Biogeochemistry (2007) 84:131–141
DOI 10.1007/s10533-007-9109-z

ORIGINAL PAPER

Storage, patterns and environmental controls of soil organic carbon in China

Yuanhe Yang · Anwar Mohammat · Jianmeng Feng · Rui Zhou · Jingyun Fang

Received: 11 September 2006 / Accepted: 23 January 2007 / Published online: 14 March 2007

Abstract Based on the data from China's second national soil survey and field observations in northwest China, we estimated soil organic carbon (SOC) storage in China and investigated its spatial and vertical distribution. China's SOC storage in a depth of 1 meter was estimated as 69.1 Pg (10^{15} g), with an average density of 7.8 kg m^{-2}. About 48% of the storage was concentrated in the top 30 cm. The SOC density decreased from the southeast to the northwest, and increased from arid to semi-humid zone in northern China and from tropical to cold-temperate zone in the eastern part of the country. The vertical distribution of SOC differed in various climatic zones and biomes; SOC distributed deeper in arid climate and water-limited biomes than in humid climate. An analysis of general linear model suggested that climate, vegetation, and soil texture significantly influenced spatial pattern of SOC, explaining 78.2% of the total variance, and that climate and vegetation interpreted 78.9% of the total variance in the vertical SOC distribution.

Y. Yang · A. Mohammat · J. Feng · R. Zhou ·
J. Fang (✉)
Department of Ecology, College of Environmental Sciences, and Key Laboratory for Earth Surface Processes of the Ministry of Education, Peking University, Beijing 100871, China
e-mail: jyfang@urban.pku.edu.cn

Keywords Climate · Spatial distribution · Soil organic carbon · Soil texture · Vegetation · Vertical distribution

Introduction

Soil is the largest organic carbon reservoir in terrestrial biosphere, containing more carbon than vegetation and the atmosphere (Schlesinger 1997), and thus plays a crucial role in the terrestrial carbon cycle (Johnston et al. 2004). Although a number of studies on soil organic carbon (SOC) storage have been reported (Post et al. 1982; Batjes 1996; Jobbágy and Jackson 2000; Bellamy et al. 2005; Liu et al. 2006), its density, regional patterns and environmental controls remain to be a large source of uncertainties in understanding the global carbon cycle (Torn et al. 1997; Jobbágy and Jackson 2000).

China, with a broad geographical span and a large climatic range extending from tropical to alpine and from arid to humid and diverse biomes from desert to rainforest, has provided a unique field for examining distribution of the SOC density and its relationship with environmental factors.

During the past 10 years, China's SOC storage has been estimated using the data either from global soil database (Peng and Apps 1997; Ni 2001) or from China's national soil survey (Fang et al. 1996; Wang et al. 2003; Wu et al. 2003a). According to these estimates, total SOC storage in China varies from 70.3 to 185.7 Pg C. The large difference between these estimates may be resulted from the following reasons: (1) difference in data used for the estimation; (2) the small number of soil profiles from the Tibetan Plateau and other northwestern regions (the area of these regions totals about 1/3 of China's total area) in the second national soil survey which have been widely used to estimate China's SOC storage (Fang et al. 1996; Pan et al. 2003; Wang et al. 2003; Wu et al. 2003a); and (3) different soil depths used in the different estimations, which made these estimates incomparable to each other and with other studies in the world. Overcoming these shortages is the key for the accurate estimation of China's SOC storage and the distribution of SOC density.

In this study, we first establish relationship between SOC density and soil depth for each soil type in China to estimate SOC density for different soil depths. We then use general linear model (GLM) to explore the relationships between SOC density and environmental variables (climate, vegetation and soil texture). Therefore, the objectives of this study are to (1) estimate China's SOC storage for a depth of 1 m, (2) investigate the spatial and vertical SOC distribution, and (3) examine the factors controlling SOC stocks in China.

Data and methods

Data sources

National soil survey data

From 1979 to 1985, China conducted the second national soil survey across the country (National Soil Survey Office 1993, 1994a, b, 1995a, b, 1996, 1998). The survey provides information on taxonomic classification, bulk density, soil organic matter, thickness, soil area, volume percentage of the fraction >2 mm, and so on, for 2473 soil profiles, which were sampled in the middle of each horizon (National Soil Survey Office, 1998).

Regional field survey data

Because very scarce soil profiles were surveyed in the Tibetan Plateau and other northwestern regions during the second national soil survey, we have supplemented 810 soil profiles from 270 sites (3 soil profiles for each site) during 2001–2004 (Fig. 1). For each profile, soil was sampled at each mid-depth of different layers (0–10, 10–20, 20–30,

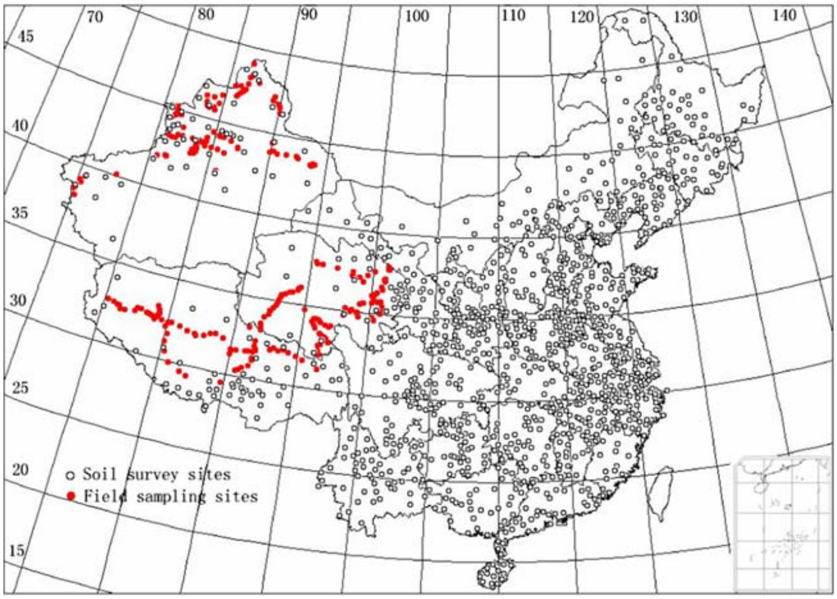

Fig. 1 Distribution of soil profiles used in this study. Solid points are profiles from field investigation, and open points are profiles from the national soil survey

30–50, 50–70, and 70–100 cm). Soil samples were taken to laboratory and air-dried, weighed, and sieved (2 mm mesh). One sub-sample was oven-dried at 105°C to a constant mass. Bulk density was estimated by the oven-dry soil mass and core volume (100 cm^3). The left sub-sample was hand-picked to remove the fine roots and then ground on a ball mill for carbon analysis. The SOC concentration was measured by a wet combustion with $K_2Cr_2O_7$ (Nelson and Sommers 1982).

Soil map and soil texture

A soil map of China with a scale of 1:4,000,000 (Tian et al. 1996) was used to document the information on distribution of soil types. Because soil taxonomy used in the second national soil survey was not fully consistent with that of the soil map, we merged some similar soils according to the principle of approximation (Li et al. 2001). Soil texture was derived from a digitized map of soil texture of China (Deng 1986), which was then aggregated to grid cells at a resolution of 0.1 × 0.1 degrees. Soil texture for each soil type was obtained by overlaying the map of soil texture over the soil map of China.

Climate data

Monthly mean air temperature and precipitation data at a resolution of 0.1 × 0.1 degrees were obtained from the 1970–1999 climate database of China (Piao et al. 2003). Climate data for each soil type was obtained from this climate dataset. Because of significant correlation between mean annual temperature (MAT) and annual precipitation (AP) ($P < 0.05$) in China, we used humidity index (H) (Eq. 1) (Tuhkanen 1980) as a bioclimatic index to explore the relationship between SOC and climate. According to three H ranges (0–20, 20–40, and 40–80), we categorized the country into three climatic regions: arid, semi-arid/semi-humid, and humid region.

$$H = \frac{\mathrm{AP}}{\mathrm{MAT} + 10} \tag{1}$$

where MAT and AP are mean annual temperature and annual precipitation, respectively.

Calculation of SOC storage

SOC density (SOCD) decreases with soil depth (Jobbágy and Jackson 2000). We used the following method to estimate SOCD. We first calculated SOCD at different soil depths, then regressed the relationship between SOCD and soil depth, and further calculated SOCD for 1 m depth. Their calculations were conducted by the following equations (Eqs. 2–4).

$$\mathrm{SOCD}_h = 0.58 \times \mathrm{BD}_h \times \mathrm{SOM}_h \times (1 - C_h)/100 \tag{2}$$

$$\mathrm{SOCD}(h) = a \times \exp^{b \times h} \tag{3}$$

$$\mathrm{SOCD} = \int_{h_1}^{h_2} \mathrm{SOCD}(h)d(h) \times 10 \tag{4}$$

where h is soil depth (cm), SOCD_h is SOCD (g cm^{-3}) at h (cm), 0.58 is the Bemmelen index that converts organic matter into organic carbon, and BD_h, SOM_h, and C_h represent bulk density (g cm^{-3}), soil organic matter (%), and volume percentage of the fraction >2 mm at h (cm), respectively; a and b are coefficients; and SOCD is SOC density for 1 m deep for each soil type (kg m^{-2}), and h_1 and h_2 are depths of soil profile (cm). The parameters in Eq. 3 are listed in Table 1.

Considering the lack of bulk density data in some profiles, we developed an empirical relationship between soil organic matter and bulk density (Fig. 2), to estimate bulk density for these profiles. Because of the lack of soil data from the Taiwan province, we used the organic carbon density of corresponding soil types in China's mainland as a substitute (Wu et al. 2003a). After excluding areas with waterbody, glaciers, perennial snow, and rock hills, total soil area used in this study amounted to 880.37×10^4 km^2. China's total SOC storage (SOCS) was calculated by the following equation:

$$\mathrm{SOCS} = \sum_{i=1}^{n} \mathrm{Area}_i \times \mathrm{SOCD}_i \tag{5}$$

Table 1 Density and storage of organic carbon at the top 30 cm and 100 cm for each soil type in China, and parameters used to fit SOC density (SOCD)

Soil type	Biome	*a*	*b*	*n*	r^2	Area (10^4 km^2)	Soil organic carbon density (kg C m^{-2})			Soil organic carbon storage (Pg C)	
							0–30 cm	0–100 cm	Proportion	0–30 cm	0–100 cm
Latosols	Forest	0.1349	–0.0077	71	0.18	3.93	3.6	9.4	0.38	0.14	0.37
Latosolic red earths	Forest	0.1936	–0.0139	95	0.50	18.10	4.7	10.5	0.45	0.85	1.90
Red earths	Forest	0.1477	–0.0144	390	0.45	57.73	3.6	7.8	0.46	2.08	4.50
Yellow earths	Forest	0.2321	–0.0168	114	0.42	23.85	5.5	11.2	0.49	1.31	2.67
Yellow-brown earths	Forest	0.1861	–0.0169	114	0.43	18.38	4.4	9.0	0.49	0.81	1.65
Brown earths	Forest	0.1515	–0.0162	293	0.41	20.15	3.6	7.5	0.48	0.72	1.51
Dark-brown earths	Forest	0.2807	–0.0188	209	0.43	40.19	6.4	12.7	0.50	2.57	5.10
Brown coniferous forest soils	Forest	0.4395	–0.0146	28	0.19	11.65	10.7	23.2	0.46	1.25	2.70
Grey forest soils	Forest	0.1984	–0.0171	25	0.47	3.15	4.7	9.5	0.49	0.15	0.30
Chernozems	Steppe	0.1856	–0.0116	298	0.27	13.21	4.8	11.3	0.43	0.63	1.49
Castanozems	Steppe	0.1605	–0.0104	178	0.31	37.49	4.1	9.9	0.41	1.54	3.71
Brown caliche soils	Steppe	0.0601	–0.0096	157	0.20	26.50	1.6	3.9	0.41	0.42	1.03
Sierozems	Steppe	0.0628	–0.0076	105	0.28	5.37	1.7	4.4	0.39	0.09	0.24
Cold calcic soils	Steppe	0.1663	–0.0136	48	0.29	11.30	4.1	9.1	0.45	0.46	1.03
Cold brown calcic soils	Steppe	0.1394	–0.0126	57	0.31	0.96	3.5	7.9	0.44	0.03	0.08
Frigid calcic soils	Steppe	0.0995	–0.0176	201	0.32	68.82	2.3	4.7	0.49	1.58	3.23
Mountain meadow soils	Meadow	0.4342	–0.0176	57	0.47	4.21	10.1	20.5	0.49	0.43	0.86
Felty soils	Meadow	0.3829	–0.0253	221	0.37	53.51	8.0	13.9	0.58	4.28	7.44
Dark felty soils	Meadow	0.3864	–0.0268	163	0.52	19.43	8.0	13.4	0.60	1.55	2.60
Meadow soils	Meadow	0.2101	–0.0149	290	0.38	25.07	5.1	10.9	0.47	1.28	2.73
Shruby meadow soils	Meadow	0.1382	–0.0184	11	0.88	2.48	3.2	6.3	0.51	0.08	0.16
Gray desert soils	Desert	0.0737	–0.0110	47	0.40	4.59	1.9	4.5	0.42	0.09	0.21
Gray-brown desert soils	Desert	0.0328	–0.0027	53	0.10	30.72	0.9	2.9	0.31	0.28	0.89
Brown desert soils	Desert	0.0201	–0.0053	38	0.15	24.29	0.6	1.6	0.38	0.15	0.39
Frigid desert soils	Desert	0.0334	–0.0028	39	0.22	14.18	1.0	3.0	0.30	0.14	0.43
Frigid frozen soils	Desert	0.1279	–0.0535	13	0.48	30.63	1.9	2.4	0.58	0.74	0.79
Paddy soils	Crop	0.1833	–0.0147	1787	0.37	30.56	4.4	9.6	0.46	1.34	2.93
Irrigated silting soils	Crop	0.1100	–0.0059	93	0.23	1.53	3.0	8.3	0.36	0.05	0.13
Irrigated desert soils	Crop	0.1464	–0.0102	89	0.45	0.92	3.8	9.2	0.41	0.03	0.08
Bleached Beijing soils	Crop	0.2096	–0.0182	75	0.58	5.27	4.9	9.7	0.51	0.26	0.51
Gray-cinnamon soils	Crop	0.2574	–0.0149	68	0.46	6.18	6.2	13.4	0.46	0.38	0.83
Black soils	Crop	0.2235	–0.0118	129	0.40	7.35	5.7	13.1	0.44	0.42	0.96
Dark loessial soils	Crop	0.1094	–0.0046	77	0.42	2.55	3.1	8.8	0.35	0.08	0.22
Limestone soils	Crop	0.2334	–0.0162	134	0.48	10.78	5.5	11.6	0.47	0.59	1.25
Yellow-cinnamon soils	Crop	0.0936	–0.0114	79	0.62	3.81	2.4	5.6	0.43	0.09	0.21
Torrid red soils	Crop	0.1234	–0.0178	45	0.38	0.70	2.9	5.8	0.50	0.02	0.04
Cinnamon soils	Crop	0.0821	–0.0712	464	0.27	25.16	2.2	5.9	0.37	0.55	1.48

Table 1 continued

Soil type	Biome	a	b	n	r^2	Area (10^4 km^2)	Soil organic carbon density (kg C m^{-2})			Soil organic carbon storage (Pg C)	
							0–30 cm	0–100 cm	Proportion	0–30 cm	0–100 cm
Castano-cinnamon soils	Crop	0.0725	–0.0053	54	0.23	4.82	2.0	5.6	0.36	0.10	0.27
Loessial soils	Crop	0.0635	–0.0060	113	0.20	12.28	1.7	4.8	0.35	0.21	0.59
Red primitive soils	Crop	0.0880	–0.0117	62	0.47	1.84	2.2	5.2	0.42	0.04	0.10
Neo-alluvial soils	Crop	0.0719	–0.0087	151	0.14	4.97	1.9	4.8	0.40	0.09	0.24
Purplish soils	Crop	0.0998	–0.0115	240	0.36	18.89	2.5	5.9	0.42	0.47	1.11
Fluvi-aquic soils	Crop	0.0830	–0.0082	762	0.19	25.66	2.2	5.7	0.39	0.56	1.46
Saijiang black soils	Crop	0.1045	–0.0113	80	0.43	3.76	2.7	6.3	0.43	0.10	0.24
Solonchaks	Others	0.0840	–0.0075	219	0.11	16.14	2.3	5.9	0.39	0.37	0.95
Solonetzs	Others	0.0716	–0.0991	70	0.17	0.87	1.9	4.6	0.41	0.02	0.04
Peat soils	Others	0.7706	–0.0063	17	0.12	1.48	21.1	57.2	0.37	0.31	0.85
Bog soils	Others	0.4496	–0.0133	117	0.21	12.61	11.1	24.8	0.45	1.40	3.13
Aeolian soils	Others	0.0360	–0.0091	115	0.16	67.53	0.9	2.4	0.38	0.61	1.62
Skeletal soils	Others	0.0906	–0.0192	107	0.22	26.10	2.1	4.0	0.53	0.55	1.04
Lithosols	Others	0.2230	–0.0523	25	0.25	18.72	3.4	4.2	0.81	0.64	0.79
Total						880.37	3.7	7.8	0.48	32.93	69.08

SOCD was expressed as a function of soil depth (h), $\mathrm{SOCD}(h) = a \times \exp^{b \times h}$, where a and b are coefficients for each soil type

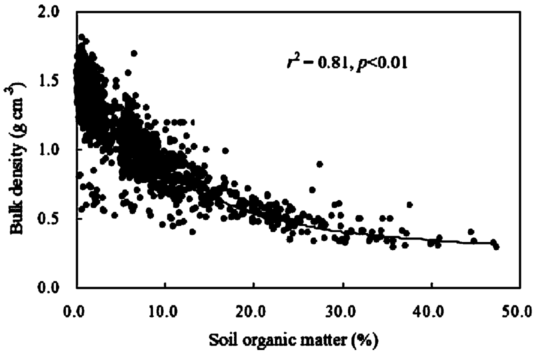

Fig. 2 Relationship between bulk density (y) and soil organic matter (x). The line is fit by $y = 0.29 + 1.2033\exp^{-0.0775x}$, which is used to estimate bulk density for soils without bulk density

where n is the number of soil types, and Area_i and SOCD_i are soil area and SOCD for soil type i.

Vertical distribution of SOC

We investigated vertical distribution of SOC within 1 m at five 20 cm intervals for three different climatic zones (arid, semi-arid/semi-humid, and humid zone). To evaluate effects of vegetation on the vertical SOC distribution, soil profiles were categorized corresponding to five biomes: forest, steppe, meadow, desert, and cropland. The relative SOC density for each depth interval was used to eliminate the effect of entire SOC density in a soil profile on the vertical distribution. The vertical distribution was represented by the proportion of the 0–20 cm layer to entire SOC density in the first meter. Low proportion of the 0–20 cm layer means deep SOC distribution, while high proportion means shallow SOC distribution (Jobbágy and Jackson 2000).

Statistical analysis

One-way ANOVA was used to evaluate whether the vertical SOC distribution significantly differed among various climatic zones and vegetation types. The general linear model (GLM) was conducted to assess the variances in SOC explained by climate, vegetation and soil texture. All analyses were performed by software package R (R Development Core Team 2005).

Results

SOC storage

Table 1 lists the organic carbon density and storage for major soil types in China. SOC density for different soil types showed a large difference, ranging from 1.6 to 57.2 kg m^{-2}, with an average of 7.8 kg m^{-2}, for a depth of 1 m. Of them, 30–81% was stored in the top 30 cm deep. Total China's SOC storage was estimated as 69.1 Pg C.

Spatial SOC distribution

SOC density decreased from the southeast to the northwest, with a minimum in northwestern desert (Fig. 3). In northern China, it increased from 1.6–4.5 kg m^{-2} in arid zone to 9.9–11.3 kg m^{-2} in semi-humid zone; and in eastern part of China, it increased from 7.8–10.5 kg m^{-2} in tropical zone to 12.7–23.2 kg m^{-2} in cold-temperate zone. High SOC stock appeared in southeastern Tibet under cold and humid climate (Fig. 3).

Vertical SOC distribution

Different vertical SOC patterns were observed in three climatic zones (Fig. 4). The percentage of SOC in the top 20 cm (relative to the first meter) in arid zone was significantly lower than those in semi-arid/semi-humid zone ($P = 0.001$) and humid zone ($P < 0.001$). However, no significant variation was found between semi-arid/semi-humid zone and humid zone ($P > 0.05$). Similarly, different vertical SOC distribution was found among five biomes (Fig. 5). The proportion of SOC in the top 20 cm averaged 42%, 48%, 34%, 32%, and 34% for forest, meadow, steppe, desert, and cropland, respectively.

Environmental factors affecting SOC patterns

The GLM analysis showed that three environmental factors (humidity index, vegetation and soil texture) used in this study all contributed to spatial and vertical distribution of SOC (Table 2). They explained 84% of total variation for the spatial SOC pattern and 83.4% of total variation for the vertical carbon distribution, but climate

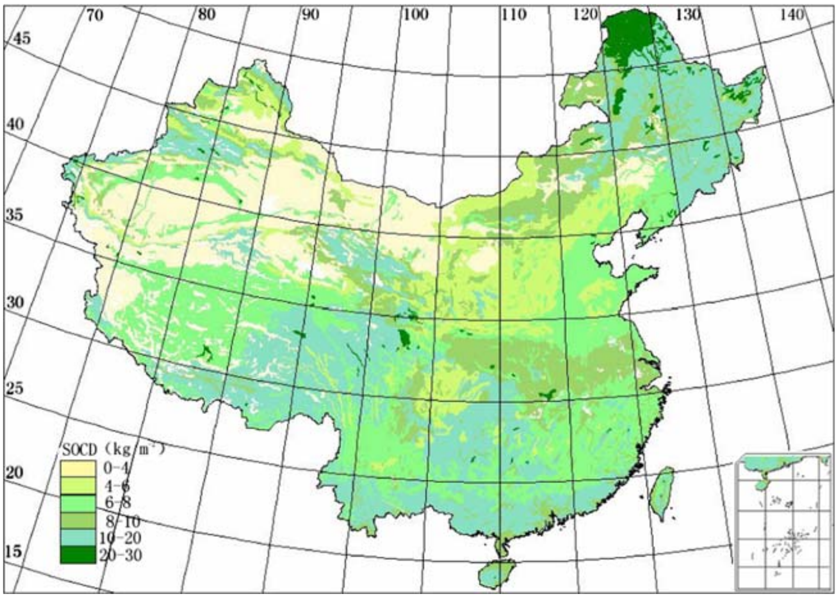

Fig. 3 Spatial distribution of SOC density in China

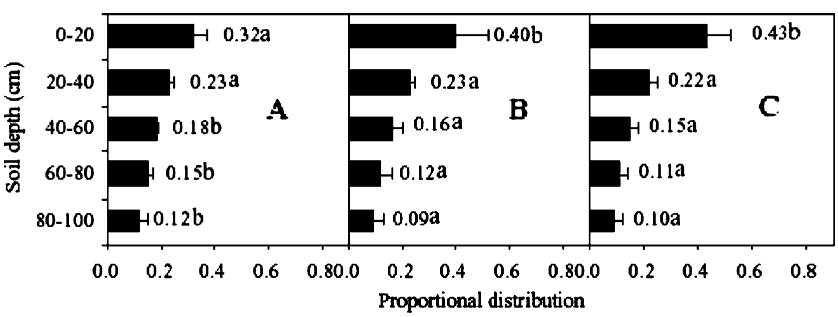

Fig. 4 Vertical SOC distribution for different climatic zones. (**A**) arid zone ($0 < H < 20$), (**B**) semi-arid/semi-humid zone ($20 < H < 40$), (**C**) humid zone ($40 < H < 80$). Black bars indicate the proportional distribution of total organic carbon in the first meter in 20 cm intervals. Letters indicate significant differences among different climatic zones at each depth interval (Tukey test, $P < 0.05$). Error bars represent one standard error of the mean

was the most important for the former (explaining 57.5%) and vegetation was the leading factor for the latter (explaining 42.7%).

Discussion

SOC estimates

Soil is the largest carbon pool in the terrestrial biosphere, and hence minor changes in SOC storage could have significant impacts on atmospheric CO_2 concentration (Johnston et al. 2004). Accurate estimate of SOC storage is required to assess the role of soil in the global carbon cycle, particularly the effect of soil on atmospheric composition (Garnett et al. 2001). Most of previous studies on the SOC estimation divided soil profile into several layers to calculate SOC density for each layer, and then summed up these densities to obtain total carbon density for the soil profile (e.g. Wu et al. 2003a). Compared with this method, based on continuous decrease in SOC density (SOCD) with soil depth (Jobbágy and Jackson 2000), we proposed a new method described above (Eqs. 2–4), which is called as continuous SOCD method, to estimate SOCD at any given depths. Using this method, we estimated China's average SOC density in the first meter was 7.8 kg m^{-2}. The estimate is smaller than the global mean

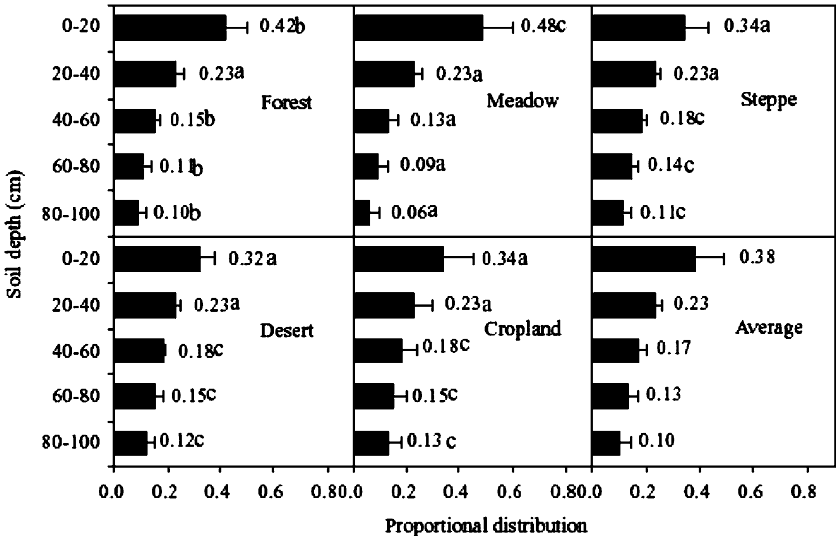

Fig. 5 Vertical SOC distributions for different biomes. Black bars indicate the proportional distribution of total organic carbon in the first meter in 20 cm intervals. Letters indicate significant difference among different biomes at each depth interval (Tukey test, $P < 0.05$). Error bars express one standard error of the mean

Table 2 Explanatory percentage for the relationship between SOCD and proportion of 0–20 cm layer (relative to the first 1 m) and environmental variables (climate, biome and soil texture) derived from general linear models

Item	d.f.	m.s.	% s.s.
SOCD			
Humidity index	1	341.5**	57.5
Biome	3	41.0**	20.7
Clay	1	25.6*	4.3
Silt	1	8.6	1.5
Residuals	17	5.6	16.0
Proportion of 0–20 cm layer			
Humidity index	1	0.040**	36.2
Biome	3	0.016**	42.7
Clay	1	0.004	3.4
Silt	1	0.001	1.1
Residuals	1	0.001	16.6

Notes: $^{**}P < 0.01$, $^{*}P < 0.1$, d.f. = degree of freedom, m.s. = mean square, % s.s. = proportion of variances explained by variable

(10.8 kg m^{-2}) reported by Post et al. (1982), likely due to the extensive arid and semi-arid regions and intensive agricultural activity in China (Wang et al. 2003; Wu et al. 2003a, b).

Table 3 lists estimates of China's SOC storage in this study and the previous estimations. Our estimate (69.1 Pg C) is significantly lower than the estimates based on the global soil database (Peng and Apps 1997; Ni 2001), perhaps due to higher carbon densities in the global soil database (Wu et al. 2003a), and is also lower than those based on the national soil survey data by Fang et al. (1996) and Wang et al. (2003), probably because of errors of bulk density, soil depth, rock fragment, and soil area in their studies. However, our estimate is close to the value (70.3 Pg C) by Wu et al. (2003a), although two estimations used different soil depths (we used a depth of 1 m for

Table 3 Comparisons of China's SOC storage between this study and previous estimates

Data source	Soil depth (m)	SOC storage (Pg)	Reference
China's first national soil survey	Average depth	185.7	Fang et al. 1996
WOSCN database (Zinke et al. 1984)	1	101.1	Peng & Apps 1997
WOSCN database (Zinke et al. 1984)	1	119.8	Ni 2001
China's second national soil survey	1	92.0	Wang et al. 2003
China's second national soil survey	Actual depth	70.3	Wu et al. 2003a
China's second national soil survey and field measurement	1	68.1	This study

each soil profile, while they applied actual profile depth reported in the national soil survey). Despite a close estimate of total China's SOC storage, a large difference in the SOC density can be observed in these two studies for some soil types. For example, Wu et al. (2003a) used lower SOCD for felty soils (9.5 kg m^{-2}) and cold calcic soils (7.4 kg m^{-2}), and higher value for dark felty soils (16.7 kg m^{-2}) and dark loessial soils (10.4 kg m^{-2}), compared to our values of 13.9, 9.1, 13.4, and 8.8 kg m^{-2}, respectively (Table 1). These discrepancies are generated either by different sample size (e.g., for felty soils) or by various soil depths (e.g., for cold calcic soils).

Factors affecting spatial SOC distribution

The patterns and controls of SOC storage are critical for understanding of the biosphere, given the feedback of SOC storage to atmospheric composition (Jastrow et al. 2005). Our capacity to predict the sequences of climate and land cover change partly depends on the understanding of distributions and controls of SOC (Jobbágy and Jackson 2000). In China, SOC density tends to decrease from the southeast to the northwest and to increase from arid to semi-humid zone in northern regions and from tropical to cold-temperate zone in eastern part of the country (Fig. 3). The GLM analysis suggests that all three environmental variables (humidity index, vegetation, and soil texture) used contributed to the spatial distribution of SOC, but climate is the most significant factor, which explains 57.5% of the variance in SOC (Table 2).

As many studies have suggested, climate has significant impacts on the SOC stock (Post et al. 1982; Schimel et al. 1994; Jobbágy and Jackson 2000; Callesen et al. 2003; Wynn et al. 2006), because it affects the balance of carbon inputs from plant production and outputs through decomposition in soil (Post et al. 1982). The patterns of SOC stock in China are roughly consistent with China's climatic patterns. Increased precipitation leads to an increase in vegetation productivity and thus an increase in SOC density in northern China from arid to semi-humid zone, while increase of SOC density from tropical to cold-temperate zone in eastern part of China is related to decreased mineralization caused by decreased temperature from the south to the north (Wu et al. 2003a).

In addition to climate, vegetation and soil texture also play important roles in sharping the SOC stock patterns, which together explained 25.1% of the variance in SOC (Table 2). Vegetation affects the SOC density through its production (Buckman et al. 2004) and litter chemistry (Wynn et al. 2006). The SOC density of forests (10.5 kg m^{-2}) is higher than that of steppe (6.6 kg m^{-2}) and desert (2.6 kg m^{-2}). Soil texture through its stabilization is attributed to the SOC density at local scale (Torn et al. 1997; Buckman et al. 2004; Wynn et al. 2006). High SOC density is found in latosols, latosolic red earths, and yellow earths, which are closely associated with their high clay content (Wu et al. 2003a).

Factors affecting vertical SOC distribution

The vertical distribution of SOC is different among climatic zones (Fig. 4) and vegetation types (Fig. 5). The SOC in arid zone is deeper than that in humid zone ($P < 0.001$) and shallower in forest and meadow than in desert, steppe and crop ($P < 0.05$). The GLM analysis on the relationships between the proportion of the top 20 cm and environmental variables indicates that the vertical SOC distribution is mainly determined by climate and vegetation (Table 2). Vegetation alone explains 42.7% of the variance, while climate accounts for 36.2% (Table 2).

The association of the vertical SOC distribution with climate may indeed be due to the replacement of vegetation types (Jobbágy and Jackson 2000; Wang et al. 2004). In addition, vegetation, through root: shoot ratio and its vertical root distribution, affects the vertical SOC distribution (Jobbágy and Jackson 2000). Deep root distribution in desert (Jackson et al. 1996) leads to deep SOC distribution, while shallow root distribution in meadow (Zhou 2001) results in shallow SOC distribution. SOC in forests is shallower than in grassland, consistent with Jobbágy and Jackson (2000).

China's average SOC density in croplands (7.7 kg m^{-2}) is lower than the global mean (11.2 kg m^{-2}) reported by Jobbágy and Jackson

(2000), likely due to long-term agricultural activity in China. The cropland soils in China also have a lower proportion of SOC in 0–20 cm (34%) than the world average (41%) presented in Jobbágy and Jackson (2000), which was mostly based on U.S. soils. It suggests that agricultural soils in China occur towards more arid extremes than in the rest of the world. This could also be expected from a much longer history of agriculture in China than in other regions of the world.

Acknowledgements We thank Biao Zhu for editing the earlier draft of this manuscript. This study was supported by the National Natural Science Foundation of China (40024101, 40228001, and 90211016) and Peking University (211 and 985 programs).

References

Batjes NH (1996) Total carbon and nitrogen in the soils of the world. Eur J Soil Sci 47:151–163

Bellamy PH, Loveland PJ, Bradley RL, Lark RM, Kirk GJD (2005) Carbon losses from all soils across England and Wales 1978–2003. Nature 437:245–248

Buckman HO, Brady NC, Weil RR (2004) Nature and properties of soil. Prentice-Hall Press, New York

Callesen I, Liski J, Raulund-rasmussen K, Olsson MT, Tau-strand L, Vsterdal L, Westman CJ (2003) Soil carbon stores in Nordic well-drained forest soils-relationships with climate and texture class. Global Change Biol 9:358–370

Deng SQ (1986) Map of soil texture of China. In: The soil atlas of China. Institute of Soil Science, Chinese Academy of Sciences (ed) Sinomaps Press, Beijing, pp 23–24

Fang JY, Liu GH, Xu SL (1996) Soil carbon pool in China and its global significance. J Environ Sci 8:249–254

Garnett MH, Ineson P, Stevenson AC, Howard DC (2001) Terrestrial organic carbon storage in a British moorland. Global Change Biol 7:375–388

Jackson RB, Canadell J, Ehleringer JR, Mooney HA, Sala OE, Schulze ED (1996) A global analysis of root distributions for terrestrial biomes. Oecologia 108:389–411

Jastrow JD, Miller RM, Matamala R (2005) Elevated atmospheric carbon dioxide increases soil carbon. Global Change Biol 11:2057–2064

Jobbágy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol Appl 10:423–436

Johnston CA, Groffman P, Breshears DD, Cardon ZG, Currie W, Emanuel W, Gaudinski J, Jackson RB, Lajtha K, Nadelhoffer K, Nelson D Jr, Post WM, Retallack G, Wielopolski L (2004) Carbon cycling in soil. Front Ecol Environ 2:522–528

Li ZX, Jiang X, Pan XZ, Zhao QG (2001) Organic carbon storage in soils of tropical and subtropical China. Water Air Soil Poll 129:45–60

Liu QH, Shi XZ, Weindorf DC, Yu DS, Zhao YC, Sun WX, Wang HJ (2006) Soil organic carbon storage of paddy soils in China using the 1:1,000,000 soil database and their implications for C sequestration. Global Biogeochem Cy:20, GB3024, doi: 10.1029/2006GB002731

National Soil Survey Office (ed) (1993) Soil species of China, vol 1. China Agricultural Press, Beijing

National Soil Survey Office (ed) (1994a) Soil species of China, vol 2. China Agricultural Press, Beijing

National Soil Survey Office (ed) (1994b) Soil species of China, vol 3. China Agricultural Press, Beijing

National Soil Survey Office (ed) (1995a) Soil species of China, vol 4. China Agricultural Press, Beijing

National Soil Survey Office (ed) (1995b) Soil species of China, vol 5. China Agricultural Press, Beijing

National Soil Survey Office (ed) (1996) Soil species of China, vol 6. China Agricultural Press, Beijing

National Soil Survey Office (ed) (1998) Soils of China. China Agricultural Press, Beijing

Nelson DW, Sommers LE (1982) Total carbon, organic carbon, and organic matter. In: Page AL (ed) Methods of soil analysis II. American Society of Agronomy, Madison, pp 539–579

Ni J (2001) Carbon storage in terrestrial ecosystems of China: estimates at different resolutions and their responses to climate change. Climatic Change 49:339–358

Pan GX, Li LQ, Wu LS, Zhang XH (2003) Storage and sequestration potential of topsoil organic carbon in China's paddy soils. Global Change Biol 10:79–92

Peng CH, Apps MJ (1997) Contribution of China to the global carbon cycle since the last glacial maximum. Tellus, Ser B 49:393–408

Piao SL, Fang JY, Zhou LM, Guo QH, Henderson M, Ji W, Li Y, Tao S (2003) Interannual variations of monthly and seasonal normalized difference vegetation index (NDVI) in China from 1982 to 1999. J Geophys Res:108(D14), 4401, doi: 10.1029/2002JD002848

Post WM, Emanuel WR, Zinke PJ, Stangenberger AG (1982) Soil carbon pools and world life zones. Nature 298:156–159

R Development Core Team (2005) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Schlesinger WH (ed) (1997) Biogeochemistry: an analysis of global change. Academic Press, San Diego

Schimel DS, Braswell BH, Holland EA, McKeown R, Ojima DS, Painter TH, Parton WJ, Townsend AR (1994) Climatic, edaphic, and biotic controls over storage and turnover of carbon in soils. Global Biogeochem Cy 8:279–293

Tian Q, Li J, Huang FH, Li J, Fei XB (1996) Chinese resources and environment database. Institute of Geographic Sciences and Natural Resources Research, Beijing

Torn MS, Trumbore SE, Chadwick OA, Chadwick OA, Vitousek PM, Hendricks DM (1997) Mineral control of soil organic carbon storage and turnover. Nature 389:170–173

Tuhkanen S (ed) (1980) Climatic parameters and indices in plant geography. Almqvist & Wiksell International, Stockholm

Wang SQ, Tian HQ, Liu JY, Pan SF (2003) Pattern and change of soil organic carbon storage in China: 1960s–1980s. Tellus, Ser B 55:416–427

Wang SQ, Huang M, Shao XM, Mickler RA, Li KR, Ji JJ (2004) Vertical distribution of soil organic carbon in China. Environ Manage:33(Suppl.1), doi: 10.1007/s00267-003-9130-5

Wynn JG, Bird MI, Vallen L, Grand-Clement E, Carter J, Berry SL (2006) Continental-scale measurement of the soil organic carbon pool with climatic, edaphic, and biotic controls. Global Biogeochem Cy:20(1), GB1007, doi: 10.1029/2005GB002576

Wu HB, Guo ZT, Peng CH (2003a) Distribution and storage of soil organic carbon in China. Global Biogeochem Cy 17, GB1048, doi: 10.1029/2001GB001844

Wu HB, Guo ZT, Peng CH (2003b) Land use induced changes of organic carbon storage in soils of China. Global Change Biol 9:305–315

Zinke PJ, Stangenberger AG, Post WM, Emanuel WR, Olson JS (1984) Worldwide organic soil carbon and nitrogen data, ORNL/TM-8857. Oak Ridge National Laboratory, Oak Ridge, Tennessee

Zhou XM (ed) (2001) Kobresia meadow of China. Science Press, Beijing