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Pattern and change of soil organic carbon storage in China: 1960s–1980s

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ABSTRACT

Soils, an important component of the global carbon cycle, can be either net sources or net sinks of atmospheric carbon dioxide (CO_2). In this study, we use the first and second national soil surveys of China to investigate patterns and changes in soil organic carbon storage (SOC) during the period from the 1960s to the 1980s. Our results show that there is a large amount of variability in SOC density among different soil types and land uses in the 1980s. The SOC density in the wetlands of Southwest China was the highest (45 kg m^{-2}), followed by meadow soils in the South (26 kg m^{-2}), forest and woodlands in the Northwest (19 kg m^{-2}), steppe and grassland in the Northwest (15 kg m^{-2}), shrubs in the Northwest (12 kg m^{-2}), paddy lands in the Northwest (13 kg m^{-2}), and drylands in the Northwest (11 kg m^{-1}). The desert soils of the Western region ranked the lowest (1 kg m^{-2}). The density of SOC was generally higher in the west than other regions. Eastern China had the lowest SOC density, which was associated with a long history of extensive land use in the region. The estimation of SOC storage for the entire nation was 93 Pg C in the 1960s and 92 Pg C in the 1980s. SOC storage decreased about 1 Pg C during the 1960s–1980s. This amount of decrease in SOC for the entire nation is small and statistically insignificant. To adequately characterize spatial variations in SOC, larger sampling sizes of soil profiles will be required in the future analyses.

1. Introduction

World soils contain an important pool of active carbon (C) that plays a major role in the global carbon cycle (Lal, 1995; Melillo et al., 1995; Prentice et al., 2001). Soils store two or three times more carbon than exists in the atmosphere as CO_2 (Davidson et al., 2000) and 2.5 to 3 times as much as that stored in plants (Post et al., 1990; Houghton et al., 1990). Through increases in organic matter, soils may sequester atmospheric carbon dioxide emitted by anthropogenic sources (Post et al., 1982, 1990; Tian et al. 1998; 1999; 2002). At present, the uncertainty in understanding the role of soils in the global carbon cycle is mainly due to the poor understanding of the spatial distribution and dynamics of soil organic carbon (Torn et al., 1997). The large, unknown C sink (1.8 Pg) in the global balance of CO_2 in Earth's atmosphere suggests a role for the world soils in the further understanding of the processes involved in carbon emissions and sequestration (Lal et al., 1995a,b; Melillo et al. 1995). Land use and soil management practices can significantly influence soil organic SOC dynamics and C flux from the soil (Paustian et al., 1995; Batjes, 1996; Post and Kwon, 2000; Tian et al. 1999, 2003; McGuire et al., 2001), although the mechanisms and processes of C sequestration in soil are not completely understood (Lal et al., 1995b; Bajracharya et al., 1998). Spatially distributed estimates of SOC pools and flux are important requirements for understanding the role of soils in the global C cycle and for assessing potential biospheric responses

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to climatic change or variation (Schimel et al., 1994; 2000).

Estimations of soil C stocks have been made at the national level (Kern, 1994; Tarnocai and Ballard, 1994; Rozhkov et al., 1996) and the global level (Bohn, 1978; Post et al., 1982; Eswaran et al., 1993; Batjes, 1996). For example, spatial patterns of SOC in the contiguous U.S.A. were estimated by aggregating soil characterization data by ecosystem, soil great group, and by the UN soil map of the world soil units (Kern, 1994). Tarnocai and Ballard (1994) characterized the spatial patterns of SOC in Canada by linking the map of the Canadian Soil Landscape with SOC values calculated from soil characterization data. On a global scale, scientists have used soil characterization data, in conjunction with ecosystem types across the globe, to estimate SOC pools (Schlesinger, 1984; Post et al., 1982; Zinke et al., 1984). Li and Zhao (2001) used data from the second national soil survey to estimate that about 28.7 ± 8.2 Pg of SOC are stored in the upper 1 m of soils in the 215×10^6 ha of tropical and subtropical China. These broad-scale analyses show that estimates of SOC at national and global scales are often accompanied by a large range of SOC due to soil spatial variability and lack of reliable field measurement.

The rate of change of soil organic matter content with changing in management is dependent on the previous history of management and environmental conditions at local, regional and national scales (Melillo et al., 1995; Lal, 1999). From the 1960s to the 1990s, China experienced significant social, economic and natural changes. China also experienced accelerated rates of land-use/cover change and urban development because of increased cultivation of land for crops and governmental changes in land use policy. Land use/cover changes and natural disturbances (i.e. wildland fires and floods) can cause changes in SOC (Houghton and Skole, 1990; Houghton, 1995; Tian et al., 1999; 2000; 2002). Therefore, there is an important need to assess impacts of changing human activities on changes of SOC.

In recent years, global climate change has focused great attention and research efforts on the study of the soil carbon cycle. While the important role of soils in the global C cycle is increasingly recognized, significant uncertainty exists in the estimation of SOC at the national level. The SOC storage in Chinese soils had been studied in many locations (Cai, 1996; Li and Zhao, 2001), but there have been few regional or national-scale assessments. Regional studies of SOC storage can improve the accuracy of estimates of global SOC, and they are valuable in assessing the role of land use/cover change in the global carbon cycle (Li and Zhao, 2001). The objectives of this paper are to estimate China's SOC storage and its change between the 1960s and the 1980s, and to provide a basis for environmentally sound management of SOC.

2. Materials and methods

2.1. Data sources

The first and second national soil surveys of China include records of 236 and 2473 typical soil profiles in the1960s and 1980s, respectively (Xiong and Li, 1978; National Soil Survey Office, 1993; 1994a,b; 1995a,b; 1996; 1998). From 1958 to 1963, China launched the first national soil survey that specially emphasized the impacts of agricultural production on soil, with a focus on arable land. Historical data that characterize the chemical and physical properties for only 236 soil profiles exist from the first national soil survey. Starting in 1980, China's soil scientists began the second national soil survey to map and characterize soils for the country. The analyses presented here are based on the databases of soil profiles from the two national soil surveys. In both databases, soil physical and chemical measurements are recorded for suborders by soil horizon. These databases seek to characterize the diversity of agricultural and non-agricultural soils which span temperate, tropical and boreal systems. We use information on taxonomic classification, geographic location, vegetation, land-use, soil depth, organic content, bulk density, area, principal properties, pH, texture and physio-chemical data. The second national soil survey collected data classified by soil species, which is an important base classification unit in Chinese Soil Taxonomy, and is defined as a soil association composed of soil pedons with the same or similar characteristics (Li and Zhao, 2001).

The total soil area of China was estimated after removal of the land area associated with surface waters, glaciers, perennial snow, bare rock and gravel hills. The total soil areas were 878.67×10^6 and 877.63×10^6 ha for the first and second national soil survey, respectively. This area represents 91% of the total land area of China (National Soil Survey Office, 1998). The two national soil surveys did not cover the Taiwan province, which has an area of about 23.95×10^6 ha.

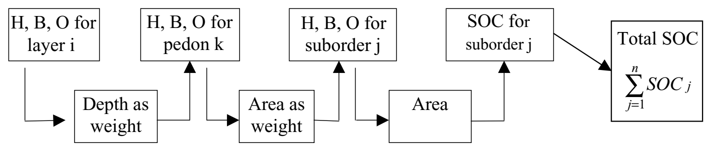

Fig. 1. Flow diagram of SOC density and storage calculation (H, depth; B, bulk density; O, organic content).

2.2. *Calculation of SOC*

Many scientists estimate SOC based on soil carbon density and soil type or ecosystem type area (Post et al., 1982; Sampson et al., 1993; Kern, 1994; Foley, 1995; Fang et al., 1996; Tian et al., 2000). In this study, we used various physio-chemical properties of every horizon from all soil profiles for the calculation of soil carbon density. We calculated SOC content as a portion of soil organic matter (Post et al., 1998). A conversion coefficient of 0.58 was used in this study, which suggested by other investigators (Nelson and Sommers, 1982; Fang et al., 1996; Post et al., 1998; Scott et al., 1999; Li and Zhao, 2001). Soil profile data were aggregated from soil order, soil suborder and great group levels of classification. To derive the average SOC content for each soil profile, we used the thickness of each horizon as the weighting coefficient (Fig. 1).

For an individual soil pedon with n layers, its SOC density (C_d) was calculated as:

$$C_\mathrm{d} = \frac{\sum_{i=1}^{n} 0.58 H_i B_i O_i}{\sum_{i=1}^{n} H_i} \tag{1}$$

where H_i is the thickness (cm) of horizon i, B_i is the bulk density (g cm^{-3}) of horizon i, O_i is the soil organic content (%) in horizon i. The average bulk density value of soil suborder is used for soil pedons with no bulk density data. Grouping data by suborder provides a better estimate than by orders because suborders give more indications of climate, drainage and soil textures, which are important factors for the accumulation of SOC (Li and Zhao, 2001).

The average SOC density (C_dj) was calculated as:

$$C_{\mathrm{d}j} = \frac{\sum_{k=1}^{n} S_k C_\mathrm{dk}}{\sum_{k=1}^{n} S_k}, \tag{2}$$

where k denotes the given soil species, $C_{\mathrm{d}k}$ is the carbon density of soil species k (kg m^{-2}), and S_k is the distribution area of soil species k (10^6 ha^2). SOC masses for each soil suborder were obtained by multiplying the carbon content for each soil suborder by the area of the respective soil suborder. The total carbon quantity of a given soil suborder in the upper 1 m was calculated as:

$$SOC_\mathrm{t} = \sum_{j=1}^{n} C_{\mathrm{d}j} S_j \tag{3}$$

where j denotes the given soil suborder, SOC_t is the carbon storage (Pg), S_j is the distributional area of the soil suborder j (10^6 ha^2), and C_dj is the average SOC density (kg m^{-2}) of the soil suborder j.

Based on each profile's location (e.g. longitude, latitude and elevation) and vegetation, we grouped soil suborders into different land use types (Hou, 1982). We assigned soil profile data for each classification category. Soil profiles without detailed vegetation information were excluded from the analysis. The standard deviation was calculated for SOC content for each soil suborder. Each map unit (1:4 000 000) on the Major Soil Regions of the Chinese map (Tian et al., 1996) was assigned a SOC density which is different between first and second national soil survey.

We calculate the confidence interval (CI) for the mean carbon density for each suborder based on samples sizes. For a large sample ($n \geq 30$), we determine confidence interval for mean carbon density (μ) as:

$$\overline{x} - z_{\alpha/2}(SD/\sqrt{n}) < \mu < \overline{x} + z_{\alpha/2}(SD/\sqrt{n}), \tag{4}$$

where z is a standard unit or z-score. $\overline{x}$ is the mean for samples (n) and SD is the standard deviation of soil carbon density for soil suborder. The value of $z_{\alpha/2}$ is 1.96, corresponding to a 95% confidence interval (CI). For a small sample ($n < 30$), we determine the confidence interval for mean carbon density (μ) as:

$$\overline{x} - t_{\alpha/2}(SD/\sqrt{n}) < \mu < \overline{x} + t_{\alpha/2}(SD/\sqrt{n}). \tag{5}$$

The degree of confidence is $1 - \alpha$ and the only difference between this confidence interval formula and the large sample formula is that $t_{\mathrm{a}/2}$ takes the place of $z_{\mathrm{a}/2}$

The value of $t_{a/2}$ for a 95% confidence interval (CI) for mean carbon density varies from one soil order to another, which depends on the number of samples.

For the national level, we used all samples to determine means and confidence intervals of bulk density, organic content, and carbon density in the 1960s and the 1980s. Finally, we used the paired *t*-test to test if the difference in SOC storage between first and second soil surveys can be distinguished from zero.

3. Results and discussion

3.1. Density and storage in SOC for the 1980s

Our results indicate that SOC density varies from 2 kg C m^{-2} in grey–brown desert soils to 45 kg C m^{-2} in Brown coniferous forest soils (Table 1). The SOC density in forest soils ranges from 10 kg m^{-2} (with 95% CI: 8, 12) in grey forest soils to 45 kg m^{-2} (with 95% CI: 38, 52) in brown coniferous forest soils. For mean forest SOC density, our result appears to have larger variation than those reported by previous estimates, ranging from 11 kg m^{-2} (Wang, 1999) to 19 kg m^{-2} (Zhou, 1998). This difference is in part because we took into account widely spatial heterogeneity in soil properties across the nation. The large variability in the estimations of SOC density might also result from different data sources and calculation methods.

Both climate and human activities have influenced SOC density across China. SOC density in Alpine soils, mostly located in northeast and southeast of the Tibet altiplano, is also high. In the northeast and southeast Tibet plateau, low temperature and high soil moisture lead to a low rate of decomposition and a relatively high content of soil organic matter. In the sparsely populated western region (e.g. the Qingzang plateau) the natural vegetation is still intact or only slightly impacted (Li and Zhao, 2001). The high productivity of the turf vegetation contributes to the development of a thick A horizon and high SOC. In densely populated east, on the other hand, the land cover is highly fragmented, showing the mosaic of crops, secondary vegetation and natural vegetation (Li and Zhao, 2001). The SOC density in the Loess Plateau and Huanghuaihai Plain, for example, was low, since there is a long

Table 1. *The comparison of SOC density of main soil suborders in the second soil survey*

Soil type	Samples (N)	Organic (%)	Depth (cm)	Bulk density (g cm^{-3})	Soil carbon density (kg C m^{-2})		
					Mean	95% CI	
Latosols	23	1.33	97	1.18	8.86	8.1	9.62
Latosolic red earths	30	1.4	112	1.35	12.28	10.97	13.59
Red earths	132	1.24	103	1.37	10.18	9.86	10.5
Yellow–brown earths	32	1.87	92	1.31	11.41	10.22	12.6
Brown earths	87	1.4	102	1.42	11.46	10.5	12.42
Dark brown earths	65	3.18	85	1.13	17.55	16.23	18.87
Brown coniferous forest soils	9	7.54	79	1.3	44.61	37.56	51.66
Dark brown earths	65	3.18	85	1.13	17.55	16.23	18.87
Black soils	37	1.87	113	1.31	17.03	14.17	19.89
Grey forest soils	8	2.3	58	1.28	10.25	8.09	12.41
Chernozems	69	1.97	115	1.29	17.99	15.83	20.15
Dark castanozems	22	1.69	112	1.24	13.61	10.12	17.1
Castanozems	20	1.01	129	1.24	9.37	6.95	11.79
Light castanozems	15	0.82	123	1.24	7.25	4.4	10.1
Brown caliche soils	19	0.64	95	1.4	4.86	3.33	6.39
Sierozems	34	0.75	113	1.35	6.71	5.51	7.91
Grey desert soils	11	0.6	86	1.25	3.73	0.09	7.37
Grey–brown desert soils	10	0.37	84	1.25	2.23	0.12	4.34
Aeolian soils	46	0.27	102	1.51	2.41	1.99	2.83
Sierozems	34	0.87	118	1.35	8.04	6.84	9.24
Frigid calcic soils	8	1.17	87	1.25	7.38	6.82	7.94
Cold brown calcic soils	4	5.43	91	1.2	34.39	31.8	36.98
Dark felty soils	69	4.03	73	1.2	20.48	18.32	22.64
Cold calcic soils	25	1.59	88	1.25	10.14	8.66	11.62

history of cultivation. Extensive agricultural land use in the past and the continuing conversion of other land cover to agriculture has strongly disturbed a large part of the native vegetation and reduced the SOC.

To further understand the effect of land use change on SOC storage, we estimated the SOC density under different land use types according to vegetation description of soil profiles in the 1980s. As there is a clear difference in climate, geography, land use and social economy, we divided the whole nation into six large sub-regions: Northeast, North, Northwest, East, South and Southwest (Fig. 2). Some islands were excluded because of their small areas. Based on a vegetation map (1:4 000 000), (Hou, 1982), we classified land use of the whole region into eight categories: dryland, paddy land, forest and woodland, shrubs, steppe and grassland, meadow, wetland and desert. The results of the average SOC content and 95% confidence interval (CI) of the land use types that occur in China are listed in Table 2, and the spatial distribution of SOC density in six sub-regions is shown in Fig. 2.

Our results show that there is a large amount of variability in SOC density among different land uses in the 1980s (Table 2). The SOC density in the wetlands of Southwest China was the highest (45 kg m^{-2} with 95% CI: 10, 80), followed by meadow soils in the South

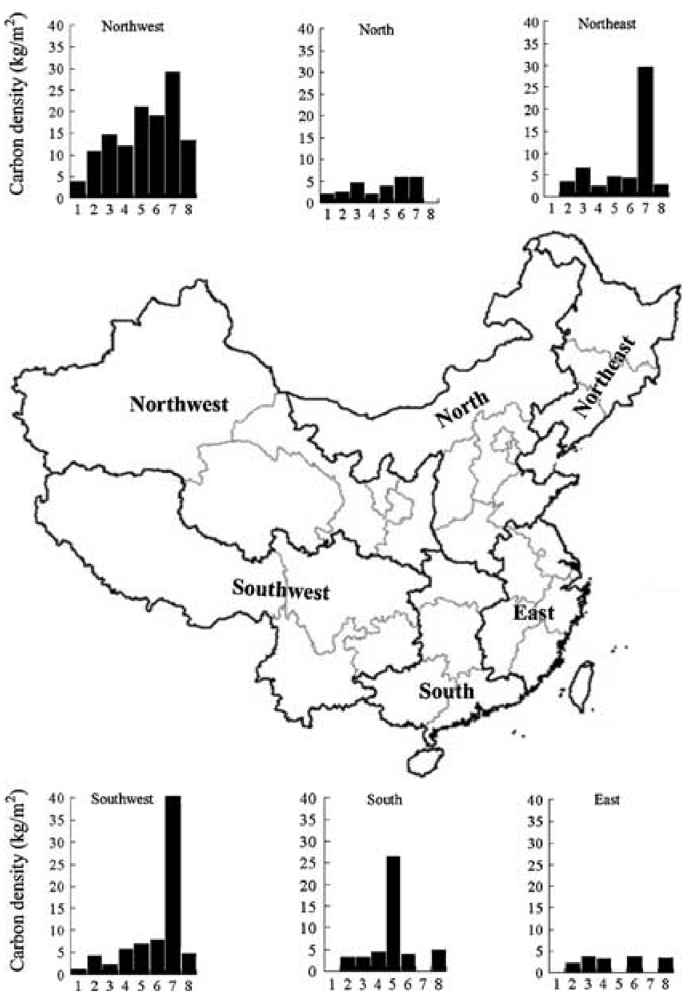

Fig. 2. SOC density for major land use types in the six sub-regions of China. Numbers 1–8 represent the desert, dryland, steppe and grassland, shrubs, meadow, forest and woodland, wetland and paddy land, respectively.

Table 2. *SOC density under land use types of large regions in China*

	Land use type	Samples (n)	Depth (cm)	Organic (%)	Bulk density g cm^{-3}	Soil carbon density (kg C m^{-2}) Mean	95% CI	
Northeast	Desert	NA[a]	NA	NA	NA	NA	NA	NA
	Dryland	183	118	1.25	1.36	3.53	2.91	4.15
	Steppe and grassland	32	97	1.32	1.37	6.68	2.4	10.96
	Shrubs	9	69	1.44	1.44	2.49	0.9	4.08
	Meadow	46	110	1.73	1.34	4.56	3.62	5.5
	Forest and woodland	55	85	2.16	1.33	4.32	3.25	5.39
	Wetland	18	105	14.23	1.04	29.48	13.08	45.88
	Paddy land	20	84	1.4	1.32	2.75	2.14	3.36
North	Desert	6	125	0.6	1.36	2.1	0.51	3.69
	Dryland	268	116	0.83	1.38	2.41	2.2	2.62
	Steppe and grassland	43	103	1.39	1.32	4.5	3.26	5.74
	Shrubs	23	89	1.11	1.34	2.09	1.25	2.93
	Meadow	27	96	1.75	1.32	3.81	2.16	5.46
	Forest and woodland	19	100	2.54	1.35	5.81	3.58	8.04
	Wetland	4	104	2.31	1.24	5.77	3.67	7.87
	Paddy land	NA	NA	NA	NA	NA	NA	NA
Northwest	Desert	74	84	0.48	1.34	3.97	3.11	4.83
	Dryland	231	129	1.07	1.32	10.88	9.99	11.77
	Steppe and grassland	41	107	1.56	1.3	14.68	8.25	21.11
	Shrubs	10	108	1.51	1.34	12.09	6.5	17.68
	Meadow	20	77	3.8	1.25	21.01	14.13	27.89
	Forest and woodland	31	95	2.66	1.29	19.04	13.85	24.23
	Wetland	13	90	5.04	1.27	29.14	5.55	52.73
	Paddy land	17	128	1.34	1.32	13.4	10.03	16.77
East	Desert	NA	NA	NA	NA	NA	NA	NA
	Dryland	104	100	0.78	1.38	2.11	1.88	2.34
	Steppe and grassland	31	81	1.57	1.38	3.65	2.22	5.08
	Shrubs	41	80	1.45	1.33	3.1	2.22	3.98
	Meadow	NA	NA	NA	NA	NA	NA	NA
	Forest and woodland	68	90	1.56	1.33	3.63	3.13	4.13
	Wetland	NA	NA	NA	NA	NA	NA	NA
	Paddy land	213	91	1.42	1.33	3.42	3.02	3.82
South	Desert	NA	NA	NA	NA	NA	NA	NA
	Dryland	75	95	1.17	1.34	3.23	2.83	3.63
	Steppe and grassland	19	118	1.19	1.32	3.12	2.32	3.92
	Shrubs	38	87	1.78	1.3	4.49	3.44	5.54
	Meadow	3	85	8.81	1.24	26.39	8.96	61.74
	Forest and woodland	67	98	1.57	1.31	3.95	3.46	4.44
	Wetland	NA	NA	NA	NA	NA	NA	NA
	Paddy land	163	92	1.61	1.29	4.9	4.15	5.65
Southwest	Desert	18	55	0.84	1.34	1.17	0.55	1.79
	Dryland	178	82	1.77	1.33	4.13	3.64	4.62
	Steppe and grassland	24	88	1.08	1.31	2.29	1.74	2.84
	Shrubs	29	71	3.33	1.31	5.75	2.76	8.74
	Meadow	28	69	4.14	1.21	6.99	4.29	9.69
	Forest and woodland	51	84	4.02	1.24	7.77	5.81	9.73
	Wetland	6	76	19.51	1.16	44.64	9.59	79.69
	Paddy land	96	81	2.12	1.29	4.6	3.88	5.32

[a]NA indicates that kind of ecosystem is not precent in the region; CI, confidence interval.

(26 kg m^{-2}, with 95% CI: 9, 43), forest and woodlands in the Northwest (19 kg m^{-2}, with 95% CI: 14, 24), steppe and grassland in the West (15 kg m^{-2}, with 95% CI: 8, 21), shrubs in the Northwest (12 kg m^{-2}, with 95% CI: 7, 18), paddy lands in the Northwest (13 kg m^{-2}, with 95% CI: 10, 17), and drylands in the Northwest (11 kg m^{-2}, with 95% CI: 10, 12). The desert soils of the Western region ranked the lowest (1 kg m^{-2}, with 95% CI: 0.6, 2).

Wetland had the greatest variability among regions (Northeast, Northwest and Southwest China) as indicated with a range of standard deviation (s.d.) from 33 to 39.There are broad ranges and heterogeneity of types of soil within land use types. This also indicates that the land use types are poor predictors of the amount of SOC content because of the great soil heterogeneity (Kern, 1994).

Of the various patterns of land use in all of China, the SOC density was generally higher in the west than in the east, and there were large variations in the area of Chinese soils under various land uses (Table 2). All types of land use showed considerable variation, but generally the tendency had higher values for wetland, meadow and forest soils. Deserts tended to have low SOC content. The soil units with the lowest SOC content were arid soils (Tables 1 and 2). Soil units from dry climates in western regions tended to have a low SOC content, except for soil units with a mesic climate in southern and eastern regions. The spatial patterns of SOC, as characterized by the land use in Fig. 2 and Table 2, displayed the greatest SOC content in areas of extensive alpine wetland, meadow, mountain forests and poorly drained soils, such as those found in the eastern regions of the Tibet Plateau and Northeast China (Tables 1 and 2). The eastern portion of East and South China, with its extensive cultivation, had a relatively low SOC content. The northern Northeast China had relatively high amounts of SOC, probably because of high amounts of precipitation and cool temperatures (Wang et al., 2002). SOC can be characterized by ecosystem zones on very broad scales. This approach, however, ignores local variations in parent materials (organic materials, coarse fragment content and mineralogy) and soil depth (Kern, 1994; Li and Zhao, 2001). There was a great deal of heterogeneity of soil within land uses, which made this method of data aggregation of limited use.

For the whole of China, our results suggested that, for the 1980s, the average SOC density in China was 10.53 kg Cm^{-2} (with 95% CI: 10.2, 10.86) and that SOC storage for the nation was 92 Pg C (with 95% CI: 89, 95) for a total soil area of 877.63 $\times$ 10^6 ha^2. Estimates of the global SOC storage vary from 1200 to 1600 Pg C (Prentice and Fung, 1990; Sombroke et al., 1993; Post et al., 1982, 1990; Foley, 1995; King et al., 1995; Batjes, 1996). Our analysis indicated that SOC storage in China is about 6–8% of the global soil organic carbon pool, noting that the area of land in China is only 6.4% of the global land area (Fang et al., 1996).

3.2. *Historical changes in SOC storage during 1960s–1980s*

Our results indicate that SOC storage in the 1960s was 93 Pg C (with 95% CI: 73, 113) for the contiguous China, and that average SOC density was 10.61 $kgCm^{-2}$ (with 95% CI: 6.21, 15.01) (Fig. 3). Compared to the total SOC storage of 92 Pg (with 95% CI: 89, 95) in the 1980s, our analysis suggests that, during the 1960s–1980s, SOC storage in China decreased by about 1 Pg C (Fig. 3). We used the paired *t*-test to determine if the difference in SOC storage between first and second soil surveys can be distinguished from zero. The results from the *t*-test show that there is no significant difference in SOC storage between two soil surveys (with 95% CI).

Although there is no significant decrease in SOC for the nation during the 1960s–1980s, regional variations in the change of SOC storage still exist. The largest change in SOC storage occurred in Northeast China and the Tibet Plateau. In Northeast China, SOC density in the eastern wetland region decreased from 40–60 to 25–40 kg m^{-2} during the period from the 1960s to the 1980s. Because primary forests have been protected in the eastern and northern mountains since the 1970s, the SOC content of mountain forests increased by about 5–10 kg m^{-2}. During the 1960s–1970s, many people immigrated into Northeast China for agricultural development forced by the Cultural Revolution. The SOC density of the Songnen Plain decreased from 16–25 to 10–16 kg m^{-2}, most of which occurred in the black soils region. In the western grassland region, the SOC density of grassland decreased by 3–10 kg m^{-2}. In the central plain region, wetland and grassland were converted to farmland and urban developments. These human disturbances reduced the soil fertility. In the southeast region of the Tibet Plateau, the SOC density of alpine meadow decreased by

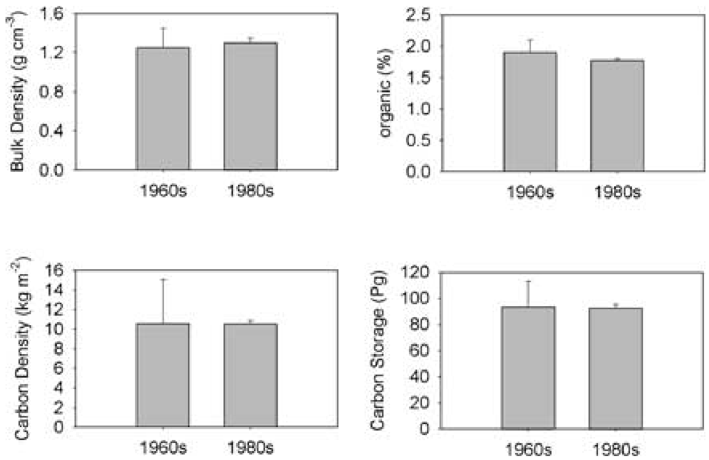

Fig. 3. Differences in bulk density (a), organic (b), carbon density (c) and carbon storage (d) between the first national soil survey in 1960s and the second national soil survey in 1980s. (Histograms and error bar show the mean and 95% confidence interval.)

10–20 kg m^{-2}. Following changes in agrarian reform policies in 1959, Tibet entered a new era of rapid agricultural development. Alpine steppe and meadow were converted to farmland in the southeast region. As a result, the SOC content of the southeast region was reduced.

In the northern and southern regions, the SOC density was reduced by 0–3 kg m^{-2} due to the expansion of agricultural land. In the grassland region of Inner Mongolia, however, the SOC density was reduced largely from 2.15–5 to 0–2.15 kg m^{-2}due to desert expansion and soil degradation. In the large areas of semi-arid and arid regions of West and Northwest China, SOC storage was reduced by about 0–3 kg m^{-2}, in part because the climate was drier and vegetation could not survive. In the mountain region, the SOC density of the steppe decreased because of the development of animal husbandry.

Our estimates of soil carbon storage and its change are comparable to other studies. Houghton (1995; 1999) estimated that, due to deforestation and other land-use changes, the total net flux of carbon to the atmosphere from terrestrial ecosystems in China was about 9.0 Pg C for the time period from 1850 to 1980 (Houghton, 1995) and 9.4 Pg C from 1850 to 1990 (Houghton, 1999), and that the annual flux was about 0.07 Pg C from 1950 to 1980, including the loss of vegetation and soil carbon. From 1900 to 1994, Tian et al. (1999) estimated that the natural ecosystems in the coterminous US lost a total of 4.8 Pg SOC due to cropland expansion and urbanization, about 0.051 PgC yr^{-1}. The land areas of China and the US are almost identical, indicating that the loss of the Chinese SOC pool was small relative to the US and global SOC loss for the study period.

3.3. *Uncertainty*

Much uncertainty still exists in the assessment of SOC storage. Uncertainty arises from a variety of sources, including different methods, unreliable data, and missing and incomplete data (Lal et al., 1995b). Moreover, the heterogeneity of SOC concentration and its dynamic nature make it unfeasible to obtain estimates of SOC changes on annual or finer time scales from direct measurement (Post et al., 1998). For example, our study was based on soil sample data derived from different research projects. These projects adopted different criteria for soil classification, mapping scales and degree of representatives of soil profiles between two national soil surveys. The lack of standardized sampling methods is also a source of sampling error. Furthermore, the lack of sufficient data on bulk density of soil horizons, climate and land-use/land-cover, insufficient depth of soil profiles (<1 m) and the limited number of soil pedons on natural soils (as compared to cultivated soils) also limits the accuracy of the results (Eswaran et al., 1993; Kern, 1994; Li and Zhao, 2001). In addition, although large numbers of soil profile data in the 1980s can make a reliable estimate for contemporary SOC storage, the small numbers of soil profiles in the 1960s can bias our estimate of SOC for that time period and hence the change in SOC during the 1960s–1980s.

Some classes in soil taxonomy have been changed in China since 1978. The 1978 version of soil taxonomy was used in this study for the first national soil survey and the 1994 version of soil taxonomy was used for the second national soil survey (National Soil Survey Office, 1998). The integration of soil and vegetation maps and soil survey data provides a basis to estimate regional SOC storage and distribution (Kern, 1994; Li and Zhao, 2001). A better framework and a good compromise for the level of detail, because of aggregation at a more specific level such as subgroup or family, would require extremely large pedon databases (Kern, 1994). In this study, based on the simple classification of land use for soil profiles, we analyzed the SOC spatial characteristics in six subregions under different land uses. However, the method could produce a relatively large variation similar to the ecosystem complexes method documented by Kern (1994).

Traditionally, we estimate soil organic carbon reservoir based on organic content to a depth of 1 m (Post et al., 1982; Foley, 1995; Lal, 1999). The subsoil below 1 m has a lot of organic and inorganic carbon, especially in tropical and subtropical soils (Sombroke et al., 1993). Estimating SOC for the entire soil profile provides a more accurate estimate of nation-wide SOC than extrapolating SOC from a 1 m sampling profile. How to extrapolate site data to regions is the critical question in the accurate estimation of soil carbon. There is an urgent need to develop robust, science-based, flexible and practical protocols for monitoring and verifying temporal changes in soil carbon (Post et al., 1998). It is obvious that there is still a need to further develop methodology to derive more accurate estimates of soil carbon. Nevertheless, this study has presented a more accurate estimate of SOC by considering the variations of different soil types, soil depth, soil horizons and their corresponding soil organic matter content, which are based on a large number of sampled soil profiles across the country. Establishing a global database on soil profile samples would certainly help to produce more realistic and representative results in soil carbon studies (Eswaran et al., 1993; Kern 1994; Post and Kwon, 2000; Li and Zhao, 2001).

4. Conclusion

Based on soil profile data from two Chinese national soil surveys, we have estimated soil organic carbon storage in the 1980s and its change over the time period from the 1960s to the 1980s for the nation. For the 1980s, our results indicated that the SOC storage in China was 92 Pg C (with 95% CI: 89, 95) for a total area of 878×10^6 ha^2, and that the average SOC density was 10.53 kg C m^{-2}(with 95% CI: 10.2, 10.86) A total of 92 Pg C in China represents about 6–8% of global SOC storage, given a global SOC pool of 1200–1600 Pg in the upper 1 m soils of the world. For the 1960s, our study showed that SOC storage in China was 93 Pg C (with 95% CI: 73, 113) for an area of 879 $\times$ 10^6ha^2, and that the average SOC density in China was 10.61 kg Cm^{-2} (with 95% CI: 6.21, 15.01). This result suggests that the SOC pool decreased about 1 Pg during the time period from the 1960s to the 1980s. This amount of decrease in SOC for the nation was small and statistically insignificant.

The density and change of SOC among sub-regions exhibit significant variability because of the spatial heterogeneity in natural environments as well as the difference in land management. The density of SOC was generally higher in the west than other regions, which indicates a low human disturbance in the west. Eastern China had the lowest SOC density, which was associated with a long history of extensive land use in the region. Northeast China appeared to experience a much greater decrease in SOC density than other regions because of intensive land exploitation during that time period. Our results further imply that the storage and change in SOC are obviously associated with land use practices. Clearly, improving land use management is essential for increasing soil carbon storage and hence sequestration of atmospheric CO_2.

Uncertainty exists in our estimates on the storage and change of SOC in China. Although the large number of soil profile data in the 1980s can lead to a reliable estimate for contemporary SOC storage, the relatively small number of soil profiles in the 1960s can bias our estimate of SOC for that time period and hence the change in SOC during the 1960s–1980s. We need to explore ways to extrapolate site data to national spatial scales. To adequately characterize spatial variations in SOC, larger sampling sizes of soil profiles will be required in future analyses. Chinese terrestrial ecosystems have experienced a rapid change in land use/cover change and substantial climate variability. An important need in the future will be to understand mechanisms controlling dynamics of SOC at a large scale.

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REFERENCES

Bajracharya, R. M., Lal, R. and Kimble, J. M. 1998. Soil organic distribution in aggregates and primary particle fractions as influenced by erosion phases and landscape position. In: *Soil processes and the carbon cycle*. (eds. R. Lal et al.) CRC Press. Boca Raton, FL, 353–367.

Batjes, N. H. 1996. Total carbon and nitrogen in the soils of the world. *Eur. J. Soil. Sci*. **47**, 151–163.

Bohn, H.. 1978 On organic soil C and CO_2. *Tellus* **30**, 472–475.

Cai, Z. 1996. Effect of land use on organic carbon storage in soils in eastern China. *Water, Air and Soil Pollution* **91**, 383–393.

Davidson E. A., Trumbore, S. E. and Amundson, R. 2000. Soil warming and organic carbon content. *Nature* **408**, 789–790.

Eswaran, H., Van Den Berg, E. and Reich, P. 1993. Organic carbon in soils of the world. *Soil Sci. Soc. Am. J*. **57**, 192–194.

Fang, J., Liu, G. and Xu, S. 1996. Carbon reservoir of terrestrial ecosystem in China. In: *Monitoring and relevant process of greenhouse gas concentration and emission*. Chinese Environment Sciences Publishing House, Beijing, 109–128.

Feng, Q., Cheng, G. and Mikami, M. 1999. Water resources in China: problems and countermeasures. *AMBIO* **28**, 202–203.

Foley, J. A. 1995. An equilibrium model of the terrestrial carbon budget. *Tellus* **47B**, 310–319.

Hou, X. 1982. *Vegetation Map of the People's Republic of China (1:4 000 000)*. Chinese Map Press, Beijing.

Houghton, R. A. 1995. Land-use change and the carbon cycle. *Global Change Bio*. **1**, 275–287.

Houghton, R. A. 1999. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus*, **51B**, 298–313.

Houghton, R. A. and Skole, D. L. 1990. Carbon. In: *The Earth as transformed by human action*. (eds. B. L.Turner, W. C. Clark, Kates, R. W., J. F. Richards, J. T. Mathews and W. B. Meyer), Cambridge University Press, Cambridge, 393–408.

Kern, J. S. 1994. Spatial patterns of soil organic carbon in the contiguous United States. *Soil Sci. Soc. Am. J*. **58**, 439–455.

King, A. W., Emanuel, W. R., Wullschleger, S. D. and Post, W. M. 1995. A search of the missing carbon sink: a model of terrestrial biospheric response to land-use change and atmospheric CO_2. *Tellus* **47B**, 501–519.

Lal, R. 1995. Global soil erosion by water and carbon dynamics. In: *Soils and global change*. (eds. R. Lal, J. Kimble, E. Levine and B. A. Stewart) Advances in Soil Sciences, CRC Press, Boca Raton, FL, 131–142

Lal, R., Fausey, N. R. and Eckert, D. J. 1995a. Land use and soil management effects on emissions of radiatively active gas from two Ohio soils. In: *Soils and global change*. (eds. R. Lal, J. Kimble, E. Levine and B. A. Stewart) Advances in Soil Sciences, CRC Press. Boca Raton, FL, 41–59.

Lal, R., Kimble, J., Levine, E. and Whitman, C. 1995b. World soils and greenhouse effect: an overview. In: *Soils and global change*. (eds. R. Lal, J. Kimble, E. Levine and B. A. Stewart). Advances in Soil Sciences, CRC Press. Boca Raton, FL, 1–7.

Lal, R. 1999. Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect. *Progr. Environ. Sci*. **1**, 307–326.

Lashof, D. and Hare, B. 1999. The role of the biotic carbon stocks in stabilizing greenhouse gas concentrations at safe levels. *Environ. Sci. Policy* **2**, 101–109.

Li, Z. and Zhao, Q. 2001. Organic carbon content and distribution in soils under different land uses in tropical and subtropical China. *Plant and Soil* **231**, 175–185.

McGuire, A. D., Sitch, S., Dargaville, R., Esser, G., Foley, J., Heimann, M., Joos, F., Kaplan, J., Kicklighter, D. W., Meier, R. A., Melillo, J. M., Moore III, B., Prentice, I. C., Ramankutty, N., Reichenau, T., Schloss, A., Tian, H., Williams, L. J. and Wittenberg, U. 2001. The effects of CO_2, climate and land-use on terrestrial carbon balance, 1920–1992: An analysis with four process-based ecosystem models. *Global Biogeochem. Cycles* **15**, 183–206.

Melillo, J. M., Kicklighter, D., McGuire, A., Peterjohn, W. and Newkirk, K. 1995. Global change and its effects on soil organic carbon stocks. In: *Dahlem Conference Proceedings*, John Wiley and Sons, New York, 175–189.

National Soil Survey Office. 1993. *Soil species of China*, Vol. I. Chinese Agriculture Press, Beijing. 1–924.

National Soil Survey Office. 1994a. *Soil species of China*, Vol. II. Chinese AgriculturePress, Beijing. 1–730.

National Soil Survey Office. 1994b. *Soil species of China*, Vol. III. Chinese AgriculturePress, Beijing. 1–744.

National Soil Survey Office. 1995a. *Soil species of China*, Vol. IV. Chinese AgriculturePress, Beijing. 1–806.

National Soil Survey Office. 1995b. *Soil species of China*, Vol. V. Chinese AgriculturePress, Beijing. 1–886.

National Soil Survey Office. 1996. *Soil species of China*, Vol. VI. Chinese Agriculture Press, Beijing. 1–880.

National Soil Survey Office. 1998. *Chinese soils*. Chinese Agriculture Press, Beijing.1–1252.

Nelson, D. W., and Sommers, L. E. 1982. Total carbon, organic carbon, and organic matter. In: *Methods of soil analysis*, Part 2. (ed. A. Klute), 2nd edn. Agron. Monogr. 9, ASA. Madison, WI, 539–579.

Paustian, K., Robertson, G. P. and Elliott, E. T. 1995. Management impacts on carbon storage and gas fluxes (CO_2, CH_4) in mid-latitudes cropland In: *Soils and global change*. (eds. R. Lal et al.) Advances in Soil Sciences. CRC Press. Boca Raton, FL, 69–83.

Post, W. M. and Kwon, W. M. 2000. Soil carbon sequestration and land-use change: processes and potential. *Global Change Biol*. **6**, 317–327.

Post, W. M., Emanuel, W. R., Zinke, P. J. and Stangenberger, A. G. 1982. Soil carbon pools and life zones. *Nature* **298**, 156–159.

Post, W. M., Peng, T. H., Emanuel, W. R., King, A. W., Dale, V. H. and Angelis, D. L. 1990. The global carbon cycle. *Am. Sci*. **78**, 310–326.

Post, W. M., Izaurralde, R. C., Mann, L. K. and Bills, N. 1998. Monitoring and verifying soil organic Carbon sequestration. In: *Carbon sequestration in soils*. (eds. N. Rosenberg, R. C. Izaurralde and E. L. Malone), Battelle Press, Columbus: 41–66.

Prentice, K. C. and Fung, I. Y. 1990. The sensitivity of terrestrial carbon storage to climate change. *Nature* **346**, 48–51.

Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M. and coauthors, 2001. The carbon cycle and atmospheric CO_2. In: *The Third Assessment Report of Intergovernmental Panel on Climate Change (IPCC)*, chapter 3 Cambridge University Press, Cambridge.

Rozhkov, V. A., Wagner, V. B., Kogut, B. M., Konyushkov, D. E., Nilsson, S., Sheremet, V. B. and Shvidenko, A. Z. 1996. Soil carbon estimates and soil carbon map for Russia. *IIASA working paper*, WR96-60, 1–44. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Sampson, R. N., Apps, M. and Brown, S. 1993. Terrestrial biosphere carbon fluxes quantification of sinks and sources of CO_2. *Water, Air Soil Pollut*. **70**, 3–15.

Sandström, S. 1993. Carbon storage and flow: their relationship to water, soil and land management. *AMBIO* **22**, 438–441.

Schimel, D. S., Braswell, B. H., Holland, E. A., McKeown, R., Ojima, D. S., Painter, T. H., Parton, W. J. and Townsend, A. R. 1994. Climatic, edaphic, and biotic controls over storage and turnover of carbon in soils. *Global Biogeochem. Cycles* **8**, 279–293.

Schimel, D., Melillo, J., Tian, H., McGuire, D., Kicklighter, D., Kittel, T., Rosenbloom, N., Running, S., Thornton, P., Ojima, D., Parton, W., Kelly, R., Sykes, M., Neilson, R. and Rizzo, B. 2000. Contribution of increasing CO_2 and climate to carbon storage by ecosystems in the United States. *Science* **287**, 2004–2006.

Schlesinger, W. H. 1984. Soil organic matter: a source of atmospheric CO_2. *The role of terrestrial vegetation in the global carbon cycle*. (ed. G. W. Woodwell) SCOPE 23. Wiley and Sons, New York, 111–127.

Scott, N. A., Tate, K. R., Ford-Robertson, J., Giltrap, D. J. and Smith, C. T. 1999. Soil carbon storage in plantation forests and pastures: land-use change implications. *Tellus* **51B**, 326–335.

Sombroke, W. G., Nachtergaele, F. O. and Hebel, A. 1993. Amount, dynamics and sequestering of carbon in tropical and subtropical soils. *AMBIO* **22**, 417–426.

Tarnocai, C. and Ballard, M. 1994. Organic carbon in Canadian soils. In: *Soil processes and greenhouse effect*. (eds. R. Lal, J. Kimble and E.Levine), USDA, Soil Conservation Service, national Soil Survey Center, Lincold, NE, 31–45.

Tian, Q., Li, J., Huang, F. and Pei, X. 1996. Chinese resources and environment database (1:4 000 000). The State Key Laboratory of Resources and Environment Information System (http://www.lreis.ac.cn). Institute of Geographic Sciences and Natural Resources Research, Beijing.

Tian, H., Melillo, J. M., Kicklighter, D. W., McGuire, A. D., Helfrich, J., Moore III, B. and Vörösmarty, C. J. 1998. Effect of interannual climate variability on carbon storage in Amazonian ecosystems. *Nature* **396**, 664–667.

Tian, H., Melillo, J. M., Kicklighter, D. W., McGuire, A. D. and Helfrich, J. 1999. The sensitivity of terrestrial carbon storage to historical climate variability and atmospheric CO_2 in the United States. *Tellus* **51B**, 414–452.

Tian, H., Melillo, J. M., Kicklighter, D. W., McGuire, A. D., Helfrich III, J., Moore III, B. and Vörösmarty, C. J. 2000. Climatic and biotic controls on annual carbon storage in Amazonian ecosystems. *Global Ecology and Biogrography* **9**, 315–335.

Tian, H., Melillo, J. M., Kicklighter, D. W., Pan, S., Liu, J. McGuire, A. D. and Moore III, B. 2003. Regional carbon dynamics in monsoon Asia and its implications to the global carbon cycle. *Global and Planetary Change* (in press).

Torn, M. S., Trunbore, S. E., Chadwick, O. A., Vitousek, P. M. and Hendricks, D. M. 1997. Mineral control of soil organic carbon storage and turnover. *Nature* **389**, 170–173.

Wang, S., Zhou, C., Li, K., Zhu, S. and Huang, F. 2001. Estimation of soil organic carbon reservoir in China. *J. Geogr. Sci*. **11**, 3–13, 2001.

Wang, S., Zhou, C., Liu, J., Tian, H., Li, K. and Yang, X. 2002. Carbon storage in northeast China as estimated from vegetation and soil inventories. *Environ. Pollut*. **116**, 157–165.

Wang, Y. 1999. Study on regional carbon cycle of forest ecosystem in China, Ph.D degree thesis, Commission for Integrated Survey of Natural Resources, Academia Sinica, Beijing, China.

Wang, Y. and Amuddson, R. 1999. The impact of land use change on C turnover in soils. *Global Biogeochem. Cycles* **13**, 47–57.

Xiong, Y. and Li, Q. 1978. *Chinese soils* (in Chinese). Science Press, Beijing, 746 pp.
Zhou, Y. 1998. A study on carbon circulation of Chinese major forest types, Master degree thesis, Commission for Integrated Survey of Natural Resources, Academia Sinica, Beijing, China.
Zhou, G. 1999. Impact of climate change on NPP of agriculture and animal husbandary in ecologically vulnerable areas: mechanism and modelling. *Resources Sci*. **21**, 46–52.
Zinke, P. J., Stangenberger, A. G., Post, W. M., Emanuel, W. R. and Olson, J. S. 1984. Worldwide organic soil carbon and nitrogen data. ORNL/TM-8857. Oak Ridge National Laboratory. Oak Ridge, Tenn.