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Regional patterns of soil organic carbon stocks in China

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Abstract

Soil organic carbon (SOC) is of great importance in the global carbon cycle. Distribution patterns of SOC in various regions of China constitute a nation-wide baseline for studies on soil carbon changes. This paper presents an integrated and multi-level study on SOC stock patterns of China, and presents baseline SOC stock estimates by great administrative regions, river watersheds, soil type regions and ecosystem. The assignment is done by means of a recently completed 1: 1,000,000 scale soil database of China, which is the most detailed and reliable one in China at the present time. SOC densities of 7292 soil profiles collected across China in the middle of the 1980s were calculated and then linked to corresponding polygons in a digital soil map, resulting in a SOC Density Map of China on a 1: 1,000,000 scale, and a 1 km $\times$ 1 km grid map. Corresponding maps of administrative regions, river watersheds, soil types (ST), and ecosystems in China were also prepared with an identical resolution and coordinate control points, allowing GIS analyses. Results show that soils in China cover an area of 9.281×10^6 km^2 in total, with a total SOC stock of 89.14 Pg (1 Pg = 10^{15} g) and a mean SOC density of 96.0 t C/ha. Confidence limits of the SOC stock and density in China are estimated as [89.23 Pg, 89.08 Pg] and [96.143 t C/ha, 95.981 t C/ha] at 95% probability, respectively. The largest total SOC stock (23.60 Pg) is found in South-west China while the highest mean SOC density (181.9 t C/ha) is found in north-east China. The total SOC stock and the mean SOC density in the Yangtze river watershed are 21.05 Pg and 120.0 t C/ha, respectively, while the corresponding figures in theYellow river watershed are 8.46 Pg and 104.3 t C/ha, respectively. The highest total SOC stocks are found in Inceptisols (34.39 Pg) with SOC density of 102.8 t C/ha. The lowest and highest mean SOC densities are found on Entisols (28.1 t C/ha), and on Histosols (994.728.1 t C/ha), repectively. Finally, the total SOC stock in shrub and forest ecosystem classes are 25.55 and 21.50 Pg, respectively; the highest mean SOC density (209.9 t C/ha) was recorded in the wetland ecosystem class and the lowest (29.0 t C/ha) in the desert ecosystem class. Among five forest ecosystem types, Evergreen conifer forest stores the highest SOC stock (6.81 Pg), and Deciduous conifer forest shows the highest SOC density (225.9 t C/ha). Figures of SOC stocks stratified by Administrative regions, river watersheds, soil types and ecosystem types presented in the study may constitute national-wide baseline for studies of SOC stock changes in various regions in the future.

Keywords: Soil organic carbon stock; 1:1,000,000 Soil Database of China

1. Introduction

Soil organic carbon (SOC) is one of the most important carbon stocks globally and has large potential to affect global climate (IPCC, 2000; Pan et al., 2002). Accordingly, scientists from all over the world have initiated many studies on SOC stock (Batjies, 1996; Bohn, 1982; Buringh, 1984; Post et al., 1982; Rozhkov, 1996; Eswarran et al., 1993; Schlesinger, 1990; Lacelle, 1997; Bolin and Sukumar, 2000). SOC stock in surface soils worldwide has been estimated to be 2011 Pg C (Bolin and Sukumar, 2000), twice the value in either living vegetation or atmospheric carbon (IPCC, 2000). However, these estimates are highly uncertain largely because of data gaps for many regions of the world. SOC stock depends on local climatic and other site-specific conditions, as well as on the type of land-use and land management, it is sensitive to human interference, and to changes in land-use and soil management. To protect or increase the existing soil C pool by sequestration of C from the atmosphere could become crucial in terms of future

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policies to mitigate the global greenhouse effect (IPCC, 2000). As part of international efforts to stabilize atmospheric greenhouse gas concentrations, signatories to the Kyoto protocol are committed to establish national inventories of the C stock, and to estimate stock changes. This requires reliable estimates of C stocks at one timeline as a baseline which is stratified by land-use, soil type, climate region and watershed, etc. Recently, C stock inventories have been established, for instance, in different European countries (Arrouays et al., 2001; Batjes, 2002; Krogh et al., 2003), in North America (Lacelle, 1997), and in China (Fang, 1996; Pan, 1999; Wang and Zhou, 1999; Wang et al., 2000; Jin, 2000; Jin et al. 2001; Ni, 2001; Wu et al., 2003; Li et al., 2003; Xie et al., 2004a, b; Cheng et al., 2004; Zhao and Li, 1997; Zhang et al., 2004; Zhou and Zhao, 2000).

In China, SOC stock estimates are also uncertain largely because of inconsistent methods and limited data (Table 1). In most prior studies (Fang, 1996; Wang and Zhou, 1999; Wang et al., 2000; Jin, 2000; Jin et al., 2001), SOC density of a soil type has been estimated by calculation of the mean SOC density of its sub-type soils weighted by area (MWA), and SOC stock of the soil type calculated by its SOC density multiplied by its area obtained from a 1:4,000,000 digital soil map, and total SOC stock was estimated by summation of all soils (Fang, 1996; Wang and Zhou, 1999; Wang et al., 2000; Jin, 2000; Jin et al., 2001). The same method was applied recently by Wu et al. (2003) to assess SOC stock and changes in China. In this case, similarly, SOC density and total SOC were estimated for soils classified at the Group level based on densities of Sub-group soils, and the SOC density of Sub-group soil was assessed as the mid-value of all representative profiles sorted to the Sub-group (MDV) (Xie et al., 2004a, b). In contrast to prior studies, SOC densities of profiles of various soil Series were calculated directly (DPS), and then the total SOC stock was estimated by summing up all Series stocks, which was calculated by multiplication of SOC density of each soil Series and their area obtained from *Soil Series of China* (volume 1–6). A serious concern is that areas of soil Series in these books were only roughly guessed (Pan, 1999). In addtion to these empirical studies, SOC density and stock have been estimated using the bio-agro-chemical model Carbon Exchange among Vegetation-Soil-Atmosphere (CEVSA), which is driven by climate, soil, and vegetation data on a 0.5° latitude × longitude grid (Li et al., 2003) SOC stock has also been estimated using the BIOME3 model based on a 1:4,000,000 scale soil-vegetation map and other data (Ni et al., 2001).

Data sources used in prior estimates have also varied greatly. Soil profile records used in a single study have varied from 236 to 3600, scales of soil maps from 1:10,000,000 to 1:4,000,000, and figures for the surface area of soils in China adopted have varied from 6.600×10^6 to $9.449 \times 10^6\,km^2$. Finally, SOC stock derived from these estimates has also varied greatly, from 50 to180 Pg, and SOC density figures from 54.6 to 190.5 t C/ha (Table 1). Therefore, the first objective of the present study was to adopt more accurate and detailed basic data and reasonable methods, to obtain SOC stock figures with less uncertainty.

Prior studies on SOC stocks in China have usually focused on various soil types (Wang and Zhou, 1999; Wang et al., 2000; Li et al., 2001; Jin, 2000; Jin et al., 2001; Pan, 1999; Xie et al., 2004, b), and various land-use types and vegetation ecosystems, such as forest (Zhou et al., 2000), farmland (Han et al., 2004; Li et al., 2002) and grassland ecosystems (Wang et al., 2004). Most of these studies have been done at the province or district level, resulting in a lack of reliable estimated SOC stocks as one nation-wide baseline, which may be stratified by land-use, soil type, climate region and watershed, etc. The second objective of this study was to build such a basline for nation-wide SOC stocks.

2. Materials and methods

2.1. Data materials

The Soil Database of China at 1:1,000,000 scale (Shi et al., 2004a), established by the Institute of Soil Science, Chinese Academy of Sciences, was used in the study. It consists of 3 parts: namely, a Soil Spatial Database (digital soil maps), a Soil Attributes Database, and a Soil Reference System. The Soil Spatial Database was derived by digitizing, sheet-mosaicing, and re-compiling *the 1:1,000,000 scale Soil Map of the People's Republic of China* (The Office for the Second National Soil Survey of China, 1995), in which the basic mapping units/soil-types are based on soil Family in Genetic Soil Classification of China (GSCC), including 926 soil types and more than 94,000 polygons. The soil attributes database consists of a total of 81 soil attribute fields, including profile code, soil name (in GSCC), profile location, horizon name, thickness of profile, bulk density, organic matter content and gravel amounts, etc. Data from 7292 profiles in various soil types involved in the Soil Attributes Database were derived from the *Soil Series of China* (volumes 1–6) and *Soil Series Records of Provinces* (total 32 volumes). In comparison with the contents of the 1:4,000,000 scale database used by other scientists in former studies, mapping soil types of the digital soil map increased from 235 to 926; polygons increased from 3090 to 94,000; maximum and minimum polygon size decreased from 0.51 to 0.03 ha and 465.5×10^3 to $155.8 \times 10^3\,km^2$, respectively; soil profiles increased from 2456 (the least 236) to 7292 (Table 1).

Other data used include: digital 1:1,000,000 scale vector maps of Administrative Regions, River Watersheds and grid map Land Cover of China at 1 km × 1 km derived from quantitative remote sensing monitoring data (MODIS data, 2001) for China's terrestrial ecosystem (Liu and Niu, 2004). In addition, a digital soil types vector map in Soil Taxonomy of the USDA (ST) is also included, which is formed by converting soil names in the GSCC to those in ST, based on the Soil Spatial Database and the Soil Reference System (Shi et al., 2004b).

Table 1
Study cases on SOC stock in China

Researchers	Soil data source		Soil classification System based on	SOC density Valuation	Soil Area (10^6 km^2)	SOC stock (Pg, 10^{15}g)	SOC density (t C/ha)
	Soil maps profiles	Number of Soil					
Fang (1996)	1:10,000,000 (1978 ed.)	725	GSCC (1970s–1980s)	MWA[a]	9.449	180±	190.5
Wang (1999, 2000)	1:4,000,000 (1988 ed.)	236			9.255	100.18	108.3
		2473			8.776	92.42	105.3
Jin et al. (2001)	1:4,000,000 (1988 ed.) 1:10,000,000(1978ed.)	3600			6.600	81.76	123.9
Wu (2003)	1:4,000,000	Unknown* 923**			8.818	70.3* 77.4**	80.0* 88.0**
Pan (1999)	No map	2500		DPS[b]	9.150	50	54.6
Xie (2004)	1:4,000,000 (1998 ed.)	2456	CST (1st version, 1991)	MWA and MDV[c]	9.240	84.4	91.4
Ni (2001)	Climate, soil, and vegetation data with 10′ resolution in longitude and latitude grids, based on balance process terrestrial biosphere model (BIOME3)			CR[d]	9.596	119.76	124.8
Li, (2003)	Climate, soil, and vegetation data with 0.5° resolution in longitude and latitude grids, based on biogeochemistry model (CEVSA).			DLA[e]	9.011	82.65	91.7
Present study	1:1,000,000 (1995 ed.)	7292	CST (3rd version, 2001) and ST	DPL[f]	9.281	89.14	96.0

*Present-day; **Under non-cultivated conditions.

[a]SOC density of a soil type is mean density of its sub-type soils weighted by their area (MWA).

[b]SOC densities of profiles of various soil Series were used (DPS).

[c]SOC density of a soil classified at Group level was mean density of its sub-Groups soils weighted by their area (MWA), and densityof Sub-group soil was assessed as the mid-value of representative profiles (MDV).

[d]Soil carbon desnsity cited from Zinke (*World Organic Soil Carbon and Nitrongen Data, ORNL Ridge National Lab. Oak Ridge,1984*) and Prentice (*Global Ecol. Biogeog. Lett., 1993*) was used to give range of carbon density of various vegetable type (CR).

[e]SOC density of a landuse type is calculated by dividing its total SOC stock by total area (DLA).

[f]SOC densities of profiles were calculated and linked with soil polygones (DPL) in the present study.

2.2. Methods

Initially, SOC densities of 7292 soil profiles included in the Soil Attributes Database were calculated and added into the database. The calculation is based on the following formula:

$$\mathrm{SOCD} = \sum_{i=1}^{n} (1 - \theta_i\%) \times \rho_i \times C_i \times T_i/100,$$

where SOCD (C kg/m^2) is soil organic carbon density of a profile, θ_i is gravel (>2 mm) content in horizon i (%), ρ_i is soil bulk density in horizon i (g/cm^3), C_i is organic carbon content in horizon i (C g/kg), T_i is the thickness of horizon i (cm), and n is the numbers of horizons involved. Depths involved in calculation are usually recorded during the field observations with the maximum depth for calculation limited to 100 cm. For better comparison among data sets, only the top 100 cm is estimated for those profile depths over 100 cm. For profiles whose actual depth is over 100 cm in nature, but less than 100 cm was observed, data of the unobserved section is estimated by statistics derived from those soils of its type (Sun et al., 2003). For instance, Xiu-hei-yellow-soil (a soil family name in GSCC, ST Mollisols) is distributed in north-east China. Based on data of the soil profiles (a total of 8 samples) the curve estimated for the soil is $Y_D = 91.782 \times \mathrm{e}\hat{}(-1.0529 \times D)$, $R = -0.607$. (where Y_D is SOC content (g/kg), and D is soil depth (cm) (Sun et al., 2003)).

In the second step, a GIS was used to link records in the Attributes Database to the Spatial Database based on soil type (using the GisLST function in ESRI ArcGIS 9.0). In this method, all SOC densities records of 7292 soil profiles added in the Soil Attributes Database are allocated one by one onto corresponding soil type polygons in the Soil Spatial Database. The assignment is done according to principles of soil type identity and similarity, soil parent material identity or similarity between the soil profiles and polygons, as well as overlapping or closeness of linked target polygons relative to soil profile locations. Thereafter, a SOCD (kg/m^2) vector map of China was compiled by linking SOC density data of soil profiles calculated with the soil spatial database (using the DPL function).

Finally, a SOCD vector map was converted into a grid map with the same grid size (1 km $\times$ 1 km) and coordinate control points as the Land Cover maps, in which the grid value may be considered as the SOC stock value (10^3 t). In the same way, vector maps of Administrative Regions and River Watersheds were also converted into grid maps. All GIS steps were done on Esri software ArcGIS 9.0. Mean SOC density of a unit type, e.g. soil type/administrative region/Watershed/land use, was calculated by dividing its total SOC stock by its total area; the total SOC stock of the unit type was calculated by summing the SOC stock for all grids with same unit type.

3. Results

3.1. SOC stock and density in the great administrative regions of China

Statistics based on 85,180 soil polygons for the SOCD (kg/m^2) vector map of China (Fig. 1) show that SOC density and stock in various polygons varied dramatically, with the lowest SOC density 1.43 t C/ha, and the highest

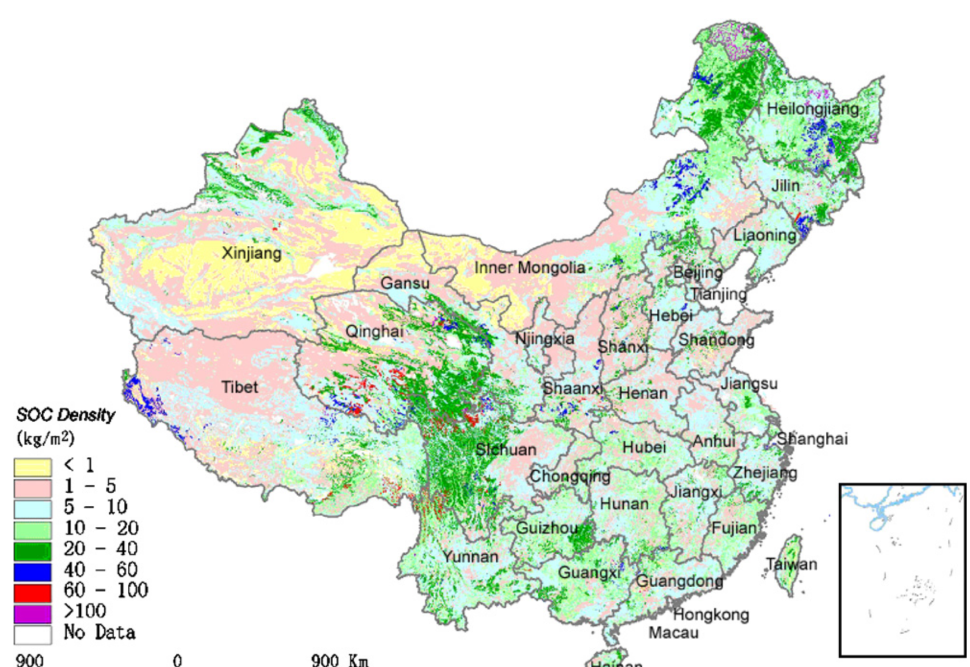

Fig. 1. Map of Soil organic carbon density in China.

4463 t C/ha. Soils in China cover a total area of $9.281 \times 10^6\,km^2$ (97.07% of the total area of China covered by the vector map), with a total SOC stock of 89.14 Pg, and a mean SOC density of 96.0 t C/ha.

Among the great administrative regions, South-west China stores the largest amount of soil carbon, with an SOC stock of 23.60 Pg. The highest mean SOC density is found in north-east China, 181.9 t C/ha, and the lowest is found in north-west China, 72.3 t C/ha (Table 2).

3.2. SOC stock and density in various river watersheds in China

Among river watersheds in China, the Yangtze River and Yellow River watersheds, both spanning from west to east China, are the longest; the Huaihe River watershed is an interlaced climate zone between the temperate and subtropic zones in east China, and the Pearl River watershed is in the south subtropic zone and the tropic zone (Guangdong province). Interior River watersheds consist of 14 interior river watersheds in west and north China. SOC stocks and densities of various watersheds are shown in Table 3. Interior River watersheds store the largest amount of soil carbon, with an SOC stock of 21.14 Pg, followed by the Yangtze River Watershed (21.05 Pg), and the Huaihe River Watershed stores the lowest amount of soil carbon (1.75 Pg). The highest mean SOC density is found in the Heilongjiang River Watershed, 211.0 t C/ha, and the lowest is found in Interior River Watersheds, 59.6 t C/ha (Table 3).

3.3. SOC stock and density in various soil orders (ST) in China

Eleven ST Orders are found in China. Among them, Inceptisols store the highest SOC stock and Andisols store the lowest because they occupy the largest and smallest areas, respectively. As for mean SOC density figures, Histosols show the highest SOC density, and Entisols the lowest, differing by a factor of 37. The standard deviation

Table 2
SOC density and stock of Great Administrative Regions in China

Great Administrative Regions in China	Included provinces or cities	Total area ($10^3\,km^2$)	SOC density (t C/ha)	SOC stock (Pg, 10^{15}g)
North China	Beijing, Tianjin, Hebei, Shanxi, Neimonggu (Inner Mongolia)	1518.4	91.2	13.79
North-east China	Liaoning, Jilin, Helongjiang	789.2	181.9	14.25
East China	Shanghai, Jiangsu, Anhui, Zhejiang, Jiangxi, Fujian, Shandong	791.6	83.0	6.31
Central-south China	Hubei, Hunan, Henan, Guangdong, Guangxi, Hainan	1010.5	98.2	9.72
South-west China	Chongqing, Sichuan, Guizhou, Yunnan, Xizang (Tibet)	2329.0	103.8	23.60
North-west China	Shaanxi, Gansu, Ningxia, Qinghai, Xinjiang	3014.0	72.3	21.10
Taiwan–Hongkong–Macau region	Taiwan, Hongkong, Macau	37.1	102.8	0.37

Table 3
SOC density and stock of the longest river watersheds in China

Watersheds	Area ($10^3\,km^2$)	SOC density (t C/ha)	SOC stock (Pg, 10^{15} g)
Heilongjiang River Watershed	673.9	211.0	14.06
Liaohe River Watershed	261.0	79.4	2.06
Haihe-Luanhe River Watersheds	322.2	84.2	2.69
Yellow River Watershed	817.0	104.3	8.46
Huaihe River Watershed	267.6	67.1	1.75
Yangtze River Watershed	1788.6	120.0	21.05
Southeastern China Coastal River Watersheds	256.2	93.6	2.64
Pearl River Watershed	536.2	115.4	6.03
Yunnan, Xizang, and Xinjiang International Rivers Watersheds	885.5	107.7	9.26
Interior River Watersheds	3681.6	59.6	21.14

of SOC density of all Orders is 297.4 t C/ha, while that of SOC stock is 10.2 Pg (Table 4). In the Yangtze River watershed, all 11 ST Orders are found, while only seven ST Orders are found in the Yellow River watershed (Table 5). Inceptisols represent most of the total SOC in the Yangtze River watershed, followed by Alfisols and Ultisols. SOC stocks of Molisols and Inceptisols in the Yellow River represent most of the watershed's total SOC. As for SOC density figures, those of Histosols are the highest in both watersheds, but Histosols in the Yellow River watershed show values about 1.5 times as high as those in the Yangtze River watershed. SOC densities of Orders are also quite different between the two longest watersheds (Table 5).

3.4. SOC stock and density in various ecosystem regions in China

Seven ecosystem types were used in the study, with SOC stock and density of each ecosystem type shown in Table 6. SOC density of farmland is higher than grassland, because desertified grassland in north-west China is included in the grassland ecosystem (Table 6). This also likely accounts for the difference in grassland SOC values between the Yangtze River watershed and the Yellow River watershed (Table 7). Although the constitutions of SOC stock of the ecosystems in theYangtze River and Yellow River watersheds are very different, the SOC stocks of shrub ecosystems in the two largest watersheds represent the biggest share (i.e. 50.62% and 49.14%), and those of urban land take the lowest share (i.e. 0.16% and 0.21%), respectively (Table 7). In addition, large differences are found between SOC density patterns of ecosystems in the two watersheds (Table 7).

Five forestland types were used in the study. Four climatic zones are found in China. Evergreen broad-leaved forest (0.293 Pg), Evergreen conifer forest (4.73 Pg), Deciduous broad-leaved forest (3.71 Pg) and Evergreen conifer forest (0.333 Pg) store the highest SOC stock in the Tropical, Subtropical, Temperate and High plateau zones, respectively (Table 8). As for mean SOC density figures, SOC densities of Evergreen conifer forest in the Tropical and Subtropical zones are the highest (i.e. 121.1 and 112.3 t C/ha), while Deciduous conifer forest (225.9 t C/ha) and Mixed forest (193.1 t C/ha) show the highest SOC density in the Temperate and High plateau zones, repectively (Table 8). Totally, among five forestland types, Evergreen conifer forest stores the highest SOC stock (6.81 Pg), and Deciduous conifer forest shows the highest SOC density (225.9 t C/ha) (Table 8).

Table 4
SOC density and stock of ST-Orders in China

ST-Orders	Area (10^3 km^2)	SOC density (t C/ha)	SOC stock (Pg, 10^{15} g)
Alfisols	1224.1	134.1	16.41
Andisols	2.7	146.3	0.04
Aridisols	1723.2	36.34	6.26
Entisols	1366.0	28.12	3.84
Histosols	63.0	994.7	6.26
Inceptisols	3346.4	102.8	34.39
Mollisols	674.0	172.9	11.65
Oxisols	53.4	86.15	0.46
Spodosols	1.4	588.5	0.08
Ultisols	799.3	119.4	9.54
Vertisols	27.5	72.83	0.20

Table 6
SOC density and stock of ecosystems in China

Ecosystems	Area (10^3 km^2)	SOC density (t C/ha)	SOC stock (Pg, 10^{15} g)
Forestland	1500.3	143.3	21.50
Shrubland	2216.0	115.3	25.55
Grassland	1376.2	82.4	11.34
Farmland	1323.2	92.2	12.20
Wetland	727.9	167.5	12.20
Desertland	2124.1	29.0	6.16
Urban area[a]	14.7	81.7[a]	0.12[a]

[a]Only showing SOC stock of soils covered by extensions of urban areas since 1980s.

Table 5
SOC density and stock of ST-Orders in Yangtze and Yellow Rivers watersheds

ST-Orders	Yangtze River watershed			Yellow River watershed		
	Area (10^3 km^2)	SOC density (t C/ha)	SOC stock (%)	Area (10^3 km^2)	SOC density (t C/ha)	SOC stock (%)
Alfisols	323.1	142.1	21.81	124.7	87.96	12.97
Andisols	0.5	127.9	0.03	—	—	—
Aridisols	36.0	33.37	0.57	106.6	43.73	5.51
Entisols	92.5	55.74	2.45	104.7	41.39	5.12
Histosols	14.5	649.6	4.48	9.1	960.5	10.33
Inceptisols	924.8	110.3	48.46	342.6	78.28	31.70
Mollisols	46.0	270.1	5.90	123.5	235.2	34.34
Oxisols	1.9	100.9	0.09	—	—	—
Spodosols	1.3	565.2	0.34	—	—	—
Ultisols	310.3	106.7	15.73	—	—	—
Vertisols	3.7	85.05	0.15	0.2	68.17	0.02

Table 7
SOC density and stock of ecosystems in Yangtze and Yellow River watersheds

Ecosystems	Yangtze River watershed			Yellow River watershed		
	Area (10^3 km^2)	SOC density (t C/ha)	SOC stock (%)	Area (10^3 km^2)	SOC density (t C/ha)	SOC stock (%)
Forestland	381.8	120.7	21.89	35.6	126.6	5.32
Shrubland	830.5	128.3	50.62	365.0	113.9	49.14
Grassland	50.5	98.7	2.37	192.7	60.9	13.87
Farmland	359.5	81.5	13.92	97.6	64.9	7.49
Wetland	113.1	197.1	10.59	74.3	252.1	22.14
Desertland	15.7	60.2	0.45	43.8	35.0	1.81
Urban area[a]	3.9	87.3[a]	0.16[a]	2.3	78.2[a]	0.21[a]

[a]Only showing SOC stock of soils covered by extensions of urban areas within the watershed since 1980s.

Table 8
SOC density and stock of forestland in different climatic zone in China

Climatic zone	Forest type	Area (10^3 km^2)	SOC density (t C/ha)	SOC stock (Pg, 10^{15} g)
Tropical	Evergreen conifer forest	4.71	121.1	0.0570
	Evergreen broad-leaved forest	26.65	109.8	0.2926
	Deciduous broad-leaved forest	0.07	117.1	0.0008
	Mixed forest	2.33	105.9	0.0247
Sub-tropical	Evergreen conifer forest	421.03	112.3	4.7265
	Evergreen broad-leaved forest	232.81	104.4	2.4313
	Deciduous broad-leaved forest	27.71	107.4	0.2976
	Mixed forest	78.71	111.2	0.8751
Temperate	Evergreen conifer forest	43.14	128.5	0.5543
	Deciduous conifer forest	164.11	225.9	3.7075
	Deciduous broad-leaved forest	274.84	168.4	4.6275
	Mixed forest	101.54	188.2	1.9108
High plateau	Evergreen conifer forest	88.27	166.3	1.4681
	Evergreen broad-leaved forest	13.15	92.0	0.1209
	Deciduous conifer forest	0.02	113.7	0.0002
	Deciduous broad-leaved forest	3.92	183.0	0.0718
	Mixed forest	17.25	193.1	0.3331
Total	Evergreen conifer forest	557.3	122.2	6.81
	Evergreen broad-leaved forest	272.7	104.3	2.84
	Deciduous conifer forest	164.1	225.9	3.71
	Deciduous broad-leaved forest	306.5	163.0	5.00
	Mixed forest	199.8	157.3	3.14

4. Discussion

4.1. Comparative analysis of studies reporting SOC stock patterns of China

Estimates of SOC stocks in China derived from available studies varied greatly (Table 1). Among published figures, Wang's 92.42 Pg for China's SOC stock (Wang et al., 2000) is the closest to the figure (89.14 Pg) generated by the present study; Li's mean SOC density figure of 91.7 t C/ha (Li et al., 2003) is the least different from the present figure (96.0 t C/ha).

Zhou (2000) estimated the SOC stock of China's forest ecosystem as 21.02 Pg and the mean SOC density as 193.6 t C/ha. Xie (2004) calculated 17.39 Pg and 115.9 t C/ha, respectively, for the same ecosystem. Comparatively, the SOC stock figure for forest ecosystems in the present study (21.50 Pg) is quite close to that of Zhou's 21.02 Pg (2000). However, the mean SOC density figure for forest ecosystems (143.3 t C/ha) found in the present study differs greatly from those in the two studies just mentioned, 50.3 t C/ha lower than Zhou's (2000), but 27.4 t C/ha higher than Xie's (2004).

Differences in data sources and methodology for estimation are the main causes of variability of results in available studies. The data source involved in the present study is the most detailed and systematic of all available studies. But was our methodology the most appropriate?

Based on the same database used in this study, the mean SOC density weighted by area (MWA) and the mid-values of SOC density of various soil profiles (MDV) were applied to the two methods of SOC density valuation used in the former studies, respectively, to estimate China's SOC stock. The values of SOC storage obtained in the study were 92.51 and 72.69 Gt when GSCC groups were the basic map unit, and 93.79 and 83.47 Gt when GSCC sub-groups were the basic map unit by using the weighted mean value (MWA) and mid-value SOC density (MDV) estimation methods, respectively. Obviously, the values obtained by the MWA method were higher than those by the MDV method, and the value 89.14 Gt obtained by the calculated profile values method (DPL), which was used in this study, represents a middle point between the other two studies. When GSCC sub-groups were the basic map unit, and the SOC density of a sub-group calculated was the average value of all associated soil profiles sorted to the sub-group, the SOC stock estimated is 90.75 Gt, which is very close to 89.14 Gt.

Other evidence for the superiority of the DPL method is derived from a preliminary study in Hebei Province. Digital soil maps at different scales varying from 1:10,000,000 to 1:500,000 used the same data from 363 soil profiles. This was achieved by linking the "weighted mean value" (MWA), "mid-value" (MDV), and "calculated profile values" (DPL) of SOC density of various soil profiles with related polygons in these soil maps, with the aid of the "GIS linkage soil type method" (GisLST). Results of this preliminary study show that, the least uncertain one was that where "calculated profile values" (DPL) were applied on the basis of soil maps at scales of 1:1,000,000 and 1:500,000 (Zhao et al., 2005, 2006). The DPL method in the present study and the SOC stock estimate results are probably the most reliable.

4.2. Statistical analysis for the SOC stock estimate

The 7292 SOC soil profile densities in the present study were linked to 85,180 soil polygons. So, there are two groups of SOC density samples for statistical analysis, soil profiles and soil polygons group samples. The sample sizes are 7292 and 85,180, and the degrees of freedom are 7291 and 85,179, respectively. Statistics descriptions are given in Table 9. A test for homogeneity variances by Fisher's method between the two group samples was done; $F(\mathrm{SD}^2_{\mathrm{polygons}}/\mathrm{SD}^2_{\mathrm{profiles}})$ was 1.0885 ($>F_{85,179,\ 7291}$). That is to say that $\sigma^2_{\mathrm{polygons}}/\sigma^2_{\mathrm{profiles}}$) is a null hypothesis, which means the standard deviations (σ) in the population of SOC densities in the two groups are different. For the average SOC density in population ($\bar{u}$) of the soil polygons group samples, the hypothesis ($\bar{u} = 105.269$ t C/ha) is accepted, where 105.269 t C/ha is the average SOC density of the soil profiles group samples. The hypothesis was tested using a T-test ($t = 0.61433$). The average SOC densities ($\bar{u}$) in the populations of the two groups are equal. The GisLST is used to link SOC density profiles with polygons in the study, resulting in a standard deviation (σ) of SOC density in the soil polygons group that is different from that in the soil profiles group, but their average SOC densities ($\bar{u}$) in the population are the same. This is a key factor in estimating SOC Stock. The method adopted in the study is probably better than others.

In this study, the SOC density vector map was converted to a grid map (1 km × 1 km). 9,281,106 soil grids are found on the map. Their mean SOC density is 96.062 t C/ha, which is less than those of the soil profiles and the soil polygons (Table 8). The mean SOC densities of soil profiles and soil polygons are only average values and have no relationship to their area, while that of the soil grids is weighted by grid area (1 km^2/grid). In the grid-based method, the mean SOC density of a soil type was calculated by dividing its total SOC stock by its total area. So the mean SOC density of grids (96.062 t C/ha) should be very close to the one (96.046 t C/ha) used in the present study, which was obtained from a SOC density vector map. Based on the SOC density of soil grids, the 95% confidence interval of the mean SOC density in the population of soil grids is estimated to be [96.143 t C/ha, 95.981 t C/ha], and that of SOC stock in the same polulation is [89.2313 Pg, 89.0801 Pg]. Therefore, the present study achieved results that are more reliable with less uncertainty than previous studies because more detailed and reliable basic data as well as the more reasonable methodology were used in the estimation.

5. Conclusions

In comparison with various 1:4,000,000 databases used in previous studies, the 1:1,000,000 soil database used in the present study is more detailed and reliable. Soil units/types in the digital soil map increased from 235 to 926; polygons increased from 3090 to 94,000; the maximum and minimum polygon sizes decreased from 0.51 to 0.03 ha, and from 465.5×10^3 to 155.8×10^3 km^2, respectively; the number of soil profiles increased from 2456 (the least 236) to 7292. By using the soil spatial database (DPL), a SOCD (kg/m^2) map of China was compiled. Data from the map indicate that soils in China cover a surface area of 9.281×10^6 km^2, with a total SOC stock of 89.14 Pg, and a

Table 9
Statistics descriptions of SOC density estimate

Samples	N	Minimum (t C/ha)	Maximum (t C/ha)	Mean (t C/ha)	SD (t C/ha)	F
Soil profiles (Profiles group)	7292	1.43	4462.49	105.269	157.265	—
Soil ploygons (Ploygons group)	85,180	1.43	4462.49	106.451	164.080	1.0885
Soil grids(1 km × 1 km) (Grids group)	9,281,106	1.43	4462.49	96.062	144.456	/

mean SOC density of 96.0 t C/ha within a depth of 1 m. The 95% confidence intervals of them are [89.2313 Pg, 89.0801 Pg] and [96.143 t C/ha, 95.981 t C/ha], respectively. Linking SOC density profiles with polygons by the GisLST method resulted in changes in the standard deviation (σ) of SOC densities (based on an *F*-test), but mean SOC densities ($\bar{u}$) in the population did not change (based on a *T*-test), which is a key factor in estimating the SOC stock. Therefore, the DPL method used in this study is probably more accurate than previous studies, and the SOC stock estimated is probably most reliable for China at the present time.

South-west China has the largest SOC stock of 23.60 Pg, and north-east China has the highest SOC density at 181.9 t C/ha, among China's 7 great administrative regions; the Yangtze River and Yellow River basins, with the largest of the ten major river basins in China, have estimated SOC stocks of 21.05 and 8.46 Pg, respectively, and mean SOC densities are estimated to be 120.0 and 104.3 t C/ha, respectively. Among the 11 ST-Soil Orders, the largest SOC stock (33.39 Pg) and density (994.7 t C/ha) are found in the Inceptisols and Histosols, respectively, and among the seven ecosystem types, the largest SOC stock (25.55 Pg) and density (167.5 t C/ha) are found in the Shrubland and Wetland systems, respectively. Remarkable variations are found in the SOC stock distribution patterns of the various regions. The SOC stock values stratified by Administrative regions, river watersheds, soil types and ecosystem types in the present study provide a baseline for SOC stock change studies in the future.

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