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REVIEW

Land use induced changes of organic carbon storage in soils of China

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Abstract

Using the data compiled from China's second national soil survey and an improved method of soil carbon bulk density, we have estimated the changes of soil organic carbon due to land use, and compared the spatial distribution and storage of soil organic carbon (SOC) in cultivated soils and noncultivated soils in China. The results reveal that ~57% of the cultivated soil subgroups (~31% of the total soil surface) have experienced a significant carbon loss, ranging from 40% to 10% relative to their noncultivated counterparts. The most significant carbon loss is observed for the non-irrigated soils (dry farmland) within a semiarid/semihumid belt from northeastern to southwestern China, with the maximum loss occurring in northeast China. On the contrary, SOC has increased in the paddy and irrigated soils in northwest China. No significant change is observed for forest soils in southern China, grassland and desert soils in northwest China, as well as irrigated soils in eastern China. The SOC storage and density under noncultivated conditions in China are estimated to ~77.4 Pg (10^{15} g) and ~8.8 kg C m^{-2}, respectively, compared to a SOC storage of ~70.3 Pg and an average SOC density of ~8.0 kg C m^{-2} under the present-day conditions. This suggests a loss of ~7.1 Pg SOC and a decrease of ~0.8 kg C m^{-2} SOC density due to increasing human activities, in which the loss in organic horizons has contributed to ~77%. This total loss of SOC in China induced by land use represents ~9.5% of the world's SOC decrease. This amount is equivalent to ~3.5 ppmv of the atmospheric CO_2 increase. Since ~78% of the currently cultivated soils in China have been degraded to a low/medium productivities and are responsible for most of the SOC loss, an improved land management, such as the development of irrigated and paddy land uses, would have a considerable potential in restoring the SOC storage. Assuming a restoration of ~50% of the lost SOC during the next 20–50 years, the soils in China would absorb ~3.5 Pg of carbon from the atmosphere.

Keywords: carbon density, carbon pool, human activities, soil organic carbon loss

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Introduction

In the last two centuries, land use has been a significant source of atmospheric CO_2 through conversion of natural vegetation to farming (Esser, 1987, 1995; Houghton, 1999; Lal, 1999; Smith *et al.*, 2000). It has been estimated to be about half of the CO_2 emission from the combustion of fossil fuels over the period from 1850 to 1990 (Houghton, 1999). In terrestrial ecosystems, the organic carbon pool in the soils is about twice greater than in living vegetation (Post *et al.*, 1990; Lal, 1999). Because soil organic carbon has generally a slower turnover rate, it may be preserved for a longer time (IGBP Terrestrial Carbon Working

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Group, 1998). The huge carbon pool of soils and significant changes of SOC related to land use suggest a considerable potential to enhance the rate of carbon sequestration in soils through the management of human activities, and thereby to decrease the atmospheric CO_2 level (Paustian *et al.*, 1997; Janzen *et al.*, 1998; Bruce *et al.*, 1999; Lal & Bruce, 1999; Post & Kwon, 2000).

A number of efforts have been carried out in determining the changes of SOC storage induced by land use at regional (Mann, 1986; Esser, 1995; Fearnside & Barbosa, 1998; Houghton *et al.*, 1999; Smith *et al.*, 2000) and global (Houghton *et al.*, 1983, 1987; Esser, 1987; Houghton, 1999) scales. However, because of the high inherent natural variability in the world's soils and variable dynamics of carbon loss under different land uses, accurate estimates of the historic loss are usually hampered by the lack of the required baseline data on soils (Lal, 1999). More exact estimates on the size of the current SOC storage and the human-induced changes at regional scale are highly needed, especially based on greater data density with direct field measurements (Bruce *et al.*, 1999). This would provide a basis for a better understanding of the future carbon fluxes between the terrestrial ecosystem and the atmosphere.

Currently, China has ~137.5 million hectares of cropland (NSSO, 1998), including the tropical zone in the south to the frigid-temperate zone in the north. The long history of agricultural exploitation and the changes of land use suggest that the terrestrial ecosystem of China would have played an important role in the global carbon cycle (Peng & Apps, 1997; Zhao *et al.*, 1997; Li & Zhao, 1998, 2001; Fang *et al.*, 2001). Using the soil survey data and models, several estimates on the changes of SOC were carried out in tropical-subtropical China (Linden *et al.*, 1996; Li & Wang, 1998; Li & Zhao, 1998, 2001; Li *et al.*, 2001) and in northern China (Wang *et al.*, 1988; Yang & Janssen, 1997; Luo *et al.*, 2000; Feng *et al.*, 2001). To date, a comprehensive estimate of the changes in SOC storage related to human activity for the whole country is, however, not yet available.

In this study, the spatial patterns of soil organic carbon density and storage under noncultivated conditions and those under present-day conditions are comparatively investigated, based on the data from China's second national soil survey (NSSO, 1993, 1994a, b, 1995a, b, 1996, 1998), which is the best and most comprehensive soil database available in China, including not only the cultivated soils but also the forest soils, grassland soils and desert soils. Since the acquired data during this investigation has a great spatial density (Fig. 1), it provides an opportunity to estimate the budget of SOC, especially the changes of SOC due to land use in China, as are the main objectives of this paper.

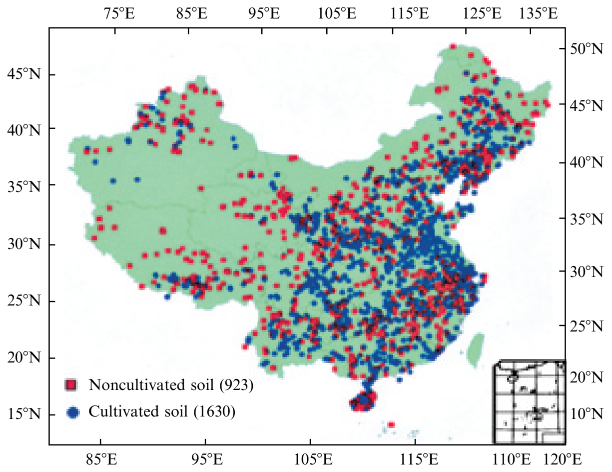

Fig. 1 Distribution of the 2553 representative soil profiles in China's second soil survey (NSSO, 1998).

Data and methods

Data used in this study are collected from the 34 411 soil profiles analysed during the second national soil survey (NSSO, 1993, 1994a, b, 1995a, b, 1996, 1998). Among these, 2553 profiles were considered the most representative of soils in the different regions of China, based on their geomorphological units, hydrothermal conditions, morphological peculiarities, and physicochemical characters (NSSO, 1993, 1994a, b, 1995a, b, 1996). These profiles were described in greater detail, including the above-ground vegetation and land use conditions (Fig. 1), while these lines of information were not completed for the other profiles. These representative profiles can be divided into two basic parts according to the land use conditions. Nine hundred and twenty three profiles (Fig. 1) were from the soils that were not cultivated in the land use history, because the profiles had not experienced any disturbance by human activity, and the current vegetation are ecologically consistent with the present climatic conditions (NSSO, 1993, 1994a, b, 1995a, b, 1996). These profiles are regarded in this study as noncultivated profiles. They have a good spatial coverage and include all the soil types. Although some of these soils were still more or less subjective to possible indirect human activity in the past, such as human-induced vegetation burning, they are the best to represent the undisturbed condition of the soils. Consequently, these data were used to reconstruct the carbon density and storage under noncultivated conditions. The other 1630 profiles (Fig. 1) were all considered cultivated profiles, including the present-day cultivated soils and those cultivated in the past; they were used for evaluating the SOC changes by land use compared to their noncultivated counterparts. The present-day SOC were calculated using the data from the total of 34 411 soil profiles analysed during the second national soil survey because of the greater density of profiles for the whole country. The difference between the reconstructed SOC under noncultivated conditions and that of the present-day would permit an estimation of SOC changes due to historical land use in China.

Because of the lack of soil data from the Taiwan region, calculation was simply made by analogy using the data of the corresponding soil subgroups from China's mainland in order to ensure integrality. This would not significantly affect the accuracy of the results because of the rather small area of the Taiwan region (~3.8% of total land surface). The considered soil surface in this study amounts to ~881.81 million hectares excluding the water, glacial and permanent snow covered areas and the rocky mountain areas (NSSO, 1998). Since the Chinese soil taxonomy (NSSO, 1998) was used in the soil surveys, we have used the same terminology in this study, which were tentatively compared with the FAO-UNESCO (1988) soil classification (Table 1). The database of electronic soil map of China used here is from Tian *et al.* (1996a). Since the soil taxonomy in the legend of the base map (Tian *et al.*, 1996a) was not entirely consistent with that in the second national soil survey, necessary mergence of some soil groups at subgroup level was made based on the principle of approximation (Li *et al.*, 2001).

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

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

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 (OM) to organic carbon content (OC) because organic matter was calculated by wet combustion with $\mathrm{Cr_2O_7}^{2-}$ (Wen, 1984), T_i, ρ_i, OM_i and C_i represent thickness (cm), bulk density ($\mathrm{g\,cm^{-3}}$), content of organic matter and volumetric percentage of the fraction $>2\,\mathrm{mm}$ (rock fragments) in the layer i, respectively.

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 data that were measured in parallel at the same time (NSSO, 1993, 1994a, b, 1995a, b, 1996) (Fig. 2). This method was frequently used in earlier studies (Grigal *et al.*, 1989; Siltanen *et al.*, 1997). The bulk density for soils without measured value was then obtained using these empirical relationships. For the soil horizons without measured rock fragment volume (C_i), mean value of the same soil subgroup was used.

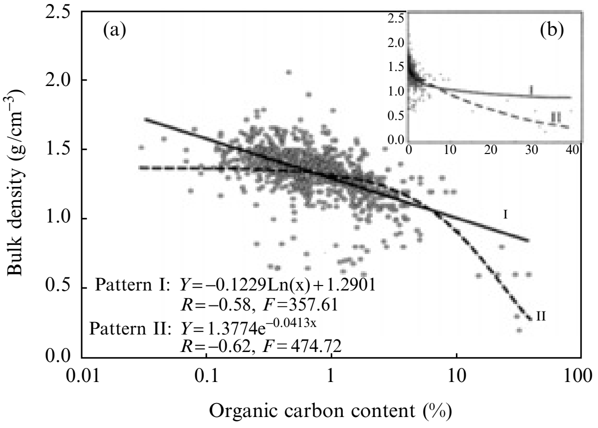

Fig. 2 Empirical relationships between soil bulk density and organic carbon content plotted on logarithmic (a) and linear (b) scales. The relationships are established based on measurements of 784 samples obtained from the National Soil Survey Office. These data show two regression patterns between bulk density and organic carbon content in soils. The coefficient of correlation ($R > \mathrm{R}_{0.001}$) and F-test values ($F > \mathrm{F}_{0.01}$) 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.

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 $\mathrm{area}_{(i)}$ and $\mathrm{SOCD}_{(i)}$ are the surface and the organic carbon density of the soil subgroup i, respectively.

The changes in SOCD (ascribed as ΔSOCD) and in SOCS (ascribed as ΔSOCS) were calculated as follows:

$$\Delta\mathrm{SOCD} = \mathrm{SOCD_{(N)}} - \mathrm{SOCD_{(P)}} \qquad (3)$$

$$\Delta\mathrm{SOCS} = \mathrm{SOCD_{(N)}} - \mathrm{SOCS_{(P)}} \qquad (4)$$

where $\mathrm{SOCD_{(N)}}$ and $\mathrm{SOCD_{(P)}}$ are the SOC density in noncultivated soils and the present-day SOC, respectively; $\mathrm{SOCS_{(N)}}$ and $\mathrm{SOCS_{(P)}}$ are respectively, the SOC storage in noncultivated soils and that of the present-day.

In the second national soil survey in China, soil profiles were generally divided into A, B and C horizons according to the pedogenic properties. A number of studies have demonstrated that cultivated soils usually have a greater carbon loss in the surface layer (A horizon or 0–30 cm depth) (Mann, 1986; Jenkinson *et al.*, 1991), while much less attention has been given to the SOC

Table 1 Organic carbon density and storage of soil groups under noncultivated conditions and present-day conditions in China

Soil group in Chinese soil taxonomy	FAO/UNESCO taxonomy	Number of subgroups (Chinese soil taxonomy)	Area (million hectare)	Organic horizons carbon density (kg C m^{-2})		Mineral horizons carbon density (kg C m^{-2})		Carbon storage (10^{10} kg)	
				Present-day conditions	Noncultivated conditions	Present-day conditions	Noncultivated conditions	Noncultivated conditions	Present-day conditions
Latosols	Haplic Acrisols	2	4.27[a]	3.03 (864)[b]	4.16 (12)	5.51	6.17	44.10	36.44
Latosolic red earths	Haplic Acrisols/Alisols	3	18.13	3.57 (193)	3.35 (19)	6.83	6.37	176.58	188.63
Red earths	Haplic Alisols/Haplic Acrisols	5	57.85	2.80 (2008)	2.90 (79)	5.06	5.05	461.52	454.80
Yellow earths	Haplic Alisols	3	23.93	5.44 (638)	7.15 (53)	5.53	5.77	308.82	262.41
Yellow-brown earths	Ferric/Haplic Luvisols	3	18.42	4.24 (273)	4.98 (21)	5.86	5.71	191.80	185.99
Yellow-cinnamon soils	Eutric Cambisols	4	3.81	2.12 (221)	2.48 (4)	4.97	6.99	25.19	18.95
Brown earths	Haplic/Albic Luvisols or Eutric/Dystric Cambisols	4	20.16	4.29 (1510)	6.94 (32)	5.42	6.94	281.13	195.77
Dark-brown earths	Haplic Luvisols/Eutric Cambisols	5	40.11	8.48 (275)	9.47 (47)	6.64	6.95	661.52	606.72
Bleached Beijing soils	Albic Luvisols	3	5.27	4.60 (282)	6.48 (8)	4.23	6.26	72.72	46.52
Brown coniferous forest soils	Humic Cambisols	3	11.66	9.48 (49)	10.41 (9)	13.90	15.43	298.67	272.59
Podzolic soils	Haplic Podzols	1	0.00	19.97 (3)	22.41 (1)	22.90	39.90	0.00	0.00
Torrid red soils	Ferralic Cambisols	2	0.69	1.68 (99)	1.77 (5)	2.88	3.14	3.45	3.19
Cinnamon soils	Eutric Cambisols	7	25.17	2.69 (1828)	4.22 (36)	3.93	4.52	226.17	166.75
Gray-cinnamon soils	Haplic/Capcic Luvisols	5	6.18	10.34 (105)	11.09 (10)	6.53	6.78	110.11	104.28
Black soils	Phaeozems	4	7.36	7.24 (435)	10.14 (13)	5.55	6.83	125.50	95.10
Gray forest soils	Albic Luvisols	2	3.15	4.68 (10)	4.78 (8)	4.48	4.48	29.26	28.83
Chernozems	Chernozems	6	13.22	7.76 (612)	13.54 (13)	5.11	6.48	277.17	170.13
Castanozems	Kastanozems	7	37.50	4.05 (918)	4.44 (26)	5.45	5.07	374.17	356.52
Castano-cinnamon soils	Kastanozems	3	4.82	1.30 (282)	0.88 (4)	4.23	4.16	24.60	26.63
Dark loessial soils	Calcisols	3	2.55	6.16 (860)	6.55 (3)	4.24	5.96	38.99	26.51
Brown caliche soils	Haplic/Haplic Calcisols	6	26.56	1.22 (68)	1.02 (11)	3.15	3.21	112.01	115.97
Sierozems	Calcaric Cambisols	4	5.38	1.41 (506)	1.45 (17)	3.90	3.02	24.68	28.63
Gray desert soils	Haplic Calcisols	6	4.60	0.89 (14)	0.85 (9)	2.17	2.01	12.93	14.07
Gray-brown desert soils	Haplic Calcisols	4	30.73	0.40 (99)	0.44 (7)	1.51	1.34	64.61	58.82
Brown desert soils	Soloncnaks	5	24.30	0.62 (19)	0.60 (6)	0.72	0.70	31.69	32.57
Loessial soils	Calcaric Regosols	1	12.29	1.38 (1368)	2.34 (10)	3.63	3.70	74.17	61.60
Red primitive soils	Lixisols	3	2.28	1.69 (449)	2.26 (9)	2.55	2.28	10.66	9.67
Neo-alluvial soils	Fluvisols	3	4.29	2.07 (872)	1.88 (16)	4.39	3.99	26.63	27.71
Takyr	Solonchaks	1	0.68	0.16 (2)	0.16 (2)	0.77	0.77	0.63	0.63
Aeolian soils	Arenosols	4	67.57	0.69 (287)	0.61 (32)	1.76	1.55	145.71	165.30
Skeletal soils	Regosols/Leptisols	4	26.11	1.92 (589)	2.02 (36)	1.87	2.01	104.36	98.89
Limestone soils	Regosols/Leptisols	4	10.77	5.40 (463)	7.03 (29)	4.26	4.80	128.68	103.99
Volcanic soils	Andosols	3	0.19	5.97 (47)	8.47 (7)	10.24	13.21	3.88	3.08
Purplish soils	Calcaric Regosols	3	18.90	2.30 (1027)	2.54 (33)	3.22	3.08	108.09	104.25

Phospho-calcic soils	Calcaric Regosols	2	0.00	10.27 (4)	10.27 (2)	3.12	3.12	0.00	0.00
Lithosols	Regosols/Leptisols	3	18.53	1.87 (179)	1.97 (15)	0.00	0.00	36.76	34.85
Meadow soils	Umbric Gleysols/Haplic Phaeozem	6	25.09	5.25 (940)	6.47 (42)	5.44	6.45	333.72	268.19
Fluvi-aquic soils	Fluvisols	7	25.68	2.11 (4206)	2.24 (19)	4.09	4.10	164.24	159.35
Saijiang black soils	Eutric Vertisols/Gleyic Cambisol	5	3.77	2.68 (271)	6.13 (2)	3.65	4.29	39.36	23.88
Shruby meadow soils	Calcaric Cambisols	2	2.48	1.69 (3)	1.77 (2)	3.25	3.28	12.64	12.26
Mountain meadow soils	Umbric Leptisols/Dystric Cambisols	3	4.22	10.27 (143)	11.97 (19)	9.73	10.97	96.17	84.39
Bog soils	Gleysols	5	12.62	16.24 (245)	17.50 (31)	10.69	11.24	376.32	339.89
Peat soils	Histosols	3	1.47	24.16 (67)	29.90 (7)	46.62	61.26	132.03	104.74
Meadow solonchaks	Solonchaks	4	10.44	1.03 (57)	1.06 (37)	2.67	2.73	40.43	38.61
Coastal solonchaks	Solonchaks	3	2.12	1.45 (146)	1.09 (14)	4.56	3.69	10.30	12.73
Acid sulphate soils	Solonchaks	2	0.02	3.52 (13)	3.52 (5)	11.33	11.33	0.30	0.30
Desert solonchaks	Solonchaks	3	2.87	1.58 (15)	1.58 (8)	2.88	2.85	12.74	12.82
Frigid plateau solonchaks	Solonchaks	3	0.69	1.48 (8)	1.48 (4)	2.51	2.51	2.76	2.76
Solonetzs	Solonchaks	5	0.87	2.20 (85)	2.39 (17)	2.43	2.60	4.38	4.03
Paddy soils	Fluvisols/Cambisols	8	30.68	4.44 (8993)	4.49 (0)	5.15	3.18	239.18	294.21
Irrigated silting soils	Calcaric Fluvisols	4	1.52	4.44 (570)	2.93 (0)	3.03	1.04	5.90	11.38
Irrigated desert soils	Calcaric Fluvisols	4	0.91	3.15 (262)	3.44 (0)	4.57	3.71	6.52	7.03
Felty soils (Alpine meadow soils)	Cambisols	4	53.54	6.65 (187)	6.96 (22)	2.82	3.04	562.94	507.26
Dark felty soils (Subalpine meadow soils)	Cambisols	4	19.44	9.86 (135)	11.12 (17)	6.79	7.82	371.99	323.71
Frigid calcic soils (Alpine steppe soils)	Cambisols	4	68.85	1.77 (106)	1.90 (11)	5.72	5.84	533.88	515.29
Cold calcic soils (Subalpine steppe soils)	Cambisols	4	11.29	3.89 (162)	2.97 (7)	5.29	4.49	83.43	103.59
Cold brown calcic soils (Mountain shrub steppe soils)	Cambisols	2	0.96	2.47 (306)	1.71(5)	4.93	4.57	6.02	7.11
Frigid desert soils (Mountain shrub steppe soils)	Gelic Arenosols	1	8.96	0.47 (3)	0.47 (3)	0.90	0.90	12.26	12.26
Cold desert soils (Subalpine desert soils)	Gelic Arenosols	1	5.22	0.72 (2)	0.72 (2)	0.33	0.33	5.45	5.45
Frigid frozen soils (Alpine frozen soils)	Gelic Regosols	1	30.65	1.55 (28)	1.58 (5)	0.85	0.85	74.34	73.46
	Total	219[c]	881.81					7744.27	7031.49

[a] Each group surface of soils in mainland was calculated by summing provential data (NSSO, 1998) and that in Taiwan was computed by the electronic map of soils (Tian *et al.*, 1996a).
[b] Mean (sample size). [c] One soil group and nine soil subgroups of very small surface weren't included.

changes in deeper horizons, which contain also a substantial amount of carbon (Sombroek *et al.*, 1993; Batjes, 1996). Moreover, the organic carbon has a turnover cycle of decadal order or even less in A horizon (organic horizon) while that in the underlying B and C horizons (mineral horizons) is on the order of hundreds/thousands years or more (Schimel *et al.*, 1994; Townsend *et al.*, 1995). These may lead to different interactions and feedbacks with the global climate system. For differentiating these two kinds of carbon pools in soils, the carbon density and storage in the organic horizons and those in the mineral horizons were separately calculated in this study. Area-weighted mean values were used in calculating the regional SOC density. GIS (Geographical Information System) technique was used to analyse and visualize the spatial distribution of SOC density and storage.

Results and discussion

Distribution and storage of soil organic carbon under noncultivated conditions

Based on the 923 noncultivated soil profiles mentioned above, the estimated SOC density and storage of all the soil groups under noncultivated conditions in China are listed in Table 1, assuming that currently cultivated soil species have the same potential of SOC reservoir to that of their noncultivated counterparts prior to the cultivation. SOC density ranges from 0.2 to 29.9 $\mathrm{kg\,C\,m^{-2}}$ for organic horizons, 0–61.3 $\mathrm{kg\,C\,m^{-2}}$ for mineral horizons, and 0.9–91.2 $\mathrm{kg\,C\,m^{-2}}$ for entire soil profiles in term of soil groups. Most of the SOC density values fall into the ranges from 4.0 to 13.0 $\mathrm{kg\,C\,m^{-2}}$.

Figure 3(a) shows the distribution of the profile SOC density at soil subgroup level under noncultivated conditions. SOC densities in the forest soils in northeast China and in the subalpine soils in the southeastern Tibetan Plateau represent the highest, mostly around 20.0 $\mathrm{kg\,C\,m^{-2}}$, and exceptionally exceed 50.0 $\mathrm{kg\,C\,m^{-2}}$. The lowest densities, mostly less than 3.0 $\mathrm{kg\,C\,m^{-2}}$, were observed for the desert soils in northwestern China. Overall, SOC density decreases from east to west, and a general increase is obvious from north to south in western China while it decreases from north to south in eastern China.

SOC density is dependent on the bioproductivity and the mineralization intensity of organic matter, which are mainly controlled by hydrothermal conditions (Duchaufour, 1983; NSSO, 1998). In southern China, the climate is strongly humid due to the influences of the Asian monsoon circulations (Zhang, 1991) while in northwestern China, the barrier effect of the Tibetan Plateau to moisture and the long distance from the ocean lead to arid climate. Cold conditions prevail across the Tibetan Plateau due to the high elevation. This climate pattern in China has strong impacts on the spatial distribution of soil organic carbon density. In eastern China, corresponding to the soil sequence of dark brown earths, black soils, chernozems, meadow soils, brown earths and cinnamon soils from north to south, the decrease of soil organic carbon density is consistent with the temperature increase because hotter conditions are favourable for the mineralization of soil organic matter. The SOC density decreases from east to west, which is in agreement with the increased aridity from east to west, associated with the lower bioproductivity. The high SOC density on the Tibetan Plateau is attributable to the cooler conditions, favourable to the accumulation of soil organic matter. For the whole country, the reconstructed average SOC density under noncultivated conditions is ~8.8 $\mathrm{kg\,C\,m^{-2}}$, and the total SOC storage is ~77.4 Pg with ~38.0 Pg in the organic horizons and ~39.4 Pg in the mineral horizons.

Present-day distribution and storage of soil organic carbon

Based on the data from 34 411 soil profiles, distribution of the SOC density under the present-day conditions in China was calculated and is given in Fig. 3(b) and Table 1. The SOC density ranges from 0.2 to 24.2 $\mathrm{kg\,C\,m^{-2}}$ for organic horizons, 0–46.6 $\mathrm{kg\,C\,m^{-2}}$ for mineral horizons, and 0.7–70.8 $\mathrm{kg\,m^{-2}}$ for entire soil profiles in term of soil groups. The majority of the SOC values ranges from 4.0 to 11.0 $\mathrm{kg\,C\,m^{-2}}$. The basic distribution pattern of SOC density is, thus, roughly similar to that under noncultivated conditions (Fig. 3a). Overall, the present-day total SOC storage is ~70.3 Pg, including 32.5 Pg in the organic horizons and 37.8 Pg in the mineral horizons. The average carbon density is ~8.0 $\mathrm{kg\,C\,m^{-2}}$.

Our result of ~70.3 Pg for the present-day SOC storage in China is lower than the estimate of 92.4 Pg by Wang *et al.* (2001), which was also based on the data of the Second National Soil Survey. The disagreement may be attributable to three aspects. Firstly, the data density used in our study (34 411 profiles) is greater than that in Wang *et al.* (2001) based on 2473 profiles. Secondly, our compensation for the fraction >2 mm in calculating the soil carbon density would account for a decrease of ~10% in our estimated SOC as this fraction was not considered by Wang *et al.* (2001). Thirdly, Wang *et al.* (2001), used the average soil bulk density of soil subgroups or groups in calculating carbon density for the soil profiles of which the bulk density was not measured while empirical relationships between soil bulk density and organic carbon content is used in our study to estimate the bulk density values of these soils.

Organic carbon storage in the world's soils was estimated to be ~1100–1700 Pg (Post *et al.*, 1982, 1990;

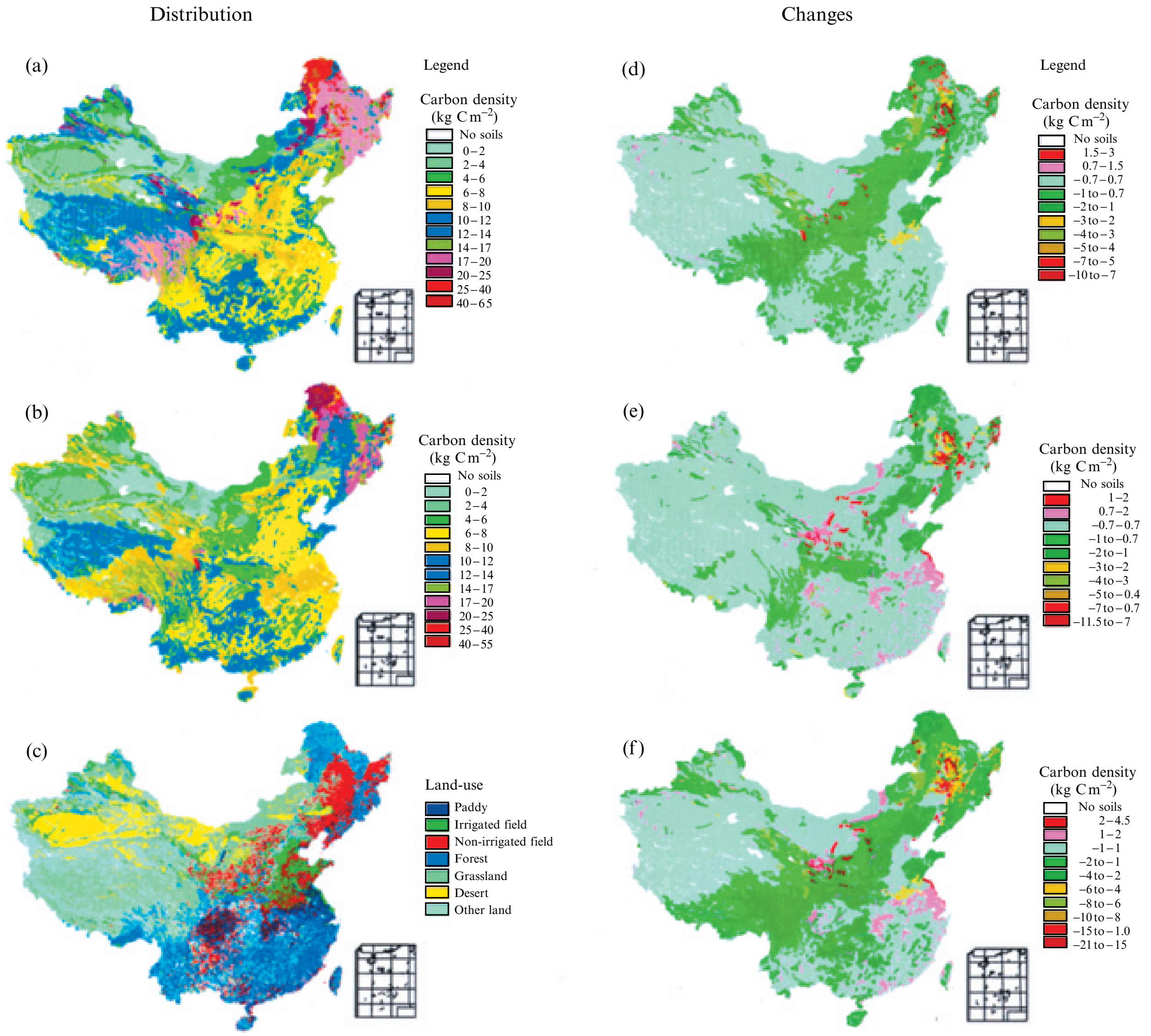

Fig. 3 Spatial distribution of SOC density, changes of SOC density and land use in China. (a) Distribution of SOC density under noncultivated conditions; (b) Distribution of SOC density under present-day conditions (including all cultivated soils and noncultivated soils); (c) Distribution of land use in China (Tian *et al*., 1996b); (d) Distribution of SOC density changes in organic horizons; (e) Distribution of SOC density changes in mineral horizons; (f) Distribution of profile SOC density changes.

Eswaran *et al*., 1993; Batjes, 1996; Lal, 1999) with a mean of ~1500 Pg. Accordingly, the present-day soil organic carbon storage in China represents ~4.7% of the world's SOC storage, contrasts with ~6.4% of the World's surface area for China. The present-day average SOC density of ~8.0 kg C m^{-2}, and that of ~8.8 kg C m^{-2} under noncultivated conditions are lower than the world's mean SOC density (~10.6 kg C m^{-2}) (Post *et al*., 1982). The lower storage and density in China are mainly due to the extended arid and semiarid regions (~40% of total land surface of the country). The more intense and longer history of agriculture in China may also account for these differences (Zhao *et al*., 1997; Li & Zhao, 2001).

Changes of soil organic carbon due to land use

Figure 4 shows the difference (expressed in percentage) between the SOC in cultivated soils and their noncultivated counterparts in 137 soil subgroups in China. These reveal three patterns of SOC changes. For ~57% of cultivated soil subgroups (78 subgroups), a significant SOC loss was found. For ~26% of cultivated subgroups (36

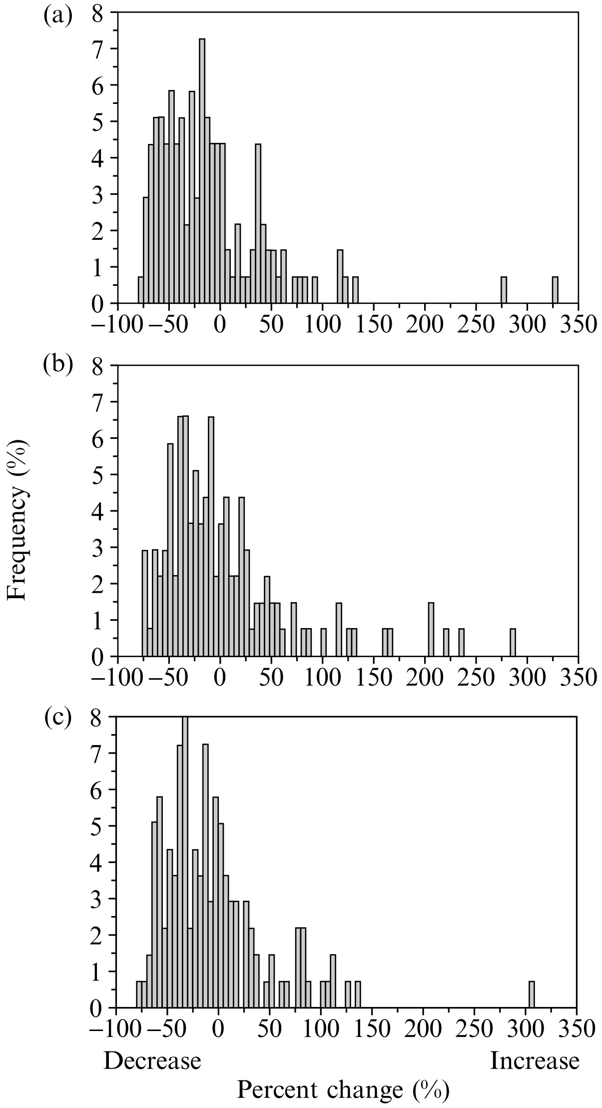

Fig. 4 Frequency distribution of the changes in soil organic carbon content of cultivated soils comparing to their noncultivated counterparts in 137 soil subgroups (a) Distribution for organic horizons; (b) Distribution for mineral horizons; (c) Distribution for soil profiles. Each bar corresponds to the ratio of the number of subgroups with a given carbon density vs. the total subgroup number. Statistics are made at the intervals of 5%.

subgroups), an obvious gain of SOC was observed compared with their noncultivated counterparts. The SOC in the other soils, ~17% of cultivated subgroups (24 soil subgroups), remains basically unchanged.

For the carbon-lost soils, the decreases of SOC mostly fall into the range of $-35 \pm 20\%$, $-20 \pm 15\%$ and $-25 \pm 15\%$ for the organic horizons (Fig. 4a), the mineral horizons (Fig. 4b) and for entire soil profiles (Fig. 4c), respectively. The decrease in organic horizons is much higher than that in mineral horizons. The loss in organic horizons estimated in this study is consistent with the recently estimated loss of ~20–63% in southern China (Li & Zhao, 2001; Li *et al.*, 2001). It is also comparable with the decrease of ~20–50% in some other places of the world (Mann, 1986; Johnson, 1992; Davidson & Ackerman, 1993). The results also show considerable carbon loss in the mineral horizons due to land use. More attention should therefore be given to land-use induced changes of SOC in the deeper carbon pool of soils in the study of global carbon cycle (Sombroek *et al.*, 1993; Li & Zhao, 2001).

Figure 3 shows the spatial distribution of the changes in SOC density in organic horizons (Fig. 3d), mineral horizons (Fig. 3e) and in entire soil profiles (Fig. 3f) from the noncultivated conditions to the present-day conditions at subgroup level. For the whole country, ~31% the total soil surface experienced a SOC loss (Fig. 3d–f). An obvious carbon-lost zone presents from northeast to southwest, mostly under semiarid and semihumid conditions. The decrease in SOC storage in this zone mostly falls into the range from 2.0 to 6.0 kg C m^{-2} with the maximum loss of more than 15.0 kg C m^{-2} in the black and meadow soils in northeast China (Fig. 3f). Within this zone, both organic horizons and mineral horizons have experienced significant SOC loss, although that in organic horizons is constantly higher than for mineral horizons (Fig. 3d–f). This differs from the soils in southern and northwest China, where carbon loss mainly occurred in organic horizons. The SOC loss in the regional black soils and sandy lands in northern China was already reported in earlier studies (Luo *et al.*, 2000; Feng *et al.*, 2001).

Our results therefore show that human activity has caused significant SOC loss in most of the cultivated soils in China. The most important loss is related to cultivations without irrigation in the semiarid and semihumid regions (Fig. 3c–f). Several factors may be taken into account for the SOC loss. Firstly, in the semiarid and semihumid regions, human activity would have made the agroecosystem more brittle than for the other regions, leading to much lower bioproductivity. Secondly, a great proportion of straw after harvesting was removed from soils and was used as domestic fuel and animal fodder (Liu & Mu, 1988). Thus the input of organic matter to soils is much lower than the natural level. Thirdly, the mineralization of organic matters is intensified by tillage through decreasing the amount of physical protection to decomposition of organic matters (NSSO, 1998; Post & Kwon, 2000). Another factor resulting in soil carbon loss is the acceleration of soil erosion by intense tillage, particularly plowing, through increasing soil exposure to wind and rain (Grant, 1997), thus favourable to SOC loss (Lal, 1995). This is confirmed by the higher SOC loss in the soils suffered from intense erosion (NSSO, 1998). Although agricultural activity is less intensive in the southeast Tibetan Plateau, the loss of SOC is significant. This may be explained by the greater sensitivity of soil erosion in the region to human activity because of the slope and relief topographies.

We observed an obvious SOC increase in ~5% of the total land surface (~26% of the cultivated soil subgroups), compared to their noncultivated counterpart (Fig. 3d–f). This phenomenon was previously reported by Lindet *et al*. (1996) and Li & Zhao (1998) from southern China. In these soils, the increase of SOC density is generally ~0.5–2.0 kg C m^{-2}. In southern China, the most significant increase in SOC is observed in the mineral horizons of paddy soils (Fig. 3d–f). This is mainly attributable to the aeration and human-induced changes of the hydrothermal regime. The longer submergence of organic matter in these soils alleviates its mineralization rate, and thus is favourable to the SOC accumulation (Stevenson, 1986; Xiong & Li, 1987; NSSO, 1998).

In the arid climatic zone in northwest China, a significant increase in SOC density is observed for the irrigated silting soils with a maximum gain of more than 3 kg C m^{-2} (representing an increase of ~200%) in contrast to their noncultivated counterparts. This is essentially due to the enhanced bioproductivity by irrigation, leading to more accumulation of organic matter, a mechanism well recognised (Mann, 1985, 1986; NSSO, 1998). Another factor is the long history of fertilization by adding organic matter, as has always been a tradition of the region. This would have significantly contributed to the observed increase in SOC, through direct input of organic matter and through promoting soil productivity (Johnson, 1992; NSSO, 1998). In these soils in China, the total net gain of SOC is estimated to ~1.5 Pg. As the surface of these cultivated soils currently represents only ~12% of the same groups, improved agricultural management practices would be expected to significantly increase carbon sequestration in these soil subgroups.

For ~64% of the total considered surface, including 24 cultivated and 81 noncultivated soil subgroups, no significant changes in SOC storage is observed (Fig. 3d–f). These areas mainly include the forest soils in southern China, the grassland and desert soils in northwest China, and the irrigated soils in eastern China. The negligible SOC loss in southern and northwest China is attributable to weak human activity in these soils. The balanced SOC in the irrigated soils in eastern China is explainable by the equilibrium between the input of organic matter, such as fertilization, and the output, such as the decomposition of the soil organic matter.

In considering all the above three cases, the net decrease of SOC due to land use in China is estimated to ~7.1 Pg (~9%), including ~5.4 Pg in organic horizons and ~1.6 Pg in mineral horizons. Since the data used in this study are from the same national soil survey, which lasted for only a few years, the contribution of climate changes to the SOC loss can be negligible. Consequently, the SOC loss is mainly attributable to land use over a long history. Although the 923 soil profiles are considered noncultivated profiles in the reconstruction of the carbon storage under noncultivated conditions, the estimate on the carbon loss due to human activity would be approximatively compared to the real natural situation, because these noncultivated soils may have also been indirectly affected by human during the long land use history.

The loss of the world's SOC by land use was estimated to be ~50.0–100.0 Pg (Houghton *et al*., 1983; Houghton, 1999; Esser, 1987; Cole, 1996; Lal, 1999) with a mean value of ~75.0 Pg. Accordingly, the decrease of SOC storage due to land use in China represents ~9.5% of the world's value. The ~7.1 Pg loss in China is higher than the ~5.0 Pg loss in the cultivated soils of the United States of America (Lal *et al*., 1999), while the area of cropland in the USA is ~1.1 times greater than that in China. Because of the longer history of agricultural exploitation, the degradation of soil resources led to greater organic carbon loss. Currently, ~78% of the croplands in China have a medium or low productivity (NSSO, 1998).

Improved soil management practices, such as soil erosion prevention, controlling the conservation tillage, residue management and improvement in the cropping systems, would be helpful to restore soil SOC storage (Bruce *et al*., 1999; Lal *et al*., 1999). These kinds of practices, in addition to the restoration of forests and grasslands on some cultivated soils, are also encouraged by related policies in China since a few years (NSSO, 1998). Our results suggest that carbon-lost soils in China have a substantial potential of restoring carbon storage. Because of the greater proportion of carbon-lost soils in China, this potential would be higher than for many other parts of the world. Assuming that half of the SOC loss in the degraded soils are restored during the next 20–50 years, as was suggested in some earlier studies (Cole, 1996; Lal *et al*., 1999), the soils in China may sequestrate ~3.5 Pg of carbon from the atmosphere, which represents a considerable offset to the industry's CO_2 emission.

Conclusions

Based on the data of the soil profiles investigated during China's Second National Soil Survey, we have comparatively examined the distribution and storages of soil organic carbon between the noncultivated situation and the present-day situation. The results reveal three cases of SOC changes in China. Significant SOC loss is observed within a belt from northeast to southwest China, mainly in nonirrigated soils under semiarid and semihumid conditions. The maximum SOC loss lies in northeast China. In contrast, the paddy soils in southern China and some irrigated soils in northwest China show a net gain in organic carbon. No significant changes are observed in the other irrigated soils in eastern China, grassland and desert soils in northwest China, and forest soils in southern China.

The current SOC storage in China is estimated to $\sim 70.3\,\mathrm{Pg}$ and the average carbon density to $\sim 8.0\,\mathrm{kg\,C\,m^{-2}}$. Under noncultivated conditions, the SOC storage and density are estimated to $\sim 77.4\,\mathrm{Pg}$ and $\sim 8.8\,\mathrm{kg\,C\,m^{-2}}$, respectively. Thus, $\sim 7.1\,\mathrm{Pg}$ SOC have been lost due to land use with an average SOC density decrease of $\sim 0.8\,\mathrm{kg\,C\,m^{-2}}$. This represents $\sim 9.5\%$ of the world's value. Soil organic horizons and mineral horizons account for $\sim 77\%$ and $\sim 23\%$ of that total loss, respectively. This suggests that human activity has also caused significant SOC loss in the mineral horizons of soils.

Because $\sim 78\%$ of the cultivated soils in China have been degraded to soils of low or medium productivity (NSSO, 1998) and most of the SOC loss occurred in cultivated soils without irrigation. Improved land management during the next 20–50 years, as suggested in earlier studies (Lal *et al.*, 1999), would provide a considerable potential to increase the SOC storage in China, and thus may significantly contribute to sequestrate carbon from the atmosphere under the global warming scenario.

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