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Potential for soil carbon sequestration of eroded areas in subtropical China

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ABSTRACT

Soil plays an important role in the global carbon cycle, and carbon sequestration in soil is important for mitigating global climate change. Historically, soil erosion led to great reductions of soil organic carbon (SOC) storage in China. Fortunately, with the economic development and remarkably effective soil erosion control measures in subtropical China over the past 20 years, soil erosion has been greatly decreased. As a result, soil organic carbon sequestration has gradually increased due to the rapid recovery of vegetation in the area. However, little information exists concerning the potential of soil carbon sequestration in the area. This paper introduces a case study in Xingguo County, Jiangxi Province, China, which used to be a typical area with significant soil loss in subtropical China. This work represents a systematic investigation of the interrelations of carbon sequestration potential with soil erosion types, altitudes, soil types and soil parent materials. In this study, 284 soil samples were collected from 151 sampling sites (51 are soil profile sites) to determine soil physicochemical properties including organic carbon content. Soil organic carbon distribution maps of the surface layer (0–20 cm) and whole profile (0–100 cm) were compiled by linking soil types to the polygons of digital soil maps using GIS. Assuming that SOC was lost following the destruction of native vegetation, these lands hold great promise for potentially sequestering carbon again. The potential of soil carbon sequestration in the study area was estimated by subtracting the organic carbon status in eroded soils from that in non-eroded soils under undisturbed forest. Results show that the potential of SOC in the surface layer is 4.47 Tg C while that in the whole profile is 12.3 Tg C for the entire county. The greatest potential for carbon sequestration (3.72 Tg C) is found in severely eroded soil, while non-eroded soil has the smallest potential. Also, soil carbon sequestration potential decreases with increasing altitude. Soils at altitudes of <300 m show the greatest potential (5.01 Tg C), while those of >800 m have the smallest potential (0.25 Tg C). Among various soil types, red earths (Humic Acrisols) have the greatest potential of carbon sequestration (5.32 Tg C), and yellow earths (Ferralic Cambisols) have the smallest (0.15 Tg C). As for soils derived from various parent materials, soils derived from phyllite possess the greatest carbon sequestration potential, and soils from Quaternary red clays have the smallest.

1. Introduction

Atmospheric concentrations of CO_2 and other greenhouse gases have increased considerably from the early 1800s to the present day mostly due to fossil-fuel combustion, and are projected to accelerate during this century. Such increases are believed to potentially cause unprecedented regional and global climatic and environmental changes (IPCC, 1995; Palumbo et al., 2004; Follett et al., 2005). Soil is an important component of the global carbon (C) cycle. Restoring and enhancing soil quality can increase soil organic carbon (SOC) content and soil productivity, and may partially mitigate the greenhouse effect (Upadhyay et al., 2005; Bayer et al., 2006; Yang et al., 2008; Zhang et al., 2008).

Recognizing the importance of SOC dynamics in alleviating the rate of atmospheric CO_2 increase, the potential to sequester soil carbon has been studied worldwide. The global potential of SOC sequestration through the adoption of conservation tillage with cover crops and crop residue mulch amounted to 0.9 ± 0.3 Pg C yr^{-1}, with a cumulative potential of soil C sequestration over 25–50 years as high as 30–60 Pg (Lal, 2004). These assessments contradict the estimate by Schlesinger and Andrews (2000) who argued that large increases in the soil C pool seemed unlikely. If other factors remain constant, the potential of SOC sequestration follows a progression of: degraded soil and desertified ecosystems > crop land > grazing lands > forest and permanent cropland (Lal et al., 2000). Smith et al. (2000) assessed a range of options for C mitigation in European agricultural soils, and

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estimated the SOC sequestration potential to be 56 Tg C yr^{-1}. Freibauer et al. (2004) estimated that agricultural soils in 15 European Union member countries (EU-15) could realistically sequester up to 16–19 Tg C yr^{-1} during the first Kyoto commitment period (2008–2012). Palumbo et al. (2004) claimed that degraded lands in the United States could sequester approximately 11 Pg C over 50 years.

To reduce the rate of atmospheric CO_2 increase, a number of research studies have been conducted in China on the potential of soil carbon sequestration. Lal (2002) estimated that the accumulative potential of soil C sequestration would increase, at an average rate of 224 Tg yr^{-1}, to 11 Pg by 2050 in China. Duan et al. (2001) proposed that the potential soil C sequestration would increase by 236 Tg C in ~40 years due to reversing desertification. Feng et al. (2001) believed that desertification control would help to sequester 533 Tg C over the past 40 years. Paddy soils in China might have a potential SOC sequestration of 0.7 Pg under present conditions (Pan et al., 2003).

However, China is also one of the countries suffering greatly from severe soil loss with eroded lands totaling 356 M ha, annual soil loss of >5 billion tons, and 5% the total loss (60 billion tons) worldwide (Ministry of Water Resources in China, 2002). Xingguo County, a typical county in the subtropical area, is one of the severely eroded areas in China with maximum soil loss >100 t ha^{-1} yr^{-1}. The county, once called the "red desert", was typical of erosion in hilly subtropical China. The area was characterized by extraordinary erosion (huge soil loss), vast eroded areas, and ultra-severe erosion damage. Fortunately, things have been greatly improved since the county was designated as one of the eight crucial regions of national soil erosion control in 1982. With the recovery of vegetation and a reduction of soil loss, more organic carbon has been sequestered in soil and the potential for carbon sequestration has been enhanced (Shi et al., 2008).

Soil organic carbon research in Xingguo County was conducted by Cheng et al. (2004) who predicted the spatial distribution of SOC in the surface layer and Zhang et al. (2004) who described the spatial and temporal evolution of SOC stock in an area of about 600 km^2. Although this research laid a foundation for estimating the potential capacity of soil carbon sequestration in China, there is no information concerning the maximum potential for soil C sequestration. Furthermore, uncertainty remains because some existing estimates were based solely on data from a few stationary in-plot experiments. This paper addresses the potential of soil carbon sequestration in Xingguo County, China by comparing the organic carbon status in eroded soils with that in non-eroded soils under undisturbed forest, and investigating the interrelationships between soil erosion types, altitude, soil types, parent materials and soil carbon sequestration.

2. Materials and methods

2.1. Research area

Xingguo County lies in the central-southern part of Jiangxi Province, China at 115°01′–115°51′E, 26°03′–26°41′N, and covers a total area of 3210 km^2 (Fig. 1). Geomorphologically, the county consists of hills, basins and high, steep, clustered mountains standing in its eastern, northern and western parts. To the south, a basin with gently undulated hills in its center forms a terrain declining from its eastern, northern and western parts towards its center and south. The county is composed of 70% mountains, 10% water bodies, 10% cropland, and 10% roads or residential areas. Its ground elevation varies from 100 to 1204 m above sea level. Subtropical humid monsoon climate prevails in the county, with an annual mean air temperature of 18.9 °C, and abundant annual rainfall (1538.7 mm). The rainy season lasts from April to June when intensive rainfall and frequent storms account for over 50% of the annual precipitation. However, when autumn comes, it is rather dry. Subtropical evergreen broad-leaf forests were once the dominant primary vegetation in this zone, but few remain after widespread destruction. Secondary forests coexist with sparse forest, grassland, and some barren land (Xie, 2003; Huang and Zhong, 1991). Red earths (Humic Acrisols) prevail in the county, while brownish red earth (Haplic Alisols), yellowish red earth (Profondic Alisols), yellow earths (Ferralic Cambisols), purple soils (Eutric-Rhodic Cambisols), paddy soils (Luvic-Hydragric Anthrosols), and meadow soils (Stagnic Umbrisols) are also found in this area (Shi et al., 2004). The parent materials in Xingguo are mainly phyllite, granite, red sandstone, purple shale, and Quaternary red clays, which strongly affect soil properties.

2.2. Soil sampling and chemical analysis

A total of 151 sampling sites were located via GPS at the end of 2001 in an effort to integrate consideration of soil types, erosion status, and other information. At 51 of the sampling sites, complete profiles were sampled. At the remaining sites, surface soil samples

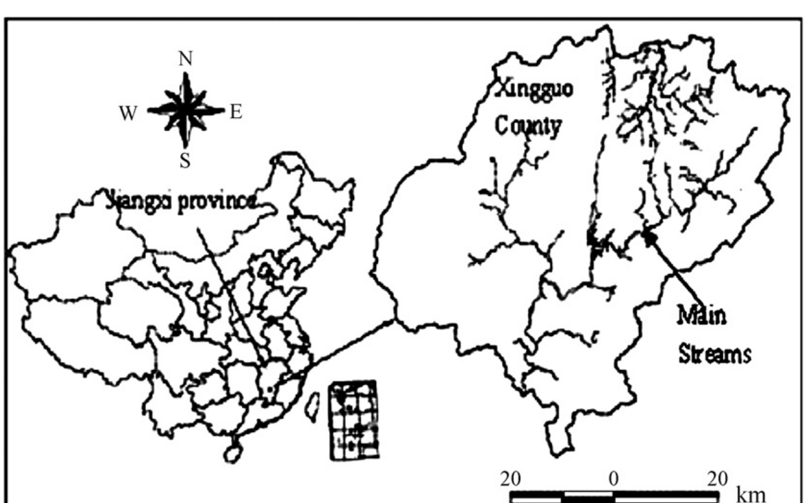

Fig. 1. Location of Xingguo County, Jiangxi Province, China.

(0–20 cm) were collected. Among the 151 sites, 105 were from red earths (Humic Acrisols), 17 were from brownish red earths (Haplic Alisols) and 29 were from yellowish red earths (Profondic Alisols) and yellow earths (Ferralic Cambisols). Of samples collected from 51 profile sites, 25 were taken from soils derived from granite, 16 from phyllite, 7 from red sandstone and 3 from purple shale and Quaternary red clays. The 51 profiles were located on barren lands, grasslands, sparse forest or forest. Because soils in the county were severely eroded, much of the A, B, and sometimes C horizons were washed away by erosion in extremely eroded areas. Although most samples were taken from eroded soils, 4 reference profiles were sampled in perfect, undisturbed forest areas and adjacent to villages or grave yards which suffered minimal erosion. Soil organic carbon contents were determined by the oil bath-K_2CrO_7 titration method (Nelson and Sommers, 1975).

2.3. Data sources and research methods

Data adopted in this study includes soil map, soil erosion map and DEM data. All maps used were transformed into GRID format in ARC/INFO© by vectorizing them in HEAD-UP with the aid of Arcview 3.2© software (ESRI, The Redlands, CA). A 1:100,000 soil map of Xingguo County was compiled during the Second National Soil Survey in the early 1980s. A 1:50,000 soil erosion map of the county was compiled on the basis of interpreted results of satellite remote sensing data (CCT) (Shi et al., 1996). The soil erosion map was then compiled by the following steps: (1) soil erosion was categorized into 4 types (non-eroded, slightly, moderately and severely eroded soils) based on soil losses observed and summarized from various erosion plots (Shi et al., 2008); (2) corresponding relationships between remote sensing image characteristics and soil erosion types were used to establish interpretation indices; and (3) distribution of erosion types was interpreted with remote sensing images, and individually field-validated (Shi et al., 1996). The 1:100,000 DEM was derived from a digital topographic map. All altitude data were extracted from the DEM. Soil attribute data, such as organic carbon content, was spatially allocated onto maps using “GIS linkage based on soil type”. In doing so, soil attribute data, including soil organic carbon content from sampling locations, was linked to the corresponding polygons of digital soil maps according to rules of identity of soil types, parent materials, sampling sites, and distribution areas to form a spatial map of soil attributes (Zhao et al., 2006; Wang et al., 2009). It is very unlikely that cultivated lands such as paddy fields and uplands in this area were returned to native vegetation, so they have not been included in this study.

3. Results

3.1. Distribution patterns of soil erosion

Three stages can be identified in the 42-year (1958–2000) evolution of soil erosion in Xingguo County (Wang et al., 2005). In the first stage (1958–1975), soil erosion expansion was obvious because vegetation was destroyed by human activity. By 1975, soil erosion in the county was both extreme and extensive. Severely eroded soil covered the largest area ever seen, up to 743 km^2 (about 30% of the study area). By contrast, non-eroded soil covered only 456 km^2 (Table 1) at the same time. In the second stage (1975–1982), soil erosion retreated due to reduced destruction by human activity. In 1982, the county was designated as one of eight key regions requiring national intervention to curb erosion. As a result, in the third stage (1982–2000), soil erosion was totally controlled and the eroded soil was comprehensively improved due to large scale biological and engineering measures such as reforestation. Organic carbon was continuously sequestrated in soil largely because of the comprehensive recovery of vegetation and remarkable decline in areas of eroded soil. Studies have shown that the area of severely eroded soil decreased from 743 km^2 in 1975 to 197 km^2 in 2000. Concurrently, the area of non-eroded soil increased from 456 km^2 in 1975 to 1896 km^2 in 2000 (Wang et al., 2005).

Table 1
Distribution patterns of various types of soil erosion in Xingguo County in China in 1975.

	Types of erosion				Total
	Non-eroded	Slight	Moderate	Severe	
Area (km^2)	456	719	558	743	2476
Percentage (%)	18.4	29.0	22.6	30.0	100

3.2. Spatial distribution patterns of soil organic carbon

Fig. 2 was compiled by spatially allocating SOC data from the surface layer (0–20 cm) of 85 non-cultivated soils onto the soil map using “GIS linkage based on soil types”. Similarly, Fig. 3 was compiled in the same way with SOC data from 46 soil profiles (0–100 cm). Fig. 2 shows that the vast majority of the area (1352 km^2 or 54.6% of total area) is covered by soil with a SOC density of 20–30 t C ha^{-1} in the surface layer (0–20 cm). About 40.0% (990 km^2) of the area is covered by soil with a SOC density of less than 20 t C ha^{-1} in the surface layer. Those with SOC densities of 30–40 and 40–60 t C ha^{-1} cover only 4.4% and 1% of the total study area, respectively. These explain the fact that the SOC densities of surface soils in barren land, sparse forest land and forest land are mostly lower than 30 t C ha^{-1}, and surface soils with SOC density higher than 30 t C ha^{-1} are only found in northwestern and eastern parts of the county. A map of the distribution pattern of SOC in the soil profile (0–100 cm) (Fig. 3) shows that soils with a SOC density of 40–60 t C ha^{-1} cover 64.2% of total study area (1589 km^2), and those with a SOC density higher than 60 t C ha^{-1} occupy only 179 km^2, 7.2% of total area. Finally, for those soils with SOC densities of <20, 20–30 and 30–40 t C ha^{-1}, each cover about 9% of the total study area. Soil profiles with high SOC density are found in the eastern and northeastern parts in the county, while those with low density are in the central and western parts.

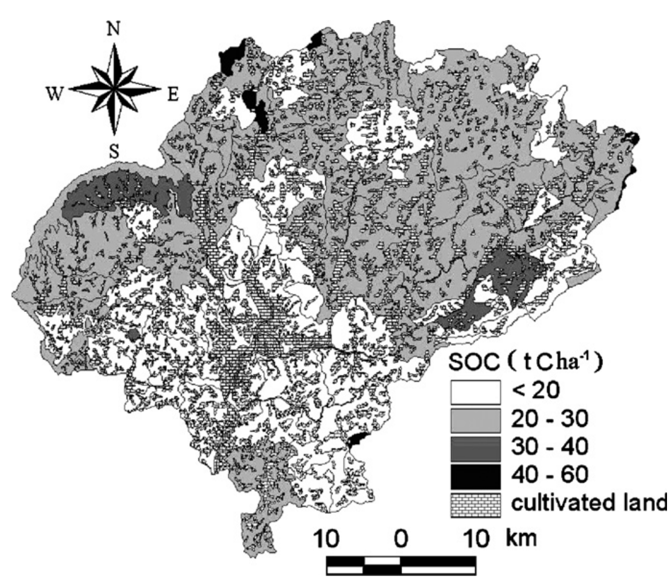

Fig. 2. Spatial distribution pattern of soil organic carbon in the surface layer (0–20 cm) of soils in Xiangguo County, China.

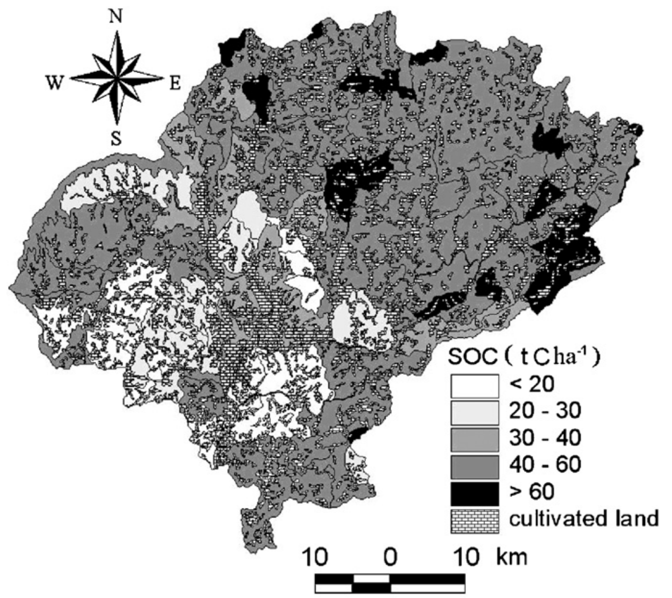

Fig. 3. Spatial distribution pattern of soil organic carbon in the whole profile (0–100 cm) of soils in Xiangguo County, China.

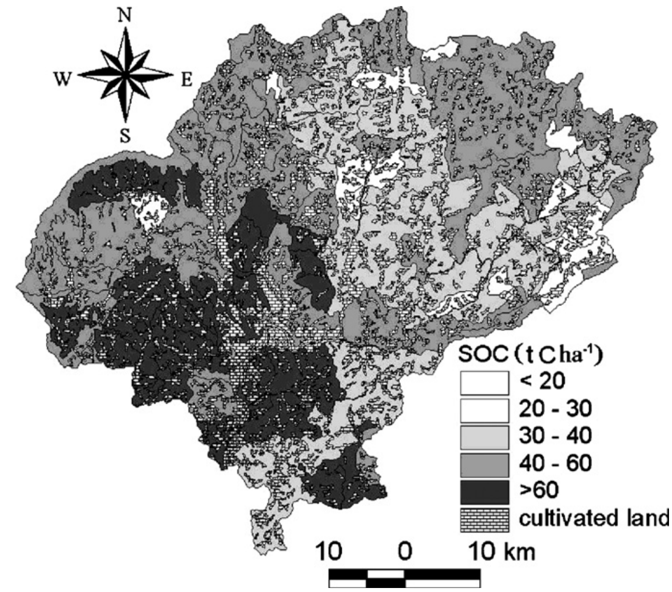

Fig. 5. Potential of soil organic carbon sequestration in the whole profile (0–100 cm) in Xiangguo County, China.

3.3. *Potential of soil organic carbon sequestration*

As vegetation returns and soil losses are remarkably reduced, eroded soils may gradually recover and re-establish their complete profiles (A–B–C horizons) as they used to be originally. To evaluate the potential of organic carbon sequestration of eroded soils, it is necessary to determine the climax status of development of eroded soils after being totally controlled. To make these comparisons, the 4 reference profiles from red, brownish red, yellowish red and yellow earths, were used to evaluate the potential for SOC sequestration of eroded lands in this study. Differences between the SOC contents of the various eroded soil profiles and the 4 reference profiles were easily calculated. Using GIS spatial analysis, maps of potential organic carbon sequestration for both surface layers (0–20 cm) and whole soil profiles (0–100 cm) were compiled (Figs. 4 and 5). Soils with a potential for organic carbon sequestration of less than 20 t C ha^{-1} in the surface layer cover 1491 km^2 and constitute 60.2% of the total study area. Those with a potential of 20–30 and 30–40 t C ha^{-1} equally cover 20% of the total study area. Fig. 5 shows that soils with a potential for organic carbon sequestration of 40–60 t C ha^{-1} in the whole profile (0–100 cm) cover 1109 km^2 and constitute 44.8% of the total study area. Soils with a potential of 30–40 t C ha^{-1} cover 686 km^2, 27.7% of the total, and those with a potential of 20–30 t C ha^{-1} cover only 2.3% of the total. The potential for organic carbon sequestration in the surface layer is high in the county's central and southern parts, and low in northern, northwestern and northeastern parts. As for potential of carbon sequestration in the profiles as a whole, they are high in the western and southwestern parts of the county and low in the northern, central and eastern parts.

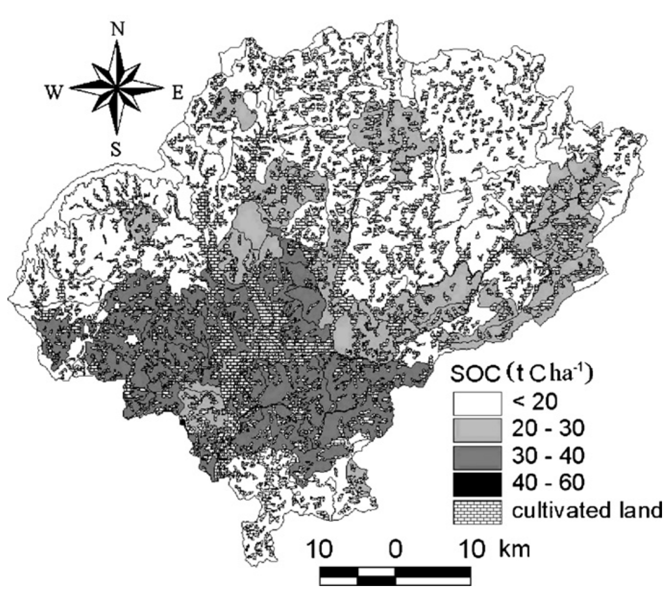

Fig. 4. Potential of soil organic carbon sequestration in the surface layer (0–20 cm) in Xiangguo County, China.

4. Discussion

4.1. *Relationship between erosion types, altitudes and the potential of soil organic carbon sequestration*

The potential rate of SOC sequestration varies with erosion types (Table 2). The potential rate in the surface layer is greatest (21.84 t C ha^{-1}) in severely eroded soils, and smallest (14.74 t C ha^{-1}) in slightly eroded soils. The total potential of SOC sequestration in the surface layer amounts to 4.47 Tg C for the whole county (Table 2). The greatest potential is found in severely eroded soil (1.62 Tg), while the smallest potential is in non-eroded soil (0.75 Tg). Despite limited thickness, surface layers are very important for sequestering SOC, accounting for 30.2–43.7% of the potential in the whole soil profile. In severely eroded soils, the surface layer accounts for 43.7% of the SOC sequestration potential of the whole profile. The total potential of SOC sequestration in the whole profile amounts to 12.3 Tg for the entire county. Among the various erosion types, severely eroded soil has the greatest total potential (3.72 Tg), while non-eroded soil has the smallest total potential (2.34 Tg). No obvious differences in the potential rate of the whole profile are found among the various erosion types despite being slightly greater (51.27 t C ha^{-1}) in non-eroded soil and smallest (48.78 t C ha^{-1}) in slightly eroded soil.

Soil organic carbon sequestration potential also varies with altitude (Table 3). The potential rate decreases from 23.70 to

Table 2
Potential for soil organic carbon sequestration of various erosion types in Xingguo County, China.

	Erosion type				Averaged	Total
	Non-eroded	Slight	Moderate	Severe		
Area (km^2)	456	719	558	743		
Potential rate (t C ha^{-1})						
0–20 cm	16.38	14.74	18.71	21.84	18.07	
0–100 cm	51.27	48.78	49.73	50.03	49.83	
Percentage of surface layers in the profile (%)	31.9	30.2	37.6	43.7	35.9	
Total potential (Tg C)						
0–20 cm	0.75	1.06	1.04	1.62		4.47
0–100 cm	2.34	3.51	2.78	3.72		12.3

11.70 t C ha^{-1} in the surface layer with the increasing altitude from 300 to 800 m. Similarly, the total potential of soils at different altitudes varies greatly. The SOC sequestration potentials in the surface layers and whole profiles decrease with increasing altitude; surface layers decrease from 2.18 to 0.06 Tg and profiles decrease from 5.01 to 0.25 Tg.

4.2. Relationship between soil types, parent materials and potential of soil organic carbon sequestration

Soil types are differentiated by their potential for organic carbon sequestration (Table 4). In the surface layer, the potential rate of organic carbon sequestration of red earths is the greatest (26.76 t C ha^{-1}), while yellowish red earths (6.32 t C ha^{-1}) or yellow earths (10.38 t C ha^{-1}) are the smallest. In the whole profile, the potential rates of organic carbon sequestration of yellow earths (59.23 t C ha^{-1}) and yellowish red earths (56.96 t C ha^{-1}) are the greatest, with red earths being moderate (48.39 t C ha^{-1}), and brownish red earths (41.86 t C ha^{-1}) being smallest. The reason is that the potential rate of SOC sequestration is mainly determined by two factors: soil organic storage per hectare in eroded soils and soil organic storage per hectare in non-eroded soils of reference profiles. The potential of SOC sequestration is estimated by subtracting the organic carbon storage per hectare in eroded soils from that in non-eroded soils of reference profiles. For surface soils, red earths are more easily damaged by soil erosion than other earths, which lead to the low soil carbon storage per hectare (eroded soils status) and high potential rate of SOC sequestration. For the whole profiles, soil carbon storage per hectare in red earths and brownish red earths (eroded soils) is slightly lower than yellowish red earths and yellow earths. However, soil carbon storage per hectare in yellowish red earths and yellow earths of reference profiles (non-eroded soils) is much higher than red earths and brownish red earths. Thus, high potential rates of SOC sequestration in yellowish red earths and yellow earths are obtained. In terms of total potential of SOC sequestration, red earths rank first with 2.94 Tg of potential in the surface layer and 5.32 Tg in the whole profile, while yellow earths rank last with only 0.03 Tg in the surface layer and 0.15 Tg in the whole profile.

Remarkable differences in carbon sequestration potential are found among soils that were derived from 5 different types of parent materials (Table 5). The differences are particularly significant in surface soils. The potential rates of surface soils derived from purple shale (31.38 t C ha^{-1}) and Quaternary red clays (30.88 t C ha^{-1}) are the greatest and more than twice as high as surface soils from phyllite (13.58 t C ha^{-1}), which is the smallest. The order of SOC sequestration potential in these soils is: purple shale > Quaternary red clays > red sandstone > granite > phyllite. For the potential rate in the whole profile, differences among these soils are comparatively small, but still show an order of: purple shale > Quaternary red clays > red sandstone > phyllite > granite. Soil derived from purple shale has the greatest potential rate (65.08 t C ha^{-1}), while soil derived from granite has the smallest potential rate (46.72 t C ha^{-1}). In terms of total potential of SOC sequestration in the surface layer and the whole profile, parent materials can be ranked as follows:

Table 3
Potential for soil organic carbon sequestration at different altitudes in Xingguo County, China.

	Altitudes (m)			
	<300	300–500	500–800	>800
Area (km^2)	921	1026	482	47
Potential rate (t C ha^{-1})				
0–20 cm	23.70	15.56	13.28	11.70
0–100 cm	54.41	46.98	46.91	52.13
Total potential (Tg C)				
0–20 cm	2.18	1.60	0.64	0.06
0–100 cm	5.01	4.82	2.26	0.25

Table 4
Potential for soil organic carbon sequestration of various soil types in Xingguo County, China.

	Soil types			
	Red earths	Brownish red earths	Yellowish red earths	Yellow earth
Area (km^2)	1100	549	801	26
Potential rate (t C ha^{-1})				
0–20 cm	26.76	18.16	6.32	10.38
0–100 cm	48.39	41.86	56.96	59.23
Total potential (Tg C)				
0–20 cm	2.94	1.00	0.51	0.03
0–100 cm	5.32	2.30	4.56	0.15

Table 5
Potential for soil organic carbon sequestration of soils derived from 5 types of parent materials in Xingguo County, China.

	Parent materials				
	Phyllite	Granite	Red sandstone	Purple shale	Quaternary red clays
Area (km^2)	1393	686	298	65	34
Potential rate (t C ha^{-1})					
0–20 cm	13.58	22.29	25.00	31.38	30.88
0–100 cm	48.86	46.72	56.85	65.08	61.47
Total potential (Tg C)					
0–20 cm	1.89	1.53	0.75	0.20	0.11
0–100 cm	6.81	3.21	1.69	0.42	0.21

phyllite > granite > red sandstone > purple shale > Quaternary red clay.

5. Conclusions

Xingguo County of Jiangxi Province, China experienced three stages of soil erosion over the past 42 years: erosion expansion, erosion retreat and comprehensive erosion control. With the recovery of vegetation, soil erosion is now under control, resulting in a high potential for SOC sequestration in previously eroded soils. The total potential of SOC in the surface layer amounts to 4.47 Tg, while that in the whole profile amounts to 12.3 Tg for the entire county. The potential in the surface layer is greater in the county's central and southern parts than in the northern, northwestern, and northeastern parts. As for those in the whole profile, they are greater in western and southwestern parts than the northern, central, and eastern parts of the county, suggesting that potential is closely related to soil erosion types, altitudes, soil types, and parent materials. The potential of severely eroded soil is the greatest (3.72 Tg C), while that of non-eroded soil (2.34 Tg C) is the smallest. Also, the potential decreases with increasing altitude. The potential of SOC in soils at altitudes less than 300 m is the greatest (5.01 Tg C), while that at altitudes of more than 800 m is as low as 0.25 Tg C. Moreover, the potential varies greatly with soil types. Red earths provide the greatest SOC sequestration potential (5.32 Tg C), followed by yellowish red earths, brownish red earths, and yellow earths. Soils derived from different parent materials vary greatly in their sequestration potential with the greatest potential in soils derived from phyllite (6.81 Tg C) and the smallest in soils from Quaternary red clays (0.21 Tg C). The SOC sequestration potential in soils from parent materials is as follows: phyllite > granite > red sandstone > purple shale > Quaternary red clays.

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