forestland. Rotten dry branches and fallen leaves on the land surface enter the soil and thereby increase the SOC content. This is consistent with the results of previous research. Meanwhile, the karst area is less developed, and the farmland area is relatively small. Agricultural inputs by human activities, such as applications of straw and farmyard manure, increase the most active factors of SOC content. The farmland soil directly receives a large amount of exogenous organic and inorganic materials, further improving the rate, quantity, and quality of SOC inputs. Under the same hydrothermal conditions, the application of farmyard manure mainly affects the crop yield and the aboveground and underground biomass, indirectly participating in soil carbon sequestration. The aboveground biomass mainly refers to straw and stubble. Straw usually enters the surface soil by application to the field and rapidly decomposes into sugars, starch, and fat, increasing the SOC source. Stubble increases the soil carbon storage under the action of microbes present in farmyard manure. The rich microbial life in farmyard manure is conducive to the conversion of exogenous organic matter into humus, for instance, promoting straw decomposition and improving the SOC pool.

4.2 Factors influencing the spatial and temporal variation of SOC in a small karst catchment

The input of organic carbon is mainly derived from dry branches, fallen leaves, and dead roots of plants (Homann et al., 2007). The output of organic carbon is mainly derived from the decomposition of organic matter by soil microorganisms. All factors that can affect SOC accumulation and decomposition may influence the distribution of SOC in the catchment (Tiessen and Stewart, 1983). In general, the level of SOC storage is affected by a combination of various natural and human factors, such as changes in vegetation, climate, soil properties, and land use patterns (Martel and Paul, 1974). The effect of vegetation types on SOC is mainly related to the quality and quantity of litter and the action of roots, which varies with vegetation type. Different quantities and qualities of SOC can be formed under the action of soil organisms and microorganisms, affecting the accumulation and turnover of SOC. Research shows that forest vegetation types and land use patterns have significant effects on litter yield and decomposition rates under the same climatic conditions, resulting in differences in SOC density among different forest vegetation types. In the present study, the results of SOC density in the Houzhai catchment show that the 20 cm soil carbon content for different vegetation types follows the order forest > shrub > grassland > dryland > paddy field. The possible reason is that numerous dry branches and fallen leaves are accumulated on the surface of shrub land and the litter is more easily decomposed into organic matter, which is conducive to the accumulation of soil organic matter and thus results in the highest SOC density.

The soil type reflects the differences of soil parent material, topography, and hydrothermal conditions. Various soil types have different pedogenetic processes, and the SOC density also differs. In 1980, the SOC content followed the order Black Lithomorphic Isohumisols > Cab Udi Orthic Entisols > Cab Medium fertility Orthic Anthrosols > Cab Low fertility Orthic Anthrosols > mud > Fec Hydragric Anthrosols > Xan Udic Fernalisols; the SOC content of Black Lithomorphic Isohumisols was significantly higher than those of the remaining six soil families. In 2015, the SOC content followed the order Black Lithomorphic Isohumisols > Cab Udi Orthic Entisols > Cab Medium fertility Orthic Anthrosols > Cab High fertility Orthic Anthrosols > Fec Hydragric Anthrosols > Cab Low fertility Orthic Anthrosols > Xan Udic Fernalisols; the SOC content of Black Lithomorphic Isohumisols was 2.50 times that of Xan Udic Fernalisols. The SOC content of calcareous soil was commonly higher than those of paddy soil and Xan Udic Fernalisols. This relationship occurred because the calcareous soil is developed from carbonate rocks, with less soil-forming material and low soil-forming rates. Meanwhile, the karst area suffers serious soil and water loss, and the soil layer is relatively shallow. Moreover, the calcareous soil is rich in calcium and magnesium ions, so it can easily bind to soil organic matter to form stable humus calcium, resulting in abundant organic carbon. The SOC content of Xan Udic Fernalisols ranked the lowest. This is because Xan Udic Fernalisols is an acidic soil in which calcium and magnesium are considerably leached, which is unfavorable for the formation of humus calcium. Black Lithomorphic Isohumisols and terra gialla, two natural soils of peak forest and peak cluster, had higher SOC content than the remaining seven cultivated soils, while the SOC content of Black Lithomorphic Isohumisols was higher than that of terra gialla. The Black Lithomorphic Isohumisols is mostly distributed on the tops of relatively high peaks, with a sporadic discontinuous regolith and shallow soil layers, whereas Cab Udi Orthic Entisolsis distributed beneath Black Lithomorphic Isohumisols and often exposed at the foot of slopes and in depressions. Most of the Cab Udi Orthic Entisolsis agricultural land with a relatively thick soil layer; thus, the SOC content of Cab Udi Orthic Entisolsis lower compared to that of Black Lithomorphic Isohumisols.

The correlation analysis between SOC density and major environmental factors in Houzhai catchment showed that gravel content, slope, aspect, rock coverage, and soil depth had significant effects on SOC content. In particular, the greatest effects were observed for soil thickness, gravel content, and rock coverage. In the small plateau karst catchment, the soil is developed in limestone, dolomite, and their interlayers. The bedrock crops out widely, with complex and diverse niche types and discontinuous shallow soil layers. The soil is characterised by a scattered distribution and varying thickness. Based on a comprehensive analysis, we consider that the SOC content in the Houzhai catchment is a result of the interaction of environmental factors and human activities. The effects of environmental factors have direct and indirect components. The direct component is that the environmental factors directly affect the input, degradation rate, and accumulation rate of SOC. For instance, the rate of soil organic matter loss in surface runoff would change along with the changes of slope. With different aspect, slope, and elevation, the microclimate environment (e.g., humidity and temperature) is different, and there exist differences in vegetation type, growth conditions, and soil organic matter degradation rate. Rock coverage directly affects the soil continuity and thickness, while rock coverage and soil thickness directly determine total soil mass. The indirect component is that these environmental factors potentially affect land use planning by humans.

4.3 Potential solutions of SOC sink in karst catchment

According to the present study, the affect of spatio-temporal variability of SOC in Houzhai catchment included the soil types, land utilisation, and major environmental factors. Soil types and environmental conditions are not easily be improved by human ability. However, major attention should be paid on land utilisation. Some previous indicated that SOC content in Karst regions is closely associated with land use (Huang et al., 2017, 2008). The SOC contents in top soils of different land uses of Karst catchment follow the order: shrub lands > arbour-shrub mixed forest lands > shrub grass lands > arbour forest lands > abandoned lands and uncultivated lands > grasslands > paddy lands > garden lands > arid lands and sloping croplands (Huang et al., 2017). Therefore, it may be a feasible way to increase SOC content and storage in Karst region by managing the land use scientifically (Huang et al., 2018). In southwest China, local governments are trying improve the ecological quality for development of tourism industry. Land use situation will be reformed. Though, much work could be done in this process to cope with land use reform and carbon sink.

5 Conclusions

Based on present study, the following conclusions were obtained:

a Throughout the entire catchment, the SOC content averaged 21.98 $g.kg^{-1}$ in 1980 and 25.07 $g.kg^{-1}$ in 2015, with an increase of 3.09 $g.kg^{-1}$. Over the 35 years, the spatially correlated distance was narrowing, the fractal dimension was obviously increasing, the spatial structure and correlation was weakening, and the spatial distribution tended to be broken, leading to reduced spatial autocorrelation of SOC.

b SOC in both periods presented a pattern of high values in the east and low values in the west, high in the periphery and low in the centre, and high in the south and low in the north. Through 35 years of development, the overall SOC content was significantly improved, except that only a few regions in the southeast saw a decline.

c The SOC contents in 1980 were ranked as follows: Black Lithomorphic Isohumisols > Cab Udi Orthic Entisols > Cab Medium fertility Orthic Anthrosols > Cab Low fertility Orthic Anthrosols > Cab High fertility Orthic Anthrosols > Fec Hydragric Anthrosols > Xan Udic Fernalisols.

The SOC contents in 2015 were ranked as follows: Black Lithomorphic Isohumisols > Cab Udi Orthic Entisols > Cab Medium fertility Orthic Anthrosols > Cab High fertility Orthic Anthrosols > Fec Hydragric Anthrosols > Cab Low fertility Orthic Anthrosols > Xan Udic Fernalisols. It may be a feasible way to increase the SOC storage in the studied catchment by scientific management of land use.

Acknowledgements

This work was financially supported by the National Key Basic Research Development Program (Grant No. 2013CB956702);the first class discipline construction project in Guizhou Province (GNYL [2017]007); regional fund of the National Natural Science Foundation of China [Grant No. 41561075]; and 100 High Level Innovating Project [Grant No. QKHRC-2015-4022] and The Team Construction of Science and Technology Innovation (No. QKH-RCTD (2015) 4012).

References

Batjes, N.H. (1996) 'Total carbon and nitrogen in the soils of the world', *European Journal of Soil Science*, Vol. 47, No. 2, pp.151–163.

Bellamy, P.H., Loveland, P.J., Bradley, R.I., Lark, R.M. and Kirk, G.J. (2005) 'Carbon losses from all soils across England and Wales 1978–2003', *Nature*, Vol. 437, No. 7056, pp.245–248.

Bergstrom, D.W., Monreal, C.M., Millette, J.A. and King, D.J. (1998) 'Spatial dependence of soil enzyme activities along a slope', *Soil Science Society of America Journal*, Vol. 62, No. 5, pp.1302–1308.

Bohn, H.L. (1982) 'Estimate of organic carbon in world soils', *Soil Science Society of America Journal*, Vol. 40, No. 3, pp.1118–1119.

Camilli, B., Dell'Abate, M.T., Mocali, S., Fabiani, A. and Dazzi, C. (2016) 'Evolution of organic carbon pools and microbial diversity in hyperarid anthropogenic soils', *Journal of Arid Environments*, Vol. 124, No. 1, pp.318–331.

Homann, P.S., Kapchinske, J. and Boyce, A. (2007) 'Relations of mineral-soil C and N to climate and texture: regional differences within the conterminous USA', *Biogeochemistry*, Vol. 85, No. 3, pp.303–3l6.

Huang, X.F., Wang, S.J. and Zhou, Y.C. (2018) 'Soil organic carbon change relating to the prevention and control of rocky desertification in Guizhou Province, SW China', *International Journal of Global Warming*, in press.

Huang, X.F., Zhou, Y.C. and Zhang, Z.M. (2017) 'Distribution characteristics of soil organic carbon under different land uses in a karst rocky desertification area', *Journal of Soil and Water Conservation*, in Chinese, Vol. 31, No. 5, pp.215–221.

Hui, L.L., Shao, J.A., Ci, E. and Xie, D.T. (2014) 'Farmland SOC dynamics and its impact factors at Zunyi County in Guizhou in the recent 30 years', *Journal of Natural Resources*, in Chinese, Vol. 29, No. 4, pp.653–665.

Jiang, Z.C., Lian, Y.Q. and Qin, X.Q. (2014) 'Rocky desertification in Southwest China: impacts, causes, and restoration', *Earth-Science Reviews*, Vol. 132, No. 3, pp.1–12.

Lal, R. (2004) 'Carbon sequestration impacts on global climate change and food security', *Science*, Vol. 304, No. 5677, pp.1623–1627.

Li, Z.P., Han, F.X., Su, Y., Zhang, T.L., Sun, B., Monts, D.L. and Plodinecb, M.J. (2007) 'Assessment of soil organic and carbonate carbon storage in China', *Geoderma*, Vol. 138, Nos. 1–2, pp.119–126.

Liu, Z.T., Liu, C.Q., Lang, Y.C. and Hu, D. (2014) 'Dissolved organic carbon and its carbon isotope compositions in hill slope soils of the karst area of southwest China: implications for carbon dynamics in limestone soil', *Geochemical Journal*, Vol. 48, No. 3, pp.277–285.

Lu, X.Q., Todab, H., Ding, F.J., Fang, S.Z., Yang, W.X. and Xua, H.G. (2014) 'Effect of vegetation types on chemical and biological properties of soils of karst ecosystems', *European Journal of Soil Biology*, Vol. 1, No. 3, pp.49–57.

Mao, D.H., Wang, Z.M., Li, L., Miao, Z.H., Ma, W.H., Song, C.C., Ren, C.Y. and Jia, M.M. (2015) 'Soil organic carbon in the Sanjiang Plain of China: storage, distribution and controlling factors', *Biogeosciences Discussions*, Vol. 149, No. 3, pp.1635–1645.

Martel, Y.A. and Paul, E.A. (1974) 'Effects of cultivation on the organic matter of grassland as determined by fraction and radiocarbon dating', *Canadian Journal of Soil Science*, Vol. 54, No. 4, pp.419–426.

Pan, G.X., Xu, X.W., Smith, P., Pan, W.N. and Rattan, L. (2010) 'An increase in topsoil SOC stock of China's croplands between 1985 and 2006 revealed by soil monitoring', *Agriculture, Ecosystems and Environment*, Vol. 136, No. 1, pp.133–138.

Persson, H. and Stadenberg, I. (2010) 'Fine root dynamics in a Norway spruce forest (Picea abies (L.) Karst) in eastern Sweden', *Plant and Soil*, Vol. 330, No. 1, pp.329–344.

Qi, Y.B., Darilek, J.L., Huang, B., Zhao, Y.C., Sun, W. and Gu, Z.Q. (2009) 'Evaluating soil quality indices in an agricultural region of Jiangsu Province, China', *Geoderma*, Vol. 149, Nos. 3–4, pp.325–334.

Rodriguez-Murillo, J.C. (2001) 'Organic carbon content under different types of land use and soil in peninsular Spain', *Biology & Fertility of Soils*, Vol. 33, No. 1, pp.53–61.

Tiessen, H. and Stewart, J.W. (1983) 'Particle-size fractions and their use in studies of soil organicmatter. II. Cultivation effects on organic matter composition in size fractions', *Soil Science Society of America Journal*, Vol. 47, No. 3, pp.509–514.

VandenBygaart, A.J., Gregorich, E.G., Angers, D.A. and Stoklas, U.F. (2004) 'Uncertainty analysis of soil organic carbon stock change in Canadian cropland from 1991 to 2001', *Global Change Biol*,. Vol. 10, No. 6, pp.983–994.

Wang, H.J., Shi, X.Z., Yu, D.S., Weindorf, D.C., Huang, B., Sun, W.X., Ritsema, C.J., Milne, E. (2009) 'Factors determining soil nutrient distribution in a small-scaled watershed in the purple soil region of Sichuan Province, China', *Soil and Tillage Research*, Vol. 105, No. 2, pp.300–306.

Wang, S.Q., Liu, J.Y. and Yu, G.R. (2003) 'Error analysis of estimating terrestrial soil organic carbon storage in China', *Chinese Journal of Applied Ecology*, in Chinese, Vol. 14, No. 5, pp.797–802.

Wei, Y., Jiang, P.k., Zhou, K., Li, G.M., Wu, Y.F. and Du, J.S. (2014) 'The carbon storage in moso bamboo plantation and its spatial variation in Anji County of southeastern China', *Journal of Soils and Sediments*, Vol. 14, No. 2, pp.320–329.

Xie, L.W., Zhong, J., Chen, F.X., Li, J.J. and Wu, L.C. (2015) 'Evaluation of soil fertility in the succession of karst rocky desertification using principal component analysis', *Solid Earth*, Vol. 6, No. 2, pp.3333–3359.

Xiong, K.N., Yuan, J.Y. and Fang, Y. (2007) *Atlas for Integrate Protection of Karst Stony Desertification in Guizhou Province*, Guizhou People's Publishing House, Guiyang, in Chinese.

Xu, E.Q. and Zhang, H.Q. (2014) 'Characterization and interaction of driving factors in karst rocky desertification: a case study from Changshun, China', *Solid Earth*, Vol. 5, No. 2, pp.1329–1340.

Yan, H.M., Cao, M.K., Liu, J.Y. and Tao, B. (2007) 'Potential and sustainability for carbon sequestration with improved soil management in agricultural soils of China', *Agriculture, Ecosystems and Environment*, Vol. 121, No. 4, pp.325–335.

Yu, G.R., Li, X.R., Wang, Q.F. and Li, S. (2010) 'Carbon storage and its spatial pattern of terrestrial ecosystem in China', *Journal of Resources and Ecology*, Vol. 1, No. 2, pp.97–109.

Zhang, J., Wang, X.J., Wang, J.P. and Wang, W.X. (2014) 'Carbon and nitrogen contents in typical plants and soil profiles in Yanqi Basin of Northwest China', *Journal of Integrative Agriculture*, Vol. 13, No. 3, pp.648–656.

Zhang, Z., Zhou, Y., Wang, S. and Huang, X. (2018b) 'The soil organic carbon stock and its influencing factors in a mountainous karst basin in P.R. China', *Carbonates & Evaporites*, Vols. 1–13, DOI: 10.1007/s13146-018-0432-3.

Zhang, Z.M., Zhou, Y.C., Wang, S.J. and Huang, X.F. (2018a) 'Spatial distribution of stony desertification and key influencing factors on different sampling scales in small karst watersheds', *International Journal of Environmental Research & Public Health*, Vol. 15, No. 4, p.743.

Zheng, H., Su, Y.R., He, X.Y., Hu, L.N., Wu, J.S., Huang, D.Y., Li, L. and Zhao, C.X. (2012) 'Modified method for estimating organic carbon density of discontinuous soil in peak-karst regions in Southwest China', *Environmental Earth Sciences*, Vol. 67, No. 6, pp.1743–1755.

Zhou, Y.C., Wang, S.J., Lu, H.M., Xie, L. and Xiao, D. (2010) 'Forest soil heterogeneity and soil sampling protocols on limestone outctops: example from SW China', *Acta Carsologica*, Vol. 39, No. 1, pp.117–226.