Distribution and storage of soil organic carbon in China

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[1] Surface soils hold the largest terrestrial organic carbon pool, although estimates of the world's soil organic carbon storage remain controversial, largely due to spatial data gaps or insufficient data density. In this study, spatial distribution and storage of soil organic carbon in China are estimated using the published data from 34,411 soil profiles investigated during China's second national soil survey. Results show that organic carbon density in soils varies from 0.73 to 70.79 kg C/m^2 with the majority ranging between 4.00 and 11.00 kg C/m^2. Carbon density decreases from east to west. A general southward increase is obvious for western China, while carbon density decreases from north to south in eastern China. Highest values are observed in forest soils in northeast China and in subalpine soils in the southeastern part of the Tibetan Plateau. The average density of ~8.01 kg C/m^2 in China is lower than the world's mean organic carbon density in soil (~10.60 kg C/m^2), mainly due to the extended arid and semi-arid regions. Total organic carbon storage in soils in China is estimated to be ~70.31 Pg C, representing ~4.7% of the world storage. Carbon storage in the surface organic horizons which is most sensitive to interactions with the atmosphere and environmental change is ~32.54 Pg C. *INDEX TERMS:* 0330 Atmospheric Composition and Structure: Geochemical cycles; 1615 Global Change: Biogeochemical processes (4805); 1815 Hydrology: Erosion and sedimentation; 1625 Global Change: Geomorphology and weathering (1824, 1886); *KEYWORDS:* organic carbon storage, carbon density, soil, China

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1. Introduction

[2] Current imbalances in the global carbon budget may be related to uncertainty of the fluxes of carbon sources/sinks [*Intergovernmental Panel on Climate Change*, 1996; *Schindler*, 1999] and also to inaccuracy in estimates of carbon storage in individual components of the Earth's system [*Edmonds*, 1992; *Jain et al.*, 1997]. Terrestrial ecosystems in the Northern Hemisphere may play a vital role in moderating CO_2 uptake in the overall carbon budget [*Kauppi et al.*, 1992; *Ciais et al.*, 1995; *Fan et al.*, 1998; *Houghton et al.*, 1999; *Fang et al.*, 2001]. Soil organic carbon is the largest terrestrial carbon pool, about two times larger than carbon storage in aboveground biomass or the atmosphere [*Post et al.*, 1990], and is an important component of the global carbon cycle. Accurate estimates of soil carbon storage are thus important for understanding CO_2 fluxes to and from the atmosphere.

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[3] Efforts to determine the carbon storage in soils at regional [*Siltanen et al.*, 1997; *Batjes and Sombroek*, 1997; *Milne and Brown*, 1997; *Tarnocai*, 1998; *Grossman et al.*, 2001; *Li et al.*, 2001] and global [*Post et al.*, 1982; *Zinke et al.*, 1984; *Eswaran et al.*, 1993; *Batjes*, 1996; *Adams and Faure*, 1998; *Jobbagy and Jackson*, 2000] scales have provided a basis for terrestrial carbon modeling [*Esser*, 1987; *Foley*, 1995; *Haxeltine and Prentice*, 1996; *François et al.*, 1998; *Kurz and Apps*, 1999; *Cox et al.*, 2000; *Kaplan*, 2001]. Two most frequently used global soil carbon databases, the worldwide organic soil carbon and nitrogen data (WOSCN) [*Zinke et al.*, 1984] in Oak Ridge National Laboratory database and the WISE (World Inventory of Soil Emission) global soil profile database [*Batjes*, 1996], contain carbon and nitrogen analytical data from merely 3,583 and 4,353 profiles of the world. The soil profiles in the WOSCN database are mainly compiled from North America [*Zinke et al.*, 1984], while the majority of soil profiles in the WISE database are collected from Africa, South America, and the Caribbean [*Batjes*, 1996]. These global databases are not likely suitable for investigating detailed soil carbon budget at national levels [*Batjes*, 1996]. More accurate estimates on soil organic carbon storage and the spatial distribution at the regional scale based on greater data densities would significantly improve our understanding of soil organic carbon sequestration at a global scale as well as its role in carbon cycles.

[4] China has an extended terrestrial surface with strong spatial climatic and topographic variability. This leads to a great diversity of soils, including the latosols in the tropical zone, podzolic soils in the frigid-temperate zone, black soils in the northeast plain, desert soils in the northwestern inland, solonchaks on the coastal plains and alpine soils on the Tibetan Plateau [*National Soil Survey Office (NSSO)*, 1998]. Consequently, soil carbon density is highly variable. A first attempt at estimating the soil organic carbon storage in China was carried out by *Fang et al.* [1996], based on data from 725 soil profiles studied in China's first soil survey in the 1960s [*Institute of Soil Science*, 1982] and some investigations of forest soils [*Zhang*, 1986]. Rough estimates were made by *Peng and Apps* [1997] and *Ni* [2001] based on data from the WOSCN data [*Zinke et al.*, 1984], which contains only a small number of soil profiles from China. A more recent estimate of soil carbon storage at the national scale was also conducted by *Wang et al.* [2001], based on the 2473 soil profile data from China's second national soil survey. Several estimates with greater data density at regional scales were carried out for soils in southeast China [*Zhao et al.*, 1997; *Li and Zhao*, 2001; *Li et al.*, 2001] as well as cryic/colder soils in northern China [*Luo et al.*, 2000; *Wang et al.*, 2002]. There is, therefore, an urgent need to more accurately estimate the organic carbon storage in soils for the whole country.

[5] In this study, the spatial pattern of soil organic carbon density and organic carbon storage are investigated based on data from 34,411 soil profiles analyzed in China's second national soil survey [*NSSO*, 1993, 1994a, 1994b, 1995a, 1995b, 1996, 1998] conducted in the 1980s. Since data density during this investigation was much greater than any soil survey data that were used in previous estimates, it would be expected to more accurately represent the current situation of soil organic carbon in China.

2. Data and Methods

[6] Data used in this study were from China's second national soil survey [*NSSO*, 1993, 1994a, 1994b, 1995a, 1995b, 1996, 1998]. Because of the lack of soil data from the Taiwan region, calculation was simply made by analogy using the data of corresponding soil subgroups from China's mainland for completeness. We assume that this treatment will not cause significant variation for total national soil carbon storage since the Taiwan region accounts for only 3.8% of China's total land area. The soil surface considered in this study amounts to ~881.81 million hectares (Mha) excluding water, glacial and permanent snow covered areas, and rock mountains [*NSSO*, 1998]. Since the Chinese soil taxonomy [*NSSO*, 1998] was used in the soil surveys, we used the same terminology in this study, but have tentatively compared it with the *Food and Agriculture Organization/UNESCO* [1988] soil classification (Table 1). The base electronic map of soil distribution used in this study is from *Tian et al.* [1996]. Soil taxonomy in the second national soil survey was not completely consistent with the legend of the soil map, necessary mergence of some soils, especially at the subgroup level was made based on the principle of approximation [*Li et al.*, 2001].

[7] Since organic carbon content varies along the soil profile, soil organic carbon density (SOCD) of each profile was calculated as follows:

$$\mathrm{SOCD} = \sum_{i=1}^{n} 0.58 \times \mathrm{T}_i \times \rho_i \times \mathrm{M}_i \times (1 - \mathrm{C}_i)/10, \qquad (1)$$

where n is the number of pedogenic horizons defined in the soil survey [*NSSO*, 1998], 0.58 is the Bemmelen index that converts organic matter concentration (M) to organic carbon content (OC) because organic matter was calculated by wet combustion with $Cr_2O_7^{2-}$ [*Wen*, 1984], T_i, ρ_i, M_i and C_i represent thickness (cm), bulk density (g/cm^3), organic matter content and volumetric percentage of the fraction >2 mm (rock fragments) in layer *i*, respectively.

[8] Because of the lack of bulk density data in some soil profiles, we have established empirical relationships between organic carbon content and bulk density based on 784 analytical samples (Figure 1), as is a method frequently used in earlier studies [*Zinke et al.*, 1984; *Grigal et al.*, 1989; *Siltanen et al.*, 1997]. Bulk density of soils without actual measured values was obtained using these empirical relationships (Figure 1). For the soil horizons without measured rock fragment volume (C_i), mean value of the same soil subgroup was used. Soil organic carbon storage (SOCS) was then computed by

$$\mathrm{SOCS} = \sum_{i=1}^{n} \mathrm{area}_i \times \mathrm{SOCD}_i, \qquad (2)$$

where area_i and SOCD_i are the surface area and the organic carbon density of the soil subgroup *i*, respectively.

[9] In China's second national soil survey, soil profiles were generally divided into A, B and C horizons based on pedogenic properties of each horizon [*NSSO*, 1998]. In the A horizon (organic horizon) of soils, organic carbon has a turnover time of decades or less, while in the underlying B and C horizons (mineral horizons) it is much slower, that is about hundreds or thousands of years or more. This may lead to different interactions and feedbacks with the global climate system [*Schimel et al.*, 1994; *Townsend et al.*, 1995]. In this study, soil profiles were considered in two parts: the organic horizons (A horizons) and the mineral horizons (including horizon B and C) with carbon densities and storages calculated separately. Density and storage in the whole soil profile was also computed. In calculating regional organic carbon density, area-weighted means were used. As GIS (Geographical Information System) is a powerful way to visualize and analyze data geographically, we used ArcView GIS to map the spatial distribution of organic carbon densities.

3. Results and Discussions

3.1. Distribution of Soil Organic Carbon Density

[10] The content of organic carbon in soils is dependent on the bioproductivity and the mineralization intensity of organic matter, which are strongly controlled by hydrothermal conditions and soil texture [*Duchaufour*, 1983; *Paul*, 1984; *NSSO*, 1998; *Lal et al.*, 2001]. China is characterized by a great spatial variability of climates, including tropical, subtropical, warm-temperate, and frigid-temperate zones going from south to north. The southern part of China is

Table 1. Organic Carbon Densities of Soil Groups in China

Soil Groups in Chinese Soil Taxonomy	FAO/UNESCO Taxonomy	Number of Subgroups (Chinese Soil Taxonomy)	Number of Profiles	Area, Million Hectare	Organic Carbon Density, kg C/m^2: Organic Horizon (A Horizon)	Organic Carbon Density, kg C/m^2: Mineral Horizon (B and C Horizons)	Organic Carbon Density, kg C/m^2: Profile	Carbon Storage, 10^{10}kg
Latosols	haplic acrisols	2	864	4.27[a]	3.03 ± 0.51[b]	5.51 ± 0.77	8.54 ± 1.21	36.44
Latosolic red earths	haplic acrisols/alisols	3	193	18.13	3.57 ± 0.51	6.83 ± 1.10	10.40 ± 1.36	188.63
Red earths	haplic alisols/haplic acrisols	5	2008	57.87	2.80 ± 0.27	5.06 ± 0.36	7.86 ± 0.55	454.80
Yellow earths	haplic alisols	3	638	23.93	5.44 ± 0.50	5.53 ± 0.40	10.97 ± 0.73	262.41
Yellow-brown earths	ferric/haplic luvisols	3	273	18.42	4.24 ± 0.62	5.86 ± 1.04	10.10 ± 1.40	185.99
Yellow-cinnamon soils	eutric cambisols	4	221	3.81	2.12 ± 0.26	2.85 ± 0.24	4.97 ± 0.40	18.95
Brown earths	haplic/albic luvisols or eutric/dystric cambisols	4	1510	20.16	4.29 ± 0.60	5.42 ± 0.71	9.71 ± 1.21	195.77
Dark-brown earths	haplic luvisols/eutric cambisols	5	275	40.11	8.47 ± 0.90	6.63 ± 0.82	15.10 ± 1.35	606.72
Bleached Beijing soils	albic luvisols	3	282	5.27	4.60 ± 0.71	4.23 ± 0.35	8.83 ± 0.82	46.52
Brown coniferous forest soils	humic cambisols	3	49	11.66	9.48 ± 3.69	13.90 ± 7.34	23.38 ± 10.54	272.59
Podzolic soils	haplic podzols	1	3	0.00	19.97 ± 0.00	22.90 ± 0.00	42.87 ± 0.00	0.00
Torrid red soils	ferralic cambisols	2	99	0.69	1.68 ± 0.29	2.88 ± 0.56	4.56 ± 0.76	3.19
Cinnamon soils	eutric cambisols	7	1828	25.17	2.69 ± 0.31	3.93 ± 0.48	6.62 ± 0.66	166.75
Gray-cinnamon soils	haplic/calcic luvisol	5	105	6.18	10.34 ± 2.94	6.53 ± 1.17	16.87 ± 3.12	104.28
Black soils	haplic phaeozems	4	435	7.36	7.24 ± 0.85	5.55 ± 0.83	12.79 ± 1.35	95.10
Gray forest soils	albic luvisols	2	10	3.15	4.68 ± 0.82	4.48 ± 0.43	9.15 ± 1.23	28.83
Chernozems	chernozems	6	612	13.22	7.76 ± 1.04	5.11 ± 0.87	12.87 ± 1.56	170.13
Castanozems	kastanozems	7	918	37.50	4.05± 0.43	5.45 ± 0.75	9.50 ± 0.90	356.52
Castano-cinnamon soils	kastanozems	3	282	4.82	1.30 ± 0.26	4.23 ± 0.47	5.53 ± 0.69	26.63
Dark loessial soils	calcisols	3	860	2.55	6.16 ± 0.78	4.24 ± 0.82	10.39 ± 1.10	26.51
Brown caliche soils	haplic calcisols	6	68	26.56	1.22 ± 0.18	3.15 ± 0.20	4.37 ± 0.29	115.97
Sierozems	calcaric/haplic cambisols	4	506	5.38	1.41 ± 0.15	3.90 ± 0.51	5.2 ± 0.56	28.63
Gray desert soils	haplic calcisols	6	14	4.60	0.89 ± 0.10	2.17 ± 0.06	3.06 ± 0.11	14.06
Gray-brown desert soils	haplic calcisols	4	99	30.73	0.40 ± 0.15	1.51 ± 0.49	1.91 ± 0.58	58.82
Brown desert soils	soloncnaks	5	19	24.30	0.62 ± 0.52	0.72 ± 0.23	1.34 ± 0.77	32.57
Loessial soils	calcaric regosols	1	1368	12.29	1.38 ± 0.17	3.63 ± 0.30	5.01 ± 0.38	61.60
Red primitive soils	luvisols	3	449	2.28	1.69 ± 0.20	2.55 ± 0.31	4.24 ± 0.39	9.67
Neo-alluvial soils	fluvisols	3	872	4.29	2.07 ± 0.29	4.39 ± 0.85	6.46 ± 1.05	27.71
Takyr	soloncnaks	1	2	0.68	0.16 ± 0.12	0.77 ± 0.77	0.93 ± 0.89	0.63
Aeolian soils	arenosols	4	287	67.57	0.69 ± 0.21	1.76 ± 0.34	2.45 ± 0.46	165.30
Skeletal soils	regosols/leptisols	4	589	26.11	1.92 ± 0.37	1.87 ± 0.77	3.79 ± 1.07	98.89
Limestone soils	regosols/leptisols	4	463	10.77	5.40 ± 0.82	4.26 ± 0.68	9.66 ± 0.96	103.99
Volcanic soils	andosols	3	47	0.19	5.97 ± 1.31	10.24 ± 7.58	16.20 ± 8.40	3.08
Purplish soils	calcaric regosols	3	1027	18.90	2.30 ± 0.30	3.22 ± 0.42	5.52 ± 0.56	104.25
Phospho-calcic soils	calcaric regosols	2	4	0.00	10.27 ± 0.49	3.12 ± 0.42	13.39 ± 0.07	0.00
Lithosols	regosols/leptisols	3	179	18.53	1.87 ± 0.32	0.00 ± 0.00	1.88 ± 0.32	34.85
Meadow soils	umbric gleysols/haplic phaeozem	6	940	25.09	5.25 ± 0.77	5.44 ± 0.63	10.69 ± 1.09	268.19
Fluvi-aquic soils	fluvisols	7	4206	25.68	2.11 ± 0.19	4.09 ± 0.27	6.20 ± 0.40	159.35
Saijiang black soils	eutric vertisols/gleyic cambisol	5	271	3.77	2.68 ± 0.39	3.65 ± 0.39	6.32 ± 0.38	23.88
Shruby meadow soils	calcic cambisols	2	3	2.48	1.69 ± 0.07	3.25 ± 0.03	4.94 ± 0.10	12.25
Mountain meadow soils	umbric leptisols/dystric cambisols	3	143	4.22	10.27 ± 2.64	9.73 ± 3.67	20.00 ± 1.96	84.39
Bog soils	gleysols	5	245	12.62	16.24 ± 4.33	10.69 ± 3.29	26.94 ± 5.81	339.89

Table 1. (continued)

Soil Groups in Chinese Soil Taxonomy	FAO/UNESCO Taxonomy	Number of Subgroups (Chinese Soil Taxonomy)	Number of Profiles	Area, Million Hectare	Organic Carbon Density, kg C/m^2			Carbon Storage, 10^{10}kg
					Organic Horizon (A Horizon)	Mineral Horizon (B and C Horizons)	Profile	
Peat soils	histosols	3	67	1.47	24.16 ± 6.64	46.62 ± 14.89	70.79 ± 13.56	104.73
Meadow solonchaks	solonchaks	4	57	10.44	1.03 ± 0.13	2.67 ± 0.22	3.70 ± 0.22	38.62
Coastal solonchaks	solonchaks	3	146	2.12	1.45 ± 0.29	4.56 ± 1.15	6.00 ± 1.31	12.73
Acid sulphate soils	solonchaks	2	13	0.02	3.52 ± 0.03	11.33 ± 0.09	14.86 ± 0.10	0.30
Desert solonchaks	solonchaks	3	15	2.87	1.58 ± 0.33	2.88 ± 0.53	4.46 ± 0.76	12.82
Frigid plateau solonchaks	solonchaks	3	8	0.69	1.48 ± 0.51	2.51 ± 0.28	3.99 ± 0.23	2.76
Solonetzs	solonchaks	5	85	0.87	2.20 ± 0.53	2.43 ± 0.26	4.63 ± 0.66	4.03
Paddy soils	fluvisols/cambisols	8	8993	30.68	4.44 ± 0.18	5.15 ± 0.30	9.59 ± 0.40	294.21
Irrigated silting soils	calcaric fluvisols	4	570	1.52	4.44 ± 0.52	3.03 ± 0.74	7.47 ± 0.77	11.38
Irrigated desert soils	calcaric fluvisols	4	262	0.91	3.15 ± 0.30	4.57 ± 0.38	7.73 ± 0.41	7.03
Felty soils (Alpine meadow soils)	cambisols	4	187	53.54	6.65 ± 1.12	2.82 ± 0.92	9.47 ± 1.70	507.26
Dark felty soils (Subalpine meadow soils)	cambisols	4	135	19.44	9.86 ± 1.92	6.79 ± 2.34	16.65 ± 2.80	323.71
Frigid calcic soils (Alpine steppe soils)	cambisols	4	106	68.85	1.77 ± 0.54	5.72 ± 3.80	7.48 ± 3.68	515.29
Cold calcic soils (Subalpine steppe soils)	cambisols	4	162	11.29	3.89 ± 0.51	5.29 ± 0.57	9.17 ± 0.96	103.59
Cold brown calcic soils (Mountain shrub steppe soils)	cambisols	2	306	0.96	2.47 ± 0.25	4.93 ± 0.81	7.40 ± 0.93	7.11
Frigid desert soils (Mountain shrub steppe soils)	gelic arenosols	1	3	8.96	0.47 ± 0.26	0.90 ± 0.27	1.37 ± 0.24	12.26
Cold desert soils (Subalpine desert soils)	gelic arenosols	1	2	5.22	0.72 ± 0.24	0.33 ± 0.04	1.04 ± 0.20	5.45
Frigid frozen soils (Alpine frozen soils)	gelic regosols	1	28	30.65	1.55 ± 0.65	0.85 ± 0.22	2.40 ± 0.72	73.46
Total		219[c]	34411	881.81				7031.45

[a]Each group surface area of soils in mainland was calculated by summing provincial data [*NSSO*, 1998] and that in Taiwan was computed by the map of soils [*Tian et al.*, 1996].
[b]Mean ± standard error of the mean.
[c]One soil group and nine soil subgroups of very small area were not included.

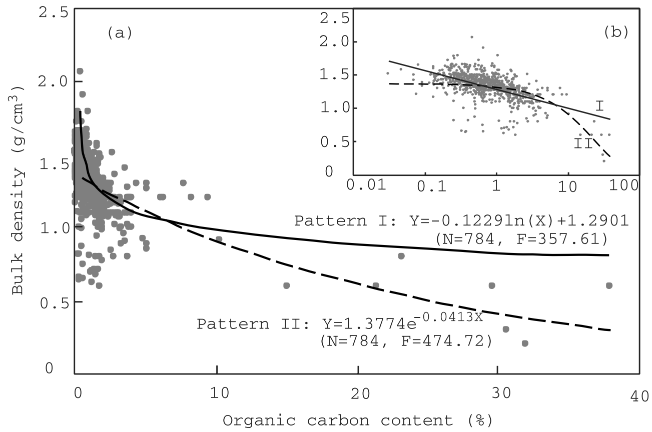

Figure 1. Empirical relationships between soil bulk density and organic carbon content plotted on (a) linear and (b) logarithmic scales. The relationships are established based on measurements of 784 samples obtained from the National Soil Survey Office [*NSSO*, 1993, 1994a, 1994b, 1995a, 1995b, 1996]. These data show two regression patterns between bulk density and organic carbon content in soils. The coefficient of correlation (R_I = 0.58 and R_{II} = 0.62 > $R_{0.001}$ = 0.32) and *F* test values (F_I = 357.61 and F_{II} = 474.72 >$F_{0.01}$ = 6.69) indicate that the relationships are statistically significant. Pattern I (continuous regression line) is suitable for samples with a carbon content <6%, and Pattern II (dotted regression line) is suitable for samples with a carbon content >6%. These relationships are used respectively based on carbon content.

strongly humid due to the influences of the Asian monsoon circulations [*Zhang*, 1991] while in northwest China, the barrier effect of the Tibetan Plateau to moisture and the long distance from the ocean result in an arid climate. So the mean annual temperature of China increases from ∼−6.5°C to ∼23.5°C with the decrease of latitude, and the annual precipitation decreases from ∼2500 mm to ∼15 mm along southeast to northwest China. Cold conditions prevail across the Tibetan Plateau due to the high elevation. The fine soil texture is distributed in southern and eastern China while the coarse is found in the northern and western part [*Xiong and Li*, 1987]. These climate patterns and soil textures have strong impacts on the spatial distribution of soil organic carbon density in China.

[11] The organic carbon densities of the soil groups in China are listed in Table 1, and the values for each of 219 soil subgroups (for terminology, see *NSSO* [1998]) are shown in Figure 2. For the whole country, soil organic carbon densities, in terms of soil subgroups, range from 0.16 to 34.37 kg C/m^2 for the organic horizons, from 0.00 to 47.62 kg C/m^2 for the mineral horizons, and from 0.73 to 70.79 kg C/m^2 for entire soil profiles. Most of the density values fall into the ranges from 1.00 to 5.00 C/m^2 for the organic horizons, 2.50 to 7.50 C/m^2 for the mineral horizons and 4.00 to 11.00 kg C/m^2 for soil profiles at the subgroup level (Figure 2). Lowest carbon density was observed for the takyr soil group, with the highest occurring in the peat soils (Table 1).

[12] Figure 3 shows the distribution of organic carbon densities in the organic horizons, mineral horizons, and soil profiles by subgroup level. Organic carbon densities are highest, generally around 20.00 kg C/m^2 and more than 50.00 kg C/m^2 at the maximum, in brown coniferous forest soils/dark brown earths/bog soils in northeast China and in the subalpine/peat soils in the southeastern Tibetan Plateau. The lowest density, generally less than 3.00 kg C/m^2, was observed for desert soils in northwest China. Overall, soil organic carbon density decreases from east to west, and a

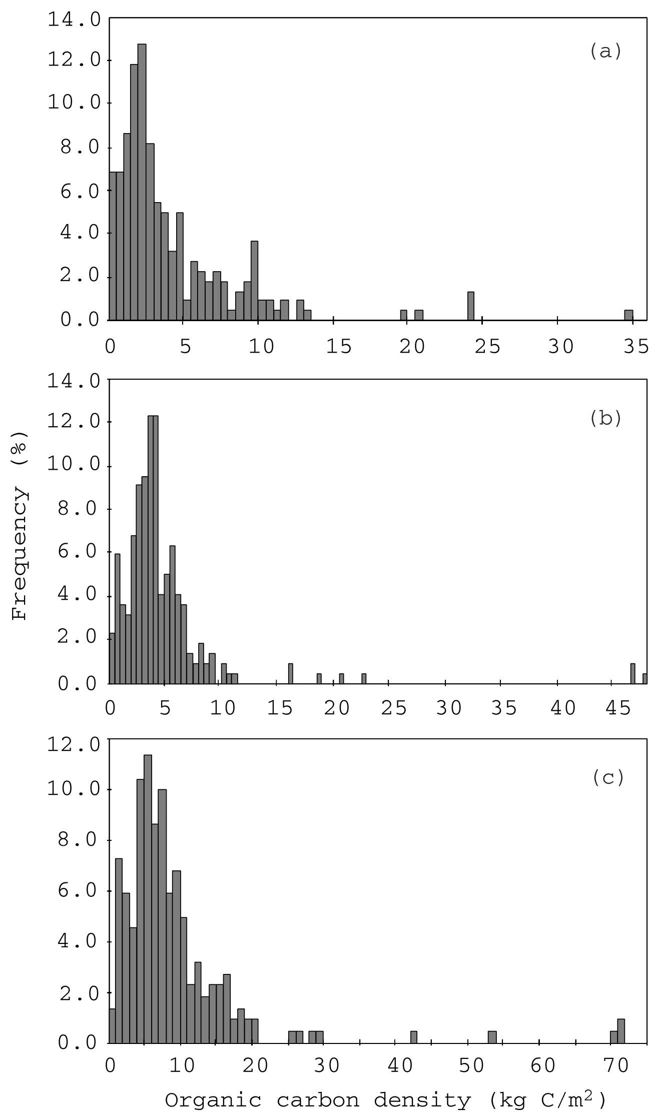

Figure 2. Frequency distribution of soil organic carbon densities in the 219 soil subgroups: (a) distribution in the organic horizons (A horizon), (b) distribution in the mineral horizons (B and C horizons), and (c) distribution in the soil profiles. Each bar corresponds to the ratio of the number of subgroups with a given carbon density versus the total subgroup number. Statistics are made at intervals of 0.5 kg C/m^2 of carbon density for Figures 2a and 2b, and at intervals of 1.0 kg C/m^2 for Figure 2c.

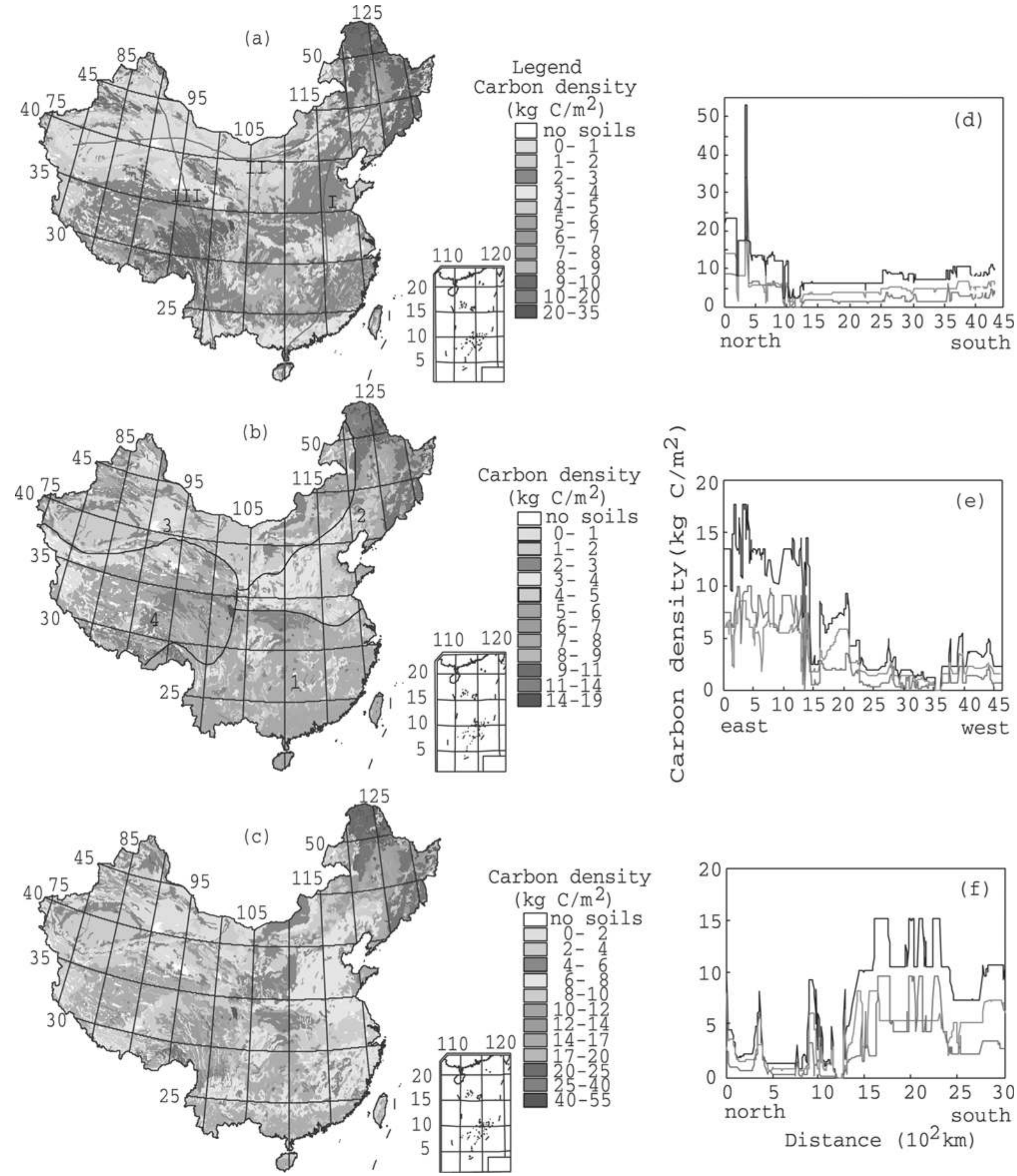

Figure 3. Spatial distribution of soil organic carbon densities in China and variations along three representative transects (I, II, and III): (a) distribution in the organic horizons (A horizon), (b) distribution in the mineral horizons (B and C horizons), and (c) distribution in the soil profiles. In (d), (e) and (f), red, green and dark lines indicate variations in the organic horizons, mineral horizons, and soil profiles, respectively. The four major climate zones in Figure 3b refer to monsoonal tropical-subtropical zone (Zone 1), the monsoonal temperate zone (Zone 2), the arid zone (Zone 3), and the frigid zone (Zone 4), respectively. See color version of this figure at back of this issue.

general increase is obvious from north to south in western China while it decreases from north to south in eastern China. These variations can be better characterized along three transects (Figure 3) that are defined based on the most dominant climate variables (temperature and humidity) and soil texture gradients.

[13] Along transect I (Figure 3d), high organic carbon density, generally around 20.00 kg C/m^2, was observed for the brown coniferous forest soils distributed in northeast China. Corresponding to the soil sequence of dark brown earths, black soils, chernozems, meadow soils, brown earths and cinnamon soils from north to south, soil organic carbon density decreases from $\sim$ 9.00 to $\sim$3.00 kg C/m^2 in the organic horizons, from $\sim$15.00 to $\sim$4.00 kg C/m^2 in the mineral horizons, and from $\sim$20.00 to $\sim$7.00 kg C/m^2 for entire soil profiles. This southward decrease is consistent with the temperature increase as hotter conditions are favorable for the mineralization of soil organic matter. Slight increases were observed for the yellow earths and latosolic red earths in southern China, attributable to higher bioproductivity, and increasing clay content by reducing carbon outputs through its stabilizing effect on soil organic carbon [*Paul*, 1984] under humid tropical and subtropical conditions.

[14] Along transect II (Figure 3e), the density of soil organic carbon decreases from east to west, following a sequence of black soils, meadow soils, castanozems, brown caliche soils, gray desert soils and gray brown desert soils. This is in agreement with increased aridity and decreased clay content in soil from east to west, leading to lower bioproductivity [*NSSO*, 1998] and less stabilized organic matter in soil [*Paul*, 1984]. Values vary from $\sim$7.50 to $\sim$1.00 C/m^2 for the organic horizons, from $\sim$6.00 to $\sim$2.00 kg C/m^2 for the mineral horizons, and from $\sim$14.00 to $\sim$3.00 kg C/m^2 for soil profiles. Two sudden decreases in organic carbon densities correspond to the transition from the black soils to castanozems, and that from the brown caliche to the desert soils, respectively.

[15] Along transect III in western China (Figure 3f), soil organic carbon density increases from the gray brown soils under arid conditions at the northern end of the transect to the alpine/subalpine soils on the Tibetan Plateau. It varies from $\sim$1.00 to $\sim$7.00 kg C/m^2 for the organic horizons, from $\sim$2.00 to $\sim$6.00 kg C/m^2 for the mineral horizons, and from $\sim$3.00 to $\sim$13.00 kg C/m^2 for the soil profiles. The high density on the Tibetan Plateau is attributable to the cooler conditions, favorable to the accumulation of soil organic matter. The decrease at the southern end of the transect corresponds to the red earths in southern China at lower elevations.

[16] In northeastern China and the southeastern Tibetan Plateau under cool and relatively humid conditions, carbon density in the organic horizons is generally higher than that in the mineral horizons (Figure 3) while an inverse pattern is observed in the other area, probably due to higher temperatures.

[17] The empirical relationship among soil organic carbon, climate variables, and soil texture was established based on 722 analytical data that were measured in parallel at the same time from the soil profiles [*NSSO*, 1993, 1994a, 1994b, 1995a, 1995b, 1996]. These soil profiles had not experienced any disturbance by human activity [*NSSO*, 1993, 1994a, 1994b, 1995a, 1995b, 1996]. The relationship is expressed as follows:

$$\begin{aligned}\mathrm{SOCD} &= 9.74341 + 0.0338\mathrm{CF} - 1.5513\mathrm{T} + 0.05759\mathrm{T}^2 \\ &\quad -7.16952 \times 10^{-4}\mathrm{T} \times \mathrm{P} + 0.01754\mathrm{P} \\ &\quad (\mathrm{N} = 722, \mathrm{F} = 37.75406),\end{aligned} \tag{3}$$

where CF is clay content in percent, T is mean annual temperature in degrees Celsius (°C), and P is annual precipitation in millimeter (mm). The *F* test value ($F > F_{0.01} = 3.05$) indicates that the relationship is statistically significant. In general, the soil organic carbon density of China is positively correlated with precipitation and clay content, and negatively correlated with temperature. Our result is qualitatively consistent with those studies reported in Australia [*Oades*, 1988], in North America [*Burke et al.*, 1989], and in South America [*Paruelo et al.*, 1997; *Alvarez and Lavado*, 1998]

3.2. Carbon Storage in Different Climatic Zones

[18] In calculating carbon storage in soils, four major climatic zones are considered (Figure 3b). These include tropical-subtropical (Zone 1) and temperate monsoon regions in eastern China (Zone 2), the arid region in northwestern China (Zone 3), and the frigid region in Tibetan Plateau (Zone 4), and are mainly defined based on temperature and proper degree of dryness [*Zhang*, 1991]. For example, the mean temperature of the coldest month (T_{cm}), the growing degree-days on 10°C (GDD_{10}) base and the proper degree of dryness (PDD) are more than 0, 4500, and less than 2.0 for the Zone 1, and less than 0, 4500 and 2.0 for Zone 2, respectively. In Zone 3, the GDD_{10} and PDD are both more than 1700 and 2.0. The Tibetan Plateau (Zone 4), with an average altitude of $\sim$5,000 m, is one of the unique regions in China. In general, the region was defined by less than 180 days in which their mean daily temperature are above 10°C [*Zhang*, 1991]. The four zones are respectively dominated by allitic, siallitic, arid, and alpine soils [*Xiong and Li*, 1987].

[19] Organic carbon density and storage in the organic and mineral horizons, and in the soil profiles in the four zones, are shown in Figure 4. In the temperate zone, siallitic soils have the highest organic carbon density (9.56 kg C/m^2) and storage (23.70 Pg C). In the arid zone in northwestern China, organic carbon density is 4.46 kg C/m^2 and carbon storage amounts to 9.90 Pg C. Moderate density and storage are observed for soils in the tropical-subtropical zone and for the Tibetan Plateau, with densities of 8.64 kg C/m^2 for former, and 9.20 kg C/m^2 for latter. Organic carbon storages of these two zones amount to 17.49 Pg C and 19.23 Pg C, respectively. Overall, average organic carbon density in China is 8.01 kg C/m^2 (3.71 kg C/m^2 in the organic horizons and 4.30 kg C/m^2 in the mineral horizons), and total soil organic carbon storage in China is 70.31 Pg C

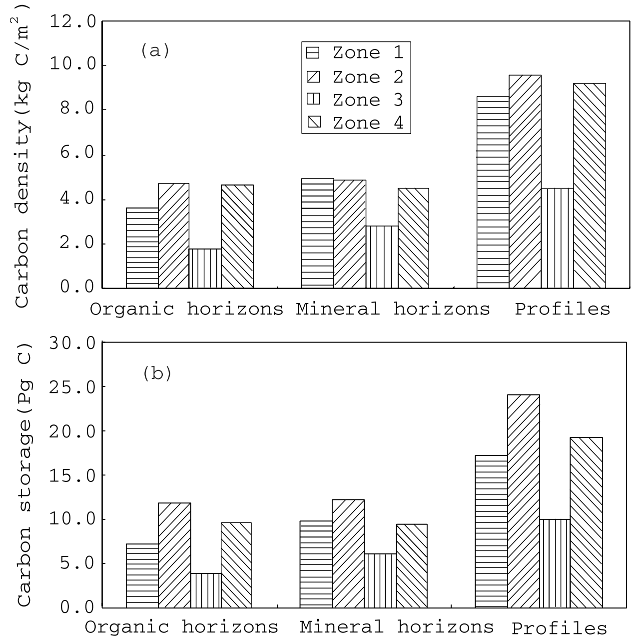

Figure 4. Soil organic carbon densities and storages in four major climate zones in China as shown in Figure 3b: (a) soil organic carbon densities, and (b) soil organic carbon storage.

(32.54 Pg C in the organic horizons and 37.78 Pg C in the mineral horizons).

3.3. Comparisons With Earlier Estimates

[20] In the worldwide organic soil carbon and nitrogen data [*Zinke et al.*, 1984], soil organic carbon density was estimated at low, medium, and high levels for each vegetation type. On the basis of the distributions of Chinese vegetation [*Hou et al.*, 1982] and the soil zone map of China [*Xiong and Li.*, 1987] in Table 2, our estimated results of soil organic carbon densities are compared with the WOSCN results for China [*Peng and Apps*, 1997; *Ni*, 2001] following a commonly used soil regionalization pattern [*Xiong and Li*, 1987]. Most of the averaged soil carbon densities in this study are lower than those from the WOSCN database. Particularly, our value of 2–2.5 kg C/m^2 for most Chinese desert soils is 2 to 8 times lower than mean values compiled by *Zinke et al.* [1984], and are consistent with recent studies by *Adams and Lioubimtseva* [2002] and *Adams et al.* [1999]. In later studies, they found that the surprisingly high values of soil carbon for the central Asian desert in the WOSCN database are mainly due to a combination of uncertainties in sampling and misassigning biome zones. The problems of misassignment of semi-desert and steppe zones into "desert" may dominate the overestimation of carbon density in Chinese desert soil (Table 2). The only exception lies in the podzolic soil zone in the northern Da Hinggan Mountains, where our estimates are significantly higher than the WOSCN's values. The zone represents only ~2% of the total soil surface. Similar densities to the WOSCN's medium values are obtained for the dark brown earth-black soil-chernozems zone and for the latosolic red earth zone.

[21] On the basis of 4353 soil profiles distributed globally, *Batjes* [1996] calculated the organic carbon density of FAO-UNESCO soil units, and re-estimated about 1462–1548 Pg C of global carbon pool in upper 100 cm. In Figure 5, the results of soil organic carbon density of China in this study are compared with the global WISE data [*Batjes*, 1996] for the first meter in terms of the FAO-UNESCO soil classi-

Table 2. Comparison Between the Organic Carbon Densities in Soil Zones Calculated in This Study and Those in the Worldwide Organic Soil Carbon and Nitrogen Database (WOSCN) [*Zinke et al.*, 1984]

		Carbon Density, kg C/m^2			
			WOSCN Database		
Soil Zones [*Xiong and Li*, 1987]	Vegetation Types [*Hou et al.*, 1982]	Current Estimates	Low	Medium	High
Latosols zone	tropical rain forest	8.5 ± 1.2[a]	9.5	10.4	11.3
Latosolic red earth zone	tropical seasonal rain forest	10.2 ± 1.3	9.5	10.4	11.3
Red earth and yellow earth zone	subtropical evergreen broad-leaved forest	8.5 ± 0.6	12.3	13.3	14.2
Yellow brown earth zone	warm temperature deciduous and evergreen broad-leaved mixed forest	9.9 ± 1.1	12.7	15.2	17.7
Brown earth, cinnamon soil and dark loessial soil zone	temperature deciduous and broad-leaved forest	7.3 ± 0.7	12.7	15.2	17.7
Dark-brown earth, black soil and chernozems zone	temperature coniferous and deciduous broad-leaved mixed forest	13.0 ± 1.3	10.5	13.0	15.5
Podsoilic soil zone of northern Da Hinggan Mountains	boreal coniferous forest	23.4 ± 10.5	12.7	16.6	20.5
Castanozems, brown caliche and sierozems zone	temperate typical steppe	8.0 ± 0.8	11.6	12.3	13.0
Cray-brown desert soil zone	temperate deserted steppe	2.8 ± 0.4	7.2	8.7	10.2
Brown desert soil zone	temperate desert	2.2 ± 0.6	4.1	6.2	8.3
Dark felty soil (subalpine meadow soil) zone	alpine meadows and swamps	13.5 ± 2.2	15.7	18.2	20.7
Cold calcic soil (subalpine steppe soil) zone	alpine steppe	7.9 ± 1.2	14.0	17.0	19.0
Felty soil (alpine meadow soil) zone	alpine meadows and swamps	9.5 ± 1.7	15.7	18.2	20.7
Frigid calcic soil (alpine steppe soil) zone	alpine steppe	7.5 ± 3.7	14.0	17.0	19.0
Frigid desert soil (alpine desert soil) zone	alpine desert	2.0 ± 0.6	14.0	17.0	19.0

[a]Mean ± standard error of the mean.

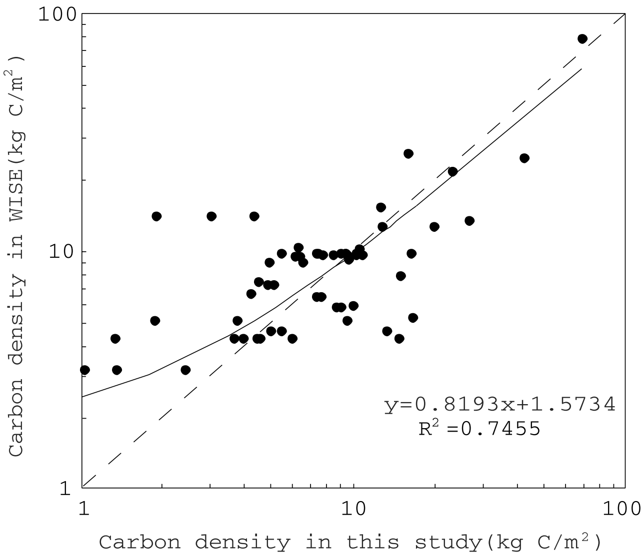

Figure 5. Comparison between the soil organic carbon densities of China in this study and those in the WISE database [*Batjes et al.*, 1996]. Organic carbon density plotted on logarithmic scale. The solid line shows a linear regression of the SOC density in our result against the WISE database, and the dashed line indicates exact agreement.

fication (Table 1). High correlation ($y = 0.82x + 1.57$, $r^2 = 0.75$, $n = 60$) between our estimated results and the estimates from the global WISE data indicates that soil organic carbon density in the WISE database are more comparable to China's soils database [*NSSO*, 1998] than that in worldwide organic carbon and nitrogen database by *Zinke et al.* [1984]. However, an apparent difference in soil organic carbon densities was observed between the WISE database and our results (Figure 5). For example, when the soils have high carbon densities (>10 kg C/m^2), the soil organic carbon densities in the global WISE database are much lower than that in China, while a reverse pattern is represented when the soils have low carbon densities (<10 kg C/m^2). The discrepancy is likely due to the much higher soil profile density (34,411 soil profiles) used in this study, while only 60 soil profiles collected from China were included in the WISE database [*Batjes*, 2002]. Given that China's terrestrial land surface has strong spatial climatic and topographic variability, the WISE database seems unsatisfactory for China.

[22] Estimated average organic carbon density in China (8.01 kg C/m^2) in this study is significantly lower than the WOSCN average density of ~10.53–12.29 kg C/m^2 [*Peng and Apps*, 1997; *Ni*, 2001] for China. Apparently higher values based on the WOSCN database were also reported for the forest and tundra mineral soils in Canada [*Siltanen et al.*, 1997]. In addition to the much higher data density used in this study, the difference may be partly due to the fact that only natural soil data were used in the WOSCN database [*Zinke et al.*, 1984], while a great proportion of the soil profiles in China have been significantly affected by the long agricultural history, which usually leads to loss of soil organic carbon [*Woomer et al.*, 1994; *Zhao et al.*, 1997].

[23] At a regional scale, our estimated ~17.5 Pg C of organic carbon storage in 202 Mha of tropical and subtropical soils in southern China is comparable with the result of 10.6 Pg C by *Zhao et al.* [1997] based on a surface of 111 Mha in southeastern China, and is overlapped by the low end of a recent estimate of 26.8 ± 7.4 Pg C soil organic carbon for the area of 215 Mha of tropical and subtropical soils in China [*Li et al.*, 2001]. The discrepancy between this study and *Li et al.* [2001] may be due to the difference in estimating the soil bulk density for samples without actual measurements. In this study we used the empirical relationships between organic carbon content and bulk density, based on 784 field measurements, to estimate carbon density of soils without observations, while *Li et al.* [2001] simply assigned a mean soil bulk density value for their corresponding subgroups or groups.

[24] Our study indicates that soil organic carbon storage in China is ~70.31 Pg C, which is significantly lower than the estimate of ~101.10 Pg C by *Peng and Apps* [1997] and that of ~117.84–119.76 Pg C by *Ni* [2001], which were based on carbon densities provided by the WOSCN database. This is obviously attributable to the generally higher carbon density in the WOSCN database. Our result of ~70.31 Pg C for soil organic carbon storage in China is also much lower than the estimates of 185.69 Pg C by *Fang et al.* [1996] and 92.4 Pg C by *Wang et al.* [2001]. The disagreement may be related to the following:

[25] 1. The data density used in our study (34,411 profiles) is much greater than that of *Fang et al.* [1996] and *Wang et al.* [2001], based on 725 and 2473 profiles, respectively. Although the soil profiles of *Wang et al.* [2001] are also from China's second national soil survey, their estimates are only based on the representative soils in the different regions of China, and the soil profiles were selected from the survey according to their geomorphological units, hydrothermal conditions, morphological peculiarities, and physicochemical characters [*NSSO*, 1993, 1994a, 1994b, 1995a, 1995b, 1996]. Our study considered all soil profiles collected by this survey, so the estimation would better represent the high spatial variability of soils in China.

[26] 2. We compensated for rock fragment (>2 mm) volume of the soil profiles resulting in a decrease of ~10% of the estimated organic carbon density and storage as this fraction was not considered by *Fang et al.* [1996] and *Wang et al.* [2001].

[27] 3. *Fang et al.* [1996] and *Wang et al.* [2001] used the average soil bulk density of soil subgroups or groups in calculating carbon density for the soil profiles in which the bulk density was not measured, unfortunately, while, in this study, the empirical relationships between soil bulk density and organic carbon content is used to estimate the bulk density values of these soils. In addition, the fact that we removed water, glacial and permanent snow covered areas, and rock mountains areas while these areas were not considered by *Fang et al.* [1996].

[28] Organic carbon storage in the world's soils was estimated at ~1100–1700 Pg C [*Post et al.*, 1982, 1990; *Prentice and Fung*, 1990; *Eswaran et al.*, 1993; *Batjes*,

1996; *Lal*, 1999; *Jobbagy and Jackson* , 2000] with a mean of ~1500 Pg C. Accordingly, the soil organic carbon storage in China represents ~4.7% of the world's soil organic carbon storage even though China has about 6.4% of the World's surface area. Lower storage in China is mainly due to extended arid and semi-arid regions (~40% of total land surface of the country). The more intense and long history of agriculture in China may also account for this difference [*Zhao et al.*, 1997; *Li and Zhao*, 2001].

4. Conclusions

[29] China holds ~6.4% of the world's surface and therefore has a significant role in the carbon cycle of global terrestrial ecosystems. On the basis of 34,411 soil profiles investigated during China's second national soil survey, we found that current organic carbon density in soils varies from 0.73 to 70.79 kg C/m^2 with high regional variability associated with spatial climate variability. The average density of ~8.01 kg C/m^2 is lower than the world's mean soil organic carbon density (~10.60 kg C/m^2) [*Post et al.*, 1982; *Foley*, 1995]. Current total organic carbon storage in Chinese soils is estimated to be ~70.31 Pg C (including 32.54 Pg C in the organic horizons and 37.78 Pg C in the mineral horizons), representing ~ 4.7% of the world's soil organic carbon storage. Because of the quick turnover time of the organic carbon in the organic horizons [*Schimel et al.*, 1994; *Townsend et al.*, 1995], the surface organic horizons (with 32.54 Pg C) would be most sensitive to interactions with the atmosphere. Lower values of the average organic density and storage values in Chinese soils compared with those of the world are mainly attributable to the extended arid and semi-arid regions as well as the long history of land use in China. Our estimates, which are based on a much higher data density and better analysis methods, are expected to provide a more realistic picture of current spatial variations in carbon densities and storage in China.

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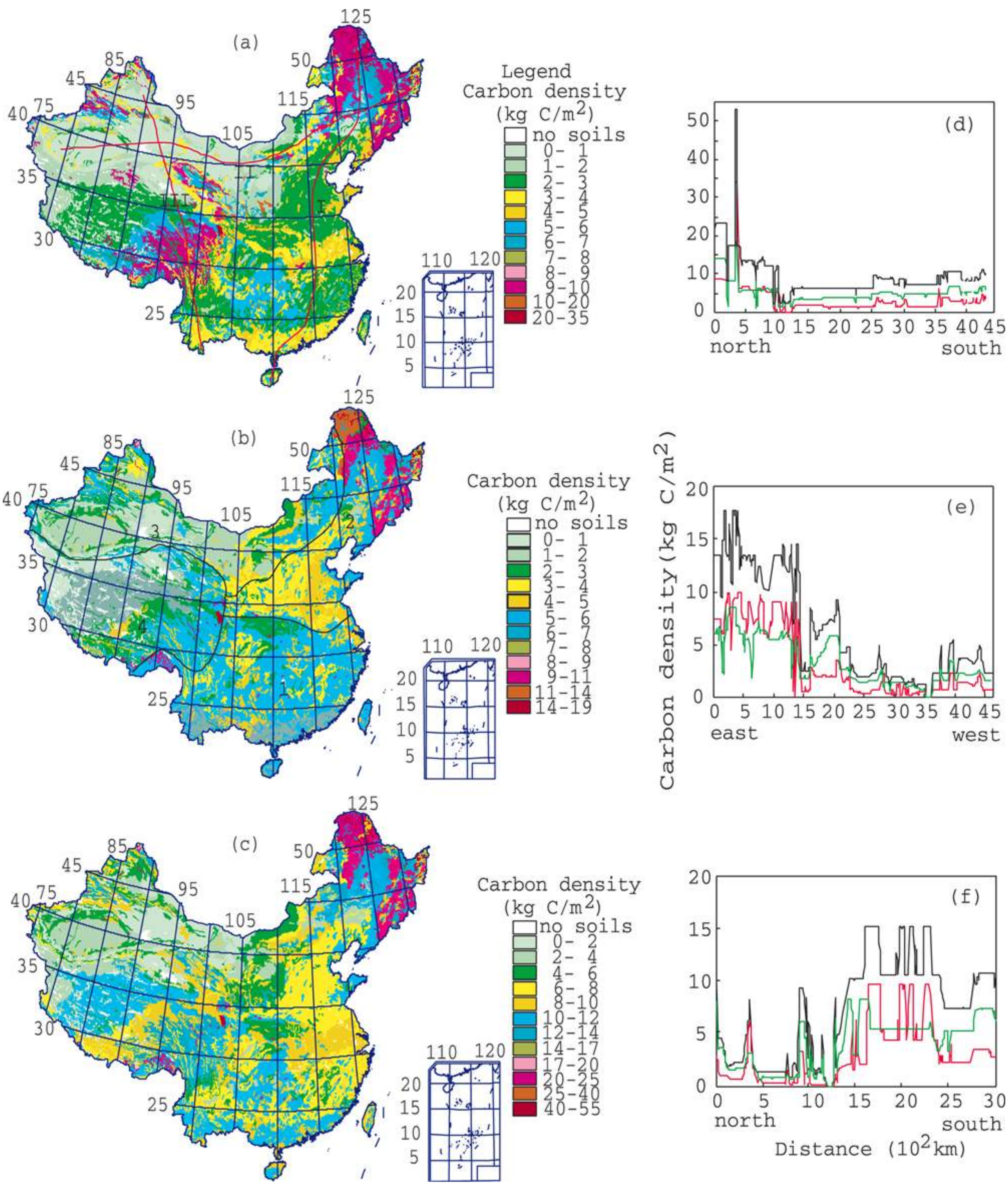

Figure 3. Spatial distribution of soil organic carbon densities in China and variations along three representative transects (I, II, and III): (a) distribution in the organic horizons (A horizon), (b) distribution in the mineral horizons (B and C horizons), and (c) distribution in the soil profiles. In (d), (e) and (f), red, green and dark lines indicate variations in the organic horizons, mineral horizons, and soil profiles, respectively. The four major climate zones in Figure 3b refer to monsoonal tropical-subtropical zone (Zone 1), the monsoonal temperate zone (Zone 2), the arid zone (Zone 3), and the frigid zone (Zone 4), respectively.