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Variation of soil organic carbon estimates in mountain regions: A case study from Southwest China

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ABSTRACT

Soil organic carbon (SOC) is an important soil component of farming systems and plays a key role in terrestrial ecosystems. However, there is a large variation in SOC estimates at both regional and global scales. The widely used soil type method is usually projected using a planimetric approach, and hence SOC estimates vary notably compared to those generated from more rigorous 3-D surfaces describing rugged terrain. In order to improve the accuracy of SOC storage estimates for regions with complex landforms, this paper examined the causes of variability in estimated SOC storage and SOC density in the upper 1 m soil depth based on 798 soil profiles from Southwest China. The study area is a region with rugged terrain, including the Guangxi Zhuang Autonomous Region, and the Guizhou and Yunnan Provinces.
Three methods, the soil profile statistics (SPS), the GIS-based planar soil type (GST-2D), and the GIS-based three-dimensional soil type (GST-3D), were applied to estimate SOC storage. Results demonstrate that the GST-3D, which used soil surface area data, was more accurate than the other two methods. The SOC storages estimated by the SPS and the GST-2D methods were lower than the GST-3D mainly due to the under-estimation of soil acreage. Of the four geomorphologic units represented in the study area, the complex landforms with slopes greater than 18.2° covered more than 30%. There is a relatively big difference (>6%) between planimetric projection area and surface area in this region, making the effect of landform on the estimate of SOC an important factor to be considered. However, such thresholds (30% and 18.2°) as terrain descriptor boundaries need to be further verified in other mountainous regions.

1. Introduction

The issue of soil organic carbon (SOC) is of increasing concern because SOC, as an important soil component in farming systems, is essential for improving soil quality, sustaining food production and quality, and maintaining water quality (Singh et al., 2007); it, therefore, has been proposed as an indicator of soil quality (Defra, 2004). The SOC stock, as a major part of the terrestrial carbon reservoir, plays an important role in the global carbon cycle. In terrestrial ecosystems, the SOC stock is nearly three times as large as carbon storage in vegetation (Schlesinger, 1990), and twice as large as global atmospheric carbon storage (Lal, 2004). Due to the large quantity stored in terrestrial ecosystems, a slight change in SOC will affect the density of greenhouse gases in the atmosphere leading to global climate change. Accurately quantifying SOC stock is considered essential to studying the soil quality and productivity, and modeling the global carbon cycle (Batjes, 1996; Morisada et al., 2004; Wang et al., 2004).

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However, there is a large variation in SOC estimates at both regional and global scales (Leifeld et al., 2005; Yu et al., 2006). For example, Bohn (1976) estimated 3000 Pg C (1 Pg = 10^{15} g) of global SOC storage, while Bolin (1977) estimated only 710 Pg C. Though more papers about the global SOC storage have recently been published, their results remain discrepant. The estimates by Batjes (1996) and Bolin and Sukumar (2000) ranged from 1462–1548 Pg C to 2011 Pg C. As for China, Fang et al. (1996) estimated 185.7 Pg C of SOC storage, whereas Pan's (1999) estimate of 50 Pg C represents the lowest in the range of published values. Yu et al. (2006) employed 7292 profiles and a 1:1,000,000 scale soil map and estimated 89.14 Pg C within 1 m soil depth. Li et al. (2007) used the inventory data from the National Soil Resource Survey and Chinese Academy of Sciences to generate an estimate of 83.8 Pg C in soil to 1 m depth.

The SOC storage estimates are obtained primarily from three methods, the soil type method, the vegetation type method, and the life zone (modeling) method. The soil type method is the most widely used among the three (Batjes, 1996, 2006; Bohn, 1976; Bolin, 1977; Liebens and VanMolle, 2003; Post et al., 1982). According to the source of area data, the soil type method can be further divided into two types: the Soil Profile Statistics (SPS) method and the GIS-based Soil Type (GST) method. The SPS method is widely used in China and the area data for soil types are cited from various soil survey reports, such as the Soil Series of China. For example, Pan (1999) and Wang et al. (2000) applied the SPS method to estimate the total SOC storage in China using a dataset of about 2500 soil profiles and the corresponding area data for each soil series (profiles). Based on the data of the second national soil survey of China, this method was also used to estimate the SOC density for Southeast China, East China and Shandong Province by Zhao et al. (1997), Li et al. (2001) and Jin et al. (2001), respectively. The GST method uses GIS and digital soil survey maps with their corresponding soil attribute database to estimate SOC storage and to provide information on the spatial distribution of SOC. With the rapid development of GIS technology, this method has been applied extensively (Batjes, 2000; Galbraith et al., 2003; Zhao et al., 2006; Yu et al., 2007).

There are often significant differences between SOC storage estimates generated by the various methods. These differences are attributed to the three factors: (1) the scale used for the soil survey map, (2) the number of soil profiles, and (3) the linking method used to combine the soil attribute database and the spatial database (digital soil map), with which SOC values are assigned to polygons (Zhao et al., 2005). Among the three factors, the uncertainty generated by the variation in SOC values assigned to soil series (polygons) may be greater than the uncertainty associated with changes in scale (Galbraith et al., 2003). Therefore, the linking method used in the GST approach is important. In China, based on the characteristics of soil survey and classification, Shi et al. (2004b) proposed a GST method using pedological professional knowledge to link the soil attributes with the spatial database, and Zhao et al. (2005), Liu et al. (2006) and Yu et al. (2006) later applied such a method to their SOC estimates.

There are also inconsistencies among the areas calculated from the GIS map and the true area of soil distribution, especially for the mountainous regions because of the distinction between the projection area on the map and the real surface area of the rugged terrain.

Southwest China is characterized by mountainous and extremely complex topography, and variable horizontal and vertical zonality of soils, which theoretically should result in a large variability in the spatial distribution of SOC in this region. As the second largest forest region in China, this area is an important component of the biosphere. Forest soils store 40% of the SOC in the world, though it covers only 27% of the global land surface (Houghton et al., 2001). In China, about 28% of forests are distributed in the southwestern region (Editorial Committee of Forest in China, 1997) which was identified as one of the regions with the highest SOC density (Yu et al., 2006). However, previous SOC storage researches of SOC storage in Southwest China were based on small scale soil maps (not higher than 1:1,000,000) (Fang et al., 1996; Wang et al., 2003; Yu et al., 2006). It is necessary to estimate the SOC in the Southwest China using more detailed maps of larger scales. The aims of this study are: (1) to estimate the SOC storage in the Southwest China; (2) to compare the differences in SOC estimates using various methods; and (3) to explore the possible causes of variation of SOC estimates.

2. Materials and methods

2.1. Study area

The study area is Southwest China, including Guangxi Zhuang Autonomous Region, Guizhou Province and Yunnan Province, located between 20°53′48″–29°15′00″N latitude and 97°31′52″–112°03′25″E longitude with an area of 806,400 km^2 or about 8.4% of the whole territory of China (Fig. 1). Its topography is characterized by high elevation in the northwest and low elevation in the southeast. With about 78% of its surface covered by mountains, the region can be divided into four geomorphologic units, the Hengduan Mountains in the west, the Yunnan Plateau in the middle, the Guizhou Plateau in the north and the Guangxi Basin in the southeast, encompassing 26.5%, 21.7%, 22.1% and 29.7% of the total study area, respectively. The Hengduan Mountains and the Yunnan Plateau both located in the Yunnan Province are divided by the Yuanjiang River, Erhai Lake and

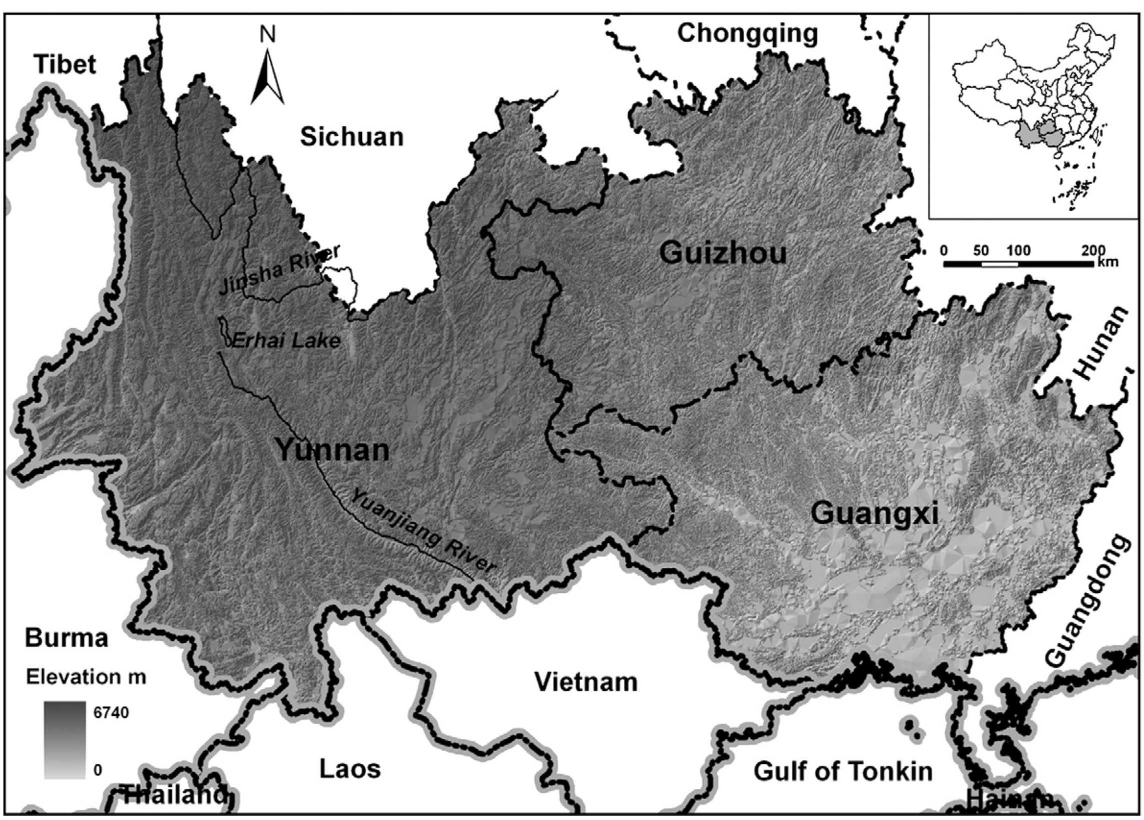

Fig. 1. The geographic location and landform of Southwest China (including Guangxi Zhuang Autonomous Region, Guizhou Province and Yunnan Province, China).

the southern of the Jinsha River. The Hengduan Mountains unit, with various elevations from 76.4 m to 6740 m, is the southern section of the Hengduan Mountain Range which borders the eastern section of the Himalayas and is filled with mountains, rivers and valleys. From peaks to river valleys, there are commonly sheer drops, which create a rugged terrain. With an average elevation over 2000 m, the Yunnan Plateau unit is characterized by a relatively level ground surface with dispersed valleys, lakes and basins. The Guizhou Plateau unit, with its world-famous karst rock formations and an average elevation of 1100 m, is characterized by rugged terrain with intersecting and dispersed mountains, gorges, valleys, hills and inter-montane basins. The Guangxi Basin unit has a diverse terrain and limestone bedrock distributed over roughly half of the total area. It has numerous mountains with elevations up to about 1500 m in the region's northern section, and hills with 80–200 m elevation distributed in the region's central area.

The study area lies in the sub-tropical monsoonal climate zone but, the low latitude location has elevated landforms, producing diverse climate zones characterized by distinct horizontal and vertical zonal boundaries. As a major forest zone in China, the area is famous for its abundant plant resources. Diverse soil types are also found produced from the region's bedrock, climate and land use.

2.2. Data sources

The soil attributes from a total of 798 soil profiles were taken from the Soil Series of Guangxi (Soil and Fertilizer Workstation of Guangxi Zhuang Autonomous Region, 1993), the Soil Series of Guizhou (Soil Survey Office of Guizhou Province, 1994) and the Soil Series of Yunnan (Soil Survey Office of Yunnan Province, 1994), 265 of which were also recorded in the Soil Series of China. This information derived from the second national soil survey of China is the most comprehensive and detailed study on soil characteristics in the area.

The above mentioned soil survey reports and soil maps were adopted in this study and were documented using the Genetic Soil Classification of China (GSCC) during the second national soil survey period (1979–1994). The GSCC was based on the geographic genesis classification system introduced from the former Soviet Union in 1954, which was strongly based on the setting of the soil's location. A uniform and relatively complete genetic soil classification of China, the "Provisional Draft of Soil Classification of China", was established in 1978 (Gong et al., 1978). In 1979, the "Soil Working Classification System (Revised draft)" was formulated for the second national soil survey. The draft, after several amendments, was developed into the version of the GSCC adopted for soil survey reports and soil maps.

The GSCC has six hierarchical levels: order, suborder, great group, subgroup, family, and series. The soil series is the basic classification levels below the high-levels of order, suborder, great group, and subgroup. Among different versions of the GSCC, the name and number of soil great groups are almost the same, so the level of great group is the most stable and consistent classification unit commonly used in China.

The 798 profiles, each representing one soil series, were classified into 225 soil families, 60 subgroups, and 26 soil great groups according to the GSCC. The data was gathered to create a soil profile database (SPD), which included information on soil type, physicochemical properties, sampling location, and distribution areas of each soil series. The statistical description of acreage for each soil series recorded in the provincial Soil Series was gathered from different administrative levels from village, town, county, and municipality to province. The total area of the 798 soil series recorded in the three Soil Series documents was 47.45 M ha.

The spatial data are sourced from: (1) the 1:500,000 Soil Map of Guangxi Zhuang Autonomous Region (Soil and Fertilizer Workstation of Guangxi Zhuang Autonomous Region, 1990), (2) the 1:500,000 Soil Map of Guizhou Province (Soil Survey Office of Guizhou Province, 1992), (3) the 1:500,000 Soil Map of Yunnan Province (Soil Survey Office of Yunnan Province, 1992), and (4) a 90×90 m resolution DEM (The National Fundamental Geographic Information Center, 1995). The map unit system of these soil maps was based on the GSCC classification units, with the basic map unit being soil family. The total mapped soil area calculated from digital data base was 78.04 M ha which was much higher than the statistical total area recorded in the adopted Soil Series.

2.3. Estimation of soil organic carbon density in a profile

For a soil profile with a depth D (cm), SOC density (kg C m^{-2}) was estimated with the following equation (Wang et al., 2003):

$$\mathrm{SOCD}_D = \sum_{i=1}^{n} \frac{(1-\delta_i\%)\times\rho_i\times C_i\times T_i}{100}$$

where SOCD_D represents the SOC density of a soil profile with a depth D (cm); n is the number of pedogenic horizons in the soil survey, $\delta_i\%$ represents the volumetric percentage of the fraction >2 mm (rock fragments), ρ_i is the bulk density (g cm^{-3}), C_i is the organic C content (g kg^{-1}), and T_i represents the thickness (cm) of the layer i. The organic C content is calculated by multiplying soil organic matter content by 0.58 (the Bemmelen index), which converts organic matter concentration recorded in the Soil Series to organic C content. The SOC was estimated to a maximum soil depth of 1 m. For profiles with no bulk density value, the mean bulk density value of the corresponding soil depth in the same soil family was used.

2.4. Estimates of soil organic carbon storage

2.4.1. Soil profile statistics method (SPS)

SPS used the Soil Profile Database (SPD) itself to estimate SOC storage. First, the information on each profile's physicochemical properties and corresponding statistical area were extracted from the above mentioned Soil Series publications. Second, the information from the 798 soil profiles in the SPD were examined and used to calculate the SOC storage for each soil series and then for each great group and the entire study area, according to the classification levels from soil series to soil great groups.

2.4.2. GIS-based 2-dimension planar soil type method (GST-2D)

The GST-2D method used 2-dimensional planimetric area to estimate the SOC storage. The SOC storage was estimated based on the acreage of each soil type calculated from the digitized soil map and the soil attributes derived from the SPD. The digitized soil map was linked with the SPD utilizing pedological professional knowledge-based (PKB) method to create a pedological professional knowledge-based database (PKD) (Shi et al., 2004b; Zhao et al., 2006). The PKD was then used for estimating the SOC storage. The SOC storage was first calculated for each soil family which was used as the basic map unit. The soil family storage values were then aggregated for each level in the classification system to great group and summed to obtain area wide total storage.

Table 1
The area of soil, SOC (soil organic carbon) storages and area-weighted means of SOC density in Southwest China estimated by the SPS (soil profile statistics), the GST-2D (GIS-based 2-dimensional planar soil type), and the GST-3D (GIS-based 3-dimensional soil type) methods

Methods	Area of soil (M ha)	Area-weighted mean of SOC density (kg C m^{-2})	SOC storage (Tg C)[a]
SPS	47.45	14.43	6847.09
GST-2D	78.04	13.98	10,913.83
GST-3D	84.02	14.12	11,867.92

[a] 1 Tg = 1012 g.

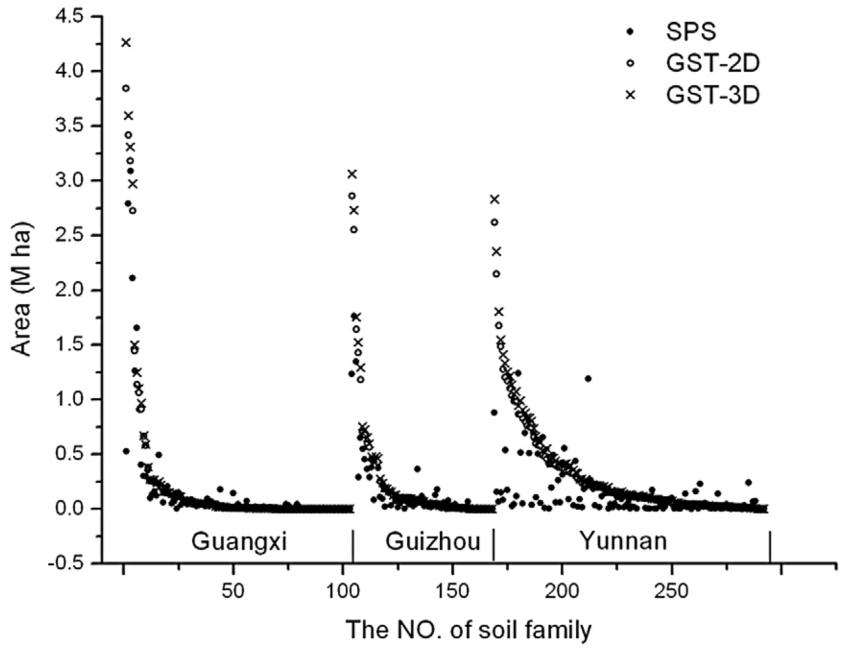

Fig. 2. Distribution areas of soil families in Southwest China estimated by the SPS (soil profile statistics), the GST-2D (GIS-based 2-dimensional planar soil type), and the GST-3D (GIS-based 3-dimensional soil type) methods.

2.4.3. GIS-based 3-dimensional soil type method (GST-3D)

The GST-3D method used the 3-dimensional surface area and soil attributes in the SPD to estimate SOC storage. The 3-dimensional surface area of each soil types was calculated from the digitized soil maps and the DEM. The PKD and calculation methods of SOC storage were same as those used in the GST-2D method, except that the 3-dimensional surface area data were used. The surface area for each soil polygon was calculated using the method of Jenness (2002).

3. Results and discussion

3.1. Regional estimates of soil organic carbon storage in Southwest China

Table 1 shows distinct differences between the estimated SOC storages (to a soil depth of 1 m) using the SPS, GST-2D, and GST-3D. The SOC storage obtained by the SPS was the lowest (6847.09 Tg), while the GST-3D method resulted in the highest estimation (11867.92 Tg). The SOC storage estimated by the SPS and the GST-3D were 37% lower and 9% higher than that by the GST-2D, respectively. However, the differences in the estimated area-weighted mean SOC density by the three methods were relatively small. The GST-2D had an estimate of 13.98 kg C m^{-2}, or the lowest estimate, but the SPS method resulted in the greatest estimate, 3% greater, than the GST-2D method.

The total soil areas used by the SPS, the GST-2D, and the GST-3D methods were 47.45 M ha, 78.04 M ha, and 84.02 M ha, respectively. These differences, 39% and 8% between SPS and GST-3D and GST-2D, respectively, would be propagated to the SOC storage estimates. It can be concluded that the differences in SOC storage estimated by the three methods was mainly derived from the differences in total soil area.

Since the map units of the adopted soil maps are soil families, the inconsistency in the total soil area among the three methods should be evident at the soil family level. Fig. 2 lists the areas for all soil families in Southwest China by the three methods. For the soil families with the greatest area, the areas obtained by the SPS were lower than that by the GST-2D, but most soil families associated with the reversed relationship were minor in extent.

With respect to the three administrative regions, the most pronounced differences in the areas of soil families occurred in the Yunnan Province (Fig. 2). There were 18 soil families with large area differences (>0.36 M ha) between the SPS and the GST-2D. They were predominately located in the Hengduan Mountain region (>55% of their areas for 12 soil families, and >80% for 6). This region has a complex

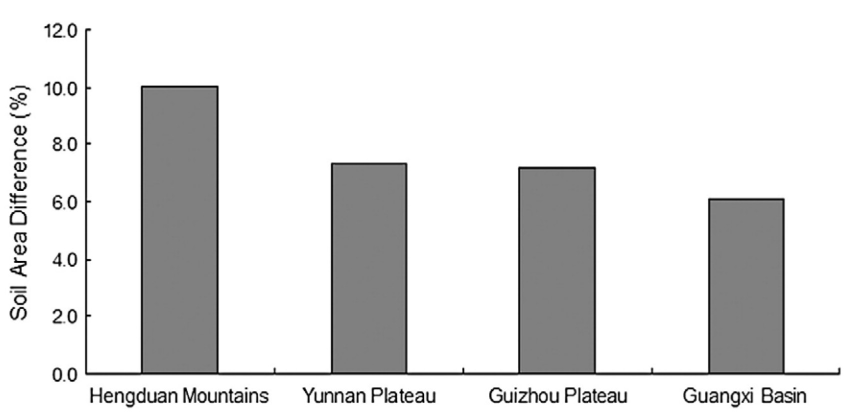

Fig. 3. The differences of soil areas between the GST-2D (GIS-based 2-dimensional planar soil type), and the GST-3D (GIS-based 3-dimensional soil type) methods in different terrain regions of Southwest China.

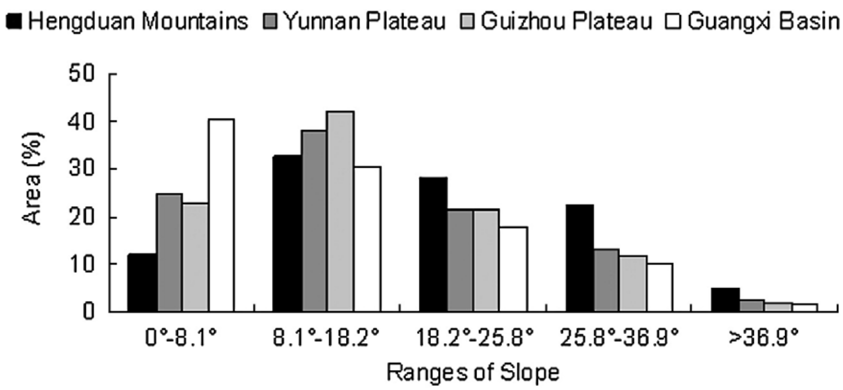

Fig. 4. Slope spectra (% of soil projection area) of different terrain regions (only soil area included) in Southwest China.

topography with mountains, rivers, and valleys, and making it difficult to measure and calculate the area of soils. This was one of the main reasons for the variation in the areas for the SPS method. In addition, the Soil Series publications may exclude some minor soil series, which also contributed to the uncertainties. The use of GIS, RS and GPS, can aid future soil surveys to reduce such uncertainties.

Although its estimates are more accurate than the SPS, the uncertainty is still observed in the GST methods due to the map scale limitations (Arnold, 1995; Galbraith et al., 2003). Map delineations and map unit composition vary with map scale. The minor soils are often eliminated or merged into other map units at the scale of 1:500,000 during the generalization process, which can result in an underestimation of area. Such elimination, however, would not occur in the statistical process of the SPS. This could result in the areas used by the SPS to be larger than that by the GST-2D for the minor soils. However, this is not the major cause of the area difference between the SPS and the GST-2D because the total areas of these soil types are small (less than 4% of the total soil area).

The GST-3D calculated the surface areas from the DEM, while the GST-2D used planar areas of each soil type. As a result, the GST-3D used the areas larger than that by the GST-2D (Fig. 2). The differences between the two methods varied with rugged topography. The impact of terrain on the soil surface area estimates increases with slope gradient. The difference is 5% for an 18.2° slope, and 10% for a 25.8° slope. In the study area 39% of the soils were located on slopes with a gradient above 18.2° and 17% of them have slope gradients above 25.8°.

The differences in the estimated soil areas between the GST-2D and the GST-3D methods varied among the four regions due to the diversity of their terrains (Figs. 3 and 4). The difference was most remarkable in the Hengduan Mountains (10%), and least in Guangxi Basin (6%). Guizhou Plateau and Yunnan Plateau have similar differences (7%). Thus, the effect of landforms on the SOC estimates should be considered in all the four terrain regions which have more than 30% of area with slopes greater than 18.2°. However, further verifications are required to test whether the percentage (30%) and the slope degree (18.2°) are also the threshold for other mountainous regions.

Since the area-weighted mean SOC density is not related to the soil distribution area but to the area proportions of representative soil profiles, the similar regional SOC density values obtained by methods with large total soil area differences are now easily understood. The similar regional SOC density trends further indicate that the variation of SOC storage estimates are also the result of differences in the area proportion of representative soil profiles and is smaller than that related to the total soil acreage.

3.2. Soil organic carbon storage estimates at soil great group level

According to Batjes (2000), a more pronounced difference can be observed between the results of regional SOC storage when estimated at the GSCC great group level, which may explain the discrepancies between the regional SOC storage values listed in Table 1.

The estimated SOC of soil great groups using the SPS, the GST-2D and the GST-3D methods are presented in Fig. 5. The SOC storage in Southwest China was primarily controlled by ten soil great groups, namely Red soils, Limestone soils, Yellow-brown soils, Latosolic red soils, Yellow soils, Paddy soils, Brown soils, Brown coniferous forest soils, Dark-brown soils and Purplish soils. The SOC storage associated with these ten great groups in Southwest China varied from 4% to 21% and when combined contributed over 95% of the total SOC storage in the region. The SOC storage of these ten main soil great groups estimated by the SPS were all remarkably lower (22–56%) than the estimates by the GST-2D, except for Brown soils and Brown coniferous forest soils, while the SOC storage estimated by the GST-3D were the highest. The estimate for paddy soils differed only by 3% among the GST-3D and the GST-2D, but larger difference (6–20%) was found for the other nine soil great groups.

The differences in the estimates of the area-weighted mean SOC density for soil great groups among the three methods are shown in Fig. 6. The SOC density values of all great groups obtained by the GST-3D were similar to that of the GST-2D (<4% difference only), while SOC density values estimated by the SPS differed more greatly from that of the GST-2D. The estimates of SOC density for Alpine frozen desert soils, Latosolic red soils, Subalpine meadow soil, Paddy soils,

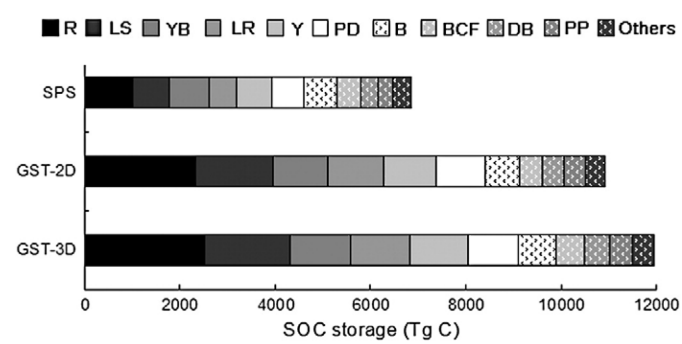

Fig. 5. SOC (soil organic carbon) storages in the upper 1 m soil depth of various soil great groups estimated by the SPS (soil profile statistics), the GST-2D (GIS-based 2-dimensional planar soil type), and the GST-3D (GIS-based 3-dimensional soil type) methods for Southwest China. Abbreviations: R: Red soils (Alisols, Acrisols), LS: Limestone soils (Luvisols, Cambisols), YB: Yellow-brown soils (Luvisols), LR: Latosolic red soils (Acrisols), Y: Yellow soils (Cambisols), PD: Paddy soils (Anthrosols), B: Brown soils (Luvisols), BCF: Brown coniferous forest soils (Alisols), DB: Dark-brown soils (Luvisols), PP: Purplish soils (Cambisols, Luvisols), Others (LA: Latosols (Acrisols), TR: Torrid red soils (Luvisols), C: Cinnamon soils (Cambisols), RP: Red primitive soils (Cambisols), NA: Neo-alluvial soils (Fluvisols), VS: Volcanic soils (Andosols), LI: Lithosols (Leptosols), SS: Skeletal soils (Arenosols, Regosols), LCB: Lime concretion black soils (Vertisols), MM: Mountain meadow soils (Regosols), FA: Fluvo-aquic soils (Cambisols), BS: Bog soils (Histosols), CS: Coastal solonchaks (Solonchaks), AS: Acid sulphate soils (Solonchaks), SM: Subalpine meadow soils (Cambisols), AFD: Alpine frozen desert soils (Leptosols)). Note: Reference method between the Genetic Soil Classification of China (GSCC) and World Reference Base for Soil Resources (WRB) is same to Shi et al.(2004a,b, 2006a,b) and soil type names in the brackets are soil groups in WRB.

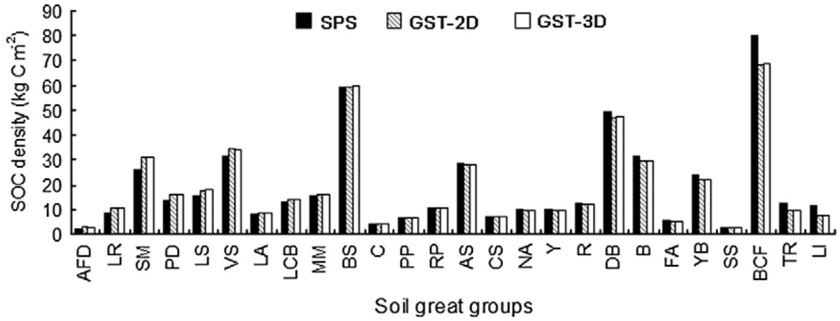

Fig. 6. Area-weighted means of SOC (soil organic carbon) density in the soil depth of 1 m estimated by the SPS (soil profile statistics), the GST-2D (GIS-based 2-dimensional planar soil type), and the GST-3D (GIS-based 3-dimensional soil type) methods for various soil great groups in Southwest China. Note: for abbreviations of soil great group names, please see Fig. 5.

Limestone soils, Volcanic soils and Latosols (which cover 36% of the total soil area) obtained by the SPS were lower than that by the GST-2D. However, the estimates of SOC density for Lithosols, Torrid red soils, Brown coniferous forest soils, Skeletal soils, Yellow-brown soils, Fluvo-aquic soils, Brown soils and Dark-brown soils (which cover only 15% of the total soil area) obtained by the SPS were all higher than that by the GST-2D. The estimates of SOC densities for all other soil great groups obtained by the SPS were close to that by the GST-2D (less than 4% difference).

The differences between SOC estimates among the three methods were mainly related to the total soil area associated with each soil great group. Compared to the GST-2D, the ten main soil great groups areas were 24%–58% lower using the SPS, except for Brown soils and Brown coniferous forest soils, and using the GST-3D were 6%–19% higher than the GST-2D based estimates, except for paddy soils.

Although the influence on the area-weighted mean SOC density for soil great groups attributable to caused by the area proportions of representative soil profiles was much smaller than that by the total soil area information, it was not neglectful due to the large soil acreage. Galbraith et al. (2003) also pointed out that inconsistency of area proportions of soil types due to the SOC density variation in the same unit will also result in uncertainties in SOC estimates apart from the obtained total soil area information. Under the fixed total soil area, the higher the estimated area for the soils with large SOC density value, the higher the obtained SOC storage for the total region. The inconsistencies of soil area proportions among the SPS, the GST-2D, and the GST-3D were found at all classification levels. For example, the area proportions of Red soil great group in the soils of the Yunnan Province obtained by the SPS, the GST-2D, and the GST-3D methods were 17.1%, 24.9%, and 24.8%, respectively. This phenomenon could also be found at subgroup level, family level, and series level (Tables 2 and 3).

For estimated SOC using soil maps, one great uncertainty lies in the variation in SOC density values assigned to the soils in the soil map units (Galbraith et al., 2003). Because of the basic map units of the adopted soil maps are soil family, the causes of variation in area proportions of soil types at soil great group, subgroup and family levels are the same as that of the total soil areas. But the inconsistency of soil area proportion at soil series level can also be attributed to the method of linking attribute data with spatial data. The GST-2D and the GST-3D employed the area derived from the corresponding soil family (the soil map polygons), and each soil family (or each kind of those polygons) usually involves more than one soil series. For example, the Arenaceous shale red soil family in the Guangxi Zhuang Autonomous Region has eight soil series with various SOC density values (Table 3). Furthermore, it is also possible to include more than one soil series in one polygon. The uncertainty would be minimized if a large scale soil map with more detailed basic mapping units (such as series) could be employed. However, there are only medium and small scales presently available for the majority of regions in China. In order to improve the precision of SOC estimates, detailed studies on the effects of soil map scale on the SOC estimates should be conducted.

3.3. Sources of variation in soil organic carbon storage estimates

SOC storage estimate variability is related to the choice of estimation method and characteristics of the source data (Yu et al., 2006). For the soil type based method, the variation is closely related to the data sources and the calculation methods. The data used for the soil type based method usually include soil attribute data and spatial data (digitized soil map). The uncertainty of attribute data used for SOC estimates is caused by the inconsistency of measuring methods and differences in sampling density. Various spatial data sources can result

Table 2
Area proportions of Red soil great group and its various subgroups and some families in Yunnan Province estimated by the SPS (soil profile statistics), the GST-2D (GIS-based 2-dimensional planar soil type), and the GST-3D (GIS-based 3-dimensional soil type) methods

GSCC soil great groups	Area percentage[a]			GSCC soil subgroups	WRB subunits[b]	Area percentage[c]			GSCC soil family	Area percentage[d]		
	SPS	GST-2D	GST-3D			SPS	GST-2D	GST-3D		SPS	GST-2D	GST-3D
Red soils	17.1	24.9	24.8	Red soils	Profondic Acrisols	56.5	30.6	30.9	Argillaceous red soils	66.8	22.5	22.6
									Purplish red soils	2.7	29.2	29.4
				Yellowish red soils	Chromic Acrisols	19.2	35.6	36.2	Purplish yellowish red soils	1.8	10.2	10.2
									Siliceous yellowish red soils	17.6	2.9	2.9
				Plateau red soils	Chromic Acrisols	19.1	30.6	29.8	Argillaceous plateau red soils	13.1	28.1	28.5
									Diluvial plateau red soils	25.6	7.6	7.4
				Weakly developed red soils	Chromic Cambisols	5.2	3.2	3.1	Argillaceous weakly developed red soils	31.4	54.2	53.9
									Calcic weakly developed red soils	49.0	9.8	10.3

[a] Area percentages in soils of Yunnan Province.
[b] Reference method between the Genetic Soil Classification of China (GSCC) and World Reference Base for Soil Resources (WRB) is same to Shi et al.(2004a,b; 2006a,b).
[c] Area percentages in Red soil great group of Yunnan Province.
[d] Area percentages in their corresponding subgroups.

Table 3
SOC (soil organic carbon) density values of soil series under Arenaceous shale red soil family (Humic Acrisols, in WRB), Red soil subgroup, Red soil great group in Guangxi Zhuang Autonomous Region and their area proportions in the total of the soil family estimated by the SPS (soil profile statistics), the GST-2D (GIS-based 2-dimensional planar soil type), and the GST-3D (GIS-based 3-dimensional soil type) methods

Soil series	SOC density (kg C m^{-2})	Area percentage		
		SPS	GST-2D	GST-3D
Strongly developed sandy arenaceous shale red soils	15.8	4.3	0.8	0.9
Moderately developed sandy arenaceous shale red soils	7.5	3.5	2.3	2.3
Strongly developed arenaceous shale red soils	21.6	32.2	1.8	1.9
Moderately developed arenaceous shale red soils	7.1	42.0	79.2	78.9
Weakly developed arenaceous shale red soils	6.1	9.3	2.4	2.5
Strongly developed clay arenaceous shale red soils	14.6	5.1	11.7	11.8
Moderately developed clay arenaceous shale red soils	3.8	2.1	0.7	0.8
Weakly developed clay arenaceous shale red soils	5.5	1.5	1.0	1.0

in the variation in the areas of each soil type. The uncertainty caused by the calculation method comes from the precision of SOC density value of the sampling points and the linking methods by which the SOC density value is assigned to soil series (polygons).

This study used same profile sources and the same equation for the SOC density value of the sampling points, so the major differences were generated from the calculation method used to determine the distribution area of each soil type and the methods of linking SOC density value with soil polygons. The area of each soil type used in the SPS was directly taken from the statistics obtained from the Second National Survey of China, whereas the area of each soil type was derived from the digitized soil maps for the GST-2D, and those maps with the DEM for the GST-3D. Since the methods assigning the SOC density value to soil series (polygons) resulted in the uncertainty of area proportion of soil types and the GST-2D and the GST-3D employed the same linking method, the differences of SOC estimates by the three methods mainly resulted from the inconsistency of obtained soil distribution areas. While differences both in the total soil acreage and in the area proportions can result in variations of SOC storage estimates, the main source of variability was in the determination of the total soil area.

Since the surface area provides a better estimate of the land area than planimetric area (Jenness, 2004), it could be inferred that the GST-3D method provides the most accurate SOC storage estimates, holding all other factors equal, because it can obtain more accurate soil area information simultaneously reducing the uncertainty of soil area proportion. Moreover, accurate soil area information would benefit future continental scale carbon cycle research.

4. Conclusions

The terrain has large effects on the estimates of SOC in rugged regions and hence the surface area should be used to generate accuracy estimation. Given the extensive area of uneven terrain in the study area and the use of common data sets it is assumed the GST-3D provides the most accurate estimate of SOC storage. The estimate of SOC storage in Southwest China in the upper 1 m soil depth was 11,867.92 Tg C by the GST-3D. An underestimated result (6847.09 Tg C) was obtained by the SPS. The difference resulted from the underestimated soil area primarily caused by the complex topography and some minor soils excluded in the Soil Series. Compared with the GST-3D, a 9% lower SOC storage (10,906.52 Tg C) was estimated by the GST-2D also due to the rugged terrain.

The effect of landforms on the SOC estimates should be considered in Southwest China because of the complex terrains and high relief. For each of the four geomorphologic units of this studied area, the complex landforms had more than 30% of area with slopes greater than or equal to 18.2°. Such complex terrains could result in a difference of more than 6% between planimetric projection area and surface area. However, there is a need to further test these figures as threshold in the other mountainous regions. In addition, uncertainties raised in the GST-3D estimates could also be caused by limitations of map scale and basic map unit. Consequently, it is necessary to further study the impact of map scale and compilation effects on SOC storage estimation.

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