Soil inorganic carbon storage pattern in China

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Abstract

Soils with pedogenic carbonate cover about 30% (3.44×10^6 km²) of China, mainly across its arid and semiarid regions in the Northwest. Based on the second national soil survey (1979–1992), total soil inorganic carbon (SIC) storage in China was estimated to be 53.3 ± 6.3 PgC (1 Pg $= 10^{15}$ g) to the depth investigated to 2 m. Soil inorganic carbon storages were 4.6, 10.6, 11.1, and 20.8 Pg for the depth ranges of 0–0.1, 0.1–0.3, 0.3–0.5, and 0.5–1 m, respectively. Stocks for 0.1, 0.3, 0.5, and 1 m of depth accounted for 8.7%, 28.7%, 49.6%, and 88.9% of total SIC, respectively. In contrast with soil organic carbon (SOC) storage, which is highest under 500–800 mm yr^{-1} of mean precipitation, SIC storage peaks where mean precipitation is <400 mm yr^{-1}. The amount and vertical distribution of SIC was related to climate and land cover type. Content of SIC in each incremental horizon was positively related with mean annual temperature and negatively related with mean annual precipitation, with the magnitude of SIC content across land cover types showing the following order: desert, grassland > shrubland, cropland > marsh, forest, meadow. Densities of SIC increased generally with depth in all ecosystem types with the exception of deserts and marshes where it peaked in intermediate layers (0.1–0.3 m for first and 0.3–0.5 m for latter). Being an abundant component of soil carbon stocks in China, SIC dynamics and the process involved in its accumulation or loss from soils require a better understanding.

Keywords: carbon cycle, carbon storage, land cover, soil inorganic carbon, vertical distribution

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Introduction

Globally, soils hold the largest terrestrial pool of carbon (C) and may be an active participant in short-term net CO₂ fluxes (Eswaran *et al.*, 2000; Mielnick *et al.*, 2005). In order to estimate C storage and fluxes in terrestrial environments, both organic and inorganic pools need to be considered. Globally, soil organic carbon (SOC) amounts to 1200–1600 Pg (1 Pg $= 10^{15}$ g) in the top meter of depth (Post *et al.*, 1982; Eswaran *et al.*, 1993, 2000; Sombroek *et al.*, 1993; Batjes, 1996; Jobbágy & Jackson, 2000). Soil inorganic carbon (SIC) storage down to the same depth reaches 940 Pg at the global scale (Eswaran
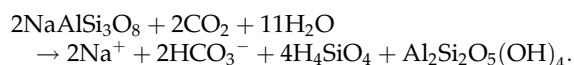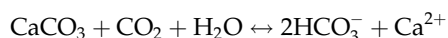
et al., 2000), being the most common form of C in arid and semiarid climates (Lal & Kimble, 2000; Mermut *et al.*, 2000). The magnitude of SIC exchange with the atmosphere is about 0.023 PgC yr^{-1} (Schlesinger, 1997) with a turnover time of about 85 000 years (Lal & Kimble, 2000). Although turnover times of some SIC fractions may be much faster on a smaller scale (Monger & Gallegos, 2000), soils are more likely to have large SIC exchange in humid regions with forest vegetation and where grassland are replaced by forest (Jobbágy & Jackson, 2003). Because of its long turnover time, formation of secondary carbonate in the soil can be an effective C sequestration mechanism (Lal & Kimble, 2000). Inorganic carbon in the soil occurs largely as carbonate minerals, such as calcium carbonate (CaCO₃) and dolomite (MgCO₃) (Batjes, 1996) and comprises two components, lithogenic inorganic carbon (LIC) and pedogenic inorganic carbon (PIC) (West *et al.*, 1988). While the first is inherited from parent material, the latter results from the precipitation of carbonate ions

derived from root and microbial respiration and calcium and magnesium ions yielded by weathering reactions (Lal & Kimble, 2000). The decrease of water content or partial pressure of CO_2, or increase of Ca^{2+} or HCO_3^- concentrations can lead to a favorable soil environment for the precipitation of PIC (Wilding et al., 1990). Pedogenic inorganic carbonate accumulation in semiarid or arid soils occurs because water deficit (evapotranspiration > precipitation) constrains significant leaching (Nordt et al., 2000), favoring PIC accumulation. Secondary carbonates could sequester atmospheric carbon dioxide on a large scale and are able to sequester organic matter, including humified compounds that are precipitated without transformation or polymerization (Duchaufour, 1976; Scharpenseel et al., 2000). For example, in the Rego Black Chernozem soils, which contain large amounts of organic matter and $CaCO_3$ in the surface horizons, bonding of organic matter to precipitated carbonates has been shown (Landi et al., 2003a, b, 2004). Where carbonate rock weathering occurs, atmospheric/soil CO_2 can be consumed as follows (Qiu et al., 2004).

$$CaCO_3 + CO_2 + H_2O \leftrightarrow 2HCO_3^- + Ca^{2+}$$

$$2NaAlSi_3O_8 + 2CO_2 + 11H_2O$$
$$\rightarrow 2Na^+ + 2HCO_3^- + 4H_4SiO_4 + Al_2Si_2O_5(OH)_4.$$

The results in Qiu et al. (2004) show that the main consumption of CO_2 in China by this reaction takes place in Guangxi, Guizhou and Chongqing provinces, and west Hubei Province and southwest Hunan Province in China, because of the high proportion of carbonate rocks and the high humidity of these areas. The carbonate weathering process consumes atmospheric CO_2 and hence, accurate calculations of these weathering rates may reveal whether they contribute significantly to the missing sink of carbon in terrestrial ecosystems (Feng et al., 2002).

Although better estimates of regional and global SOC stocks are now becoming available, this is not the case for SIC (Eswaran et al., 2000). In western and northern China, there are $2.62 \times 10^6 \, km^2$ of arid and semiarid territory in which water deficit leads to the accumulation of SIC. Desertification adds $2460 \, km^2$ per year to this figure (Feng et al., 2002). Hence, arid soils in China are potentially a big reservoir of SIC, which may have played an important contribution to C sequestration throughout the Quaternary (Pan & Guo, 2000). Feng et al. (2002) also argued that the C stored in soil carbonates in desertification-prone lands in China was an important factor affecting changes in concentrations of atmospheric carbon dioxide. Our study seeks to provide more accurate understanding of the SIC pool in China.

An earlier estimate of SIC storage in China reported by Pan & Guo (2000) suggested a value of 60 Pg but did not provide information on its horizontal and vertical distributions. Among the few investigations relating SIC to environment factors, Feng et al. (2002) suggested that the SIC content showed a stronger positive correlation with evaporation than did with other variables and also had positive and negative correlation with mean annual temperature (MAT) and mean annual precipitation (MAP), respectively. In spite of the availability of a large SIC content database for China (Pan & Guo, 2000; Feng et al., 2002), a comprehensive investigation on its distribution and relation with environmental variables and land cover types is missing. The objectives of this paper were to (1) estimate total SIC stock at different soil incremental layers in China; (2) characterize its spatial distribution; and (3) explore its relation with climate, organic carbon distributions and land cover/vegetation type.

Materials and methods

Soil profile and climate data

Soil data employed in this study were based on the second national soil survey of China conducted from 1979 to 1992 (see Wang et al., 2001, 2003, 2004). The database is composed of 2473 profiles and includes information on geographical location, altitude, depth of different soil horizons, altitude, vegetation, terrain position, parent material, land-use pattern, meteorological index, bulk density, $CaCO_3$ content and organic carbon content (National Soil Survey Office, 1993, 1994a, b, 1995a, b, 1996, 1998). Profiles without measured carbonate data (1697) were excluded from this study. We grouped the remaining soil profiles based on location (e.g. longitude, latitude and elevation), soil type and vegetation coverage.

In order to establish the relationship between SIC and SOC contents in terms of climatic parameters, MAP and MAT were generated for each site based on 670 meteorological stations covering a 30-year period (1960–1990) across China. We integrated the SIC and SOC database with 1 : 1 000 000 soil map to obtain the spatial pattern of SIC storage in China by matching SIC and SOC densities of soil subgroups with their spatial distribution. All data was transformed into $1 \, km \times 1 \, km$ grids from vector formats based on ARCGIS software (ESRI company, Redlands, CA, USA) and spatial analysis technique. Then, we extracted SOC and SIC information of different climate gradients by overlaying SIC and SOC grids with MAT and MAP grids in ARCGIS.

Calculation of soil inorganic carbon

In this work, the term carbonates refer to the sum of $CaCO_3$, $MgCO_3$ or other carbonate minerals in soils, of which $CaCO_3$ is dominant and dolomite $[CaMg(CO_3)_2]$ and $MgCO_3$ are usually minor components (Doner & Lynn, 1977). A factor of 0.12, the mole fraction of carbon in $CaCO_3$, was used to convert calcium carbonate to SIC content. A total of 776 profiles with measured carbonate information were investigated and their total storage of SIC by profile and group of profiles estimated by the following expressions:

$$C_{df} = \frac{r \cdot \sum\limits_{i=1}^{n} (\rho_i u_i o_i)}{\sum\limits_{i=1}^{n} u_i}, \qquad (1)$$

where C_{df} is the average SIC content of profile f ($kg\,m^{-3}$), ρ_i the bulk density of horizon i ($kg\,m^{-3}$), u_i the interval depth (m) determined by the type of profile f, o_i the SIC content (%) and r the mole fraction of carbon in $CaCO_3$ ($r = 0.12$). The average bulk density value of soil subgroup is used for soil profiles with no bulk density data. Grouping data by subgroups provided a better estimate than by soil groups because of the greater detail on climate, drainage and soil texture (Li & Zhao, 2001). We calculated the total SIC storage of soil subgroup as

$$S = \sum_{i=1}^{p} \overline{C_{dki}} \cdot \overline{h_{ki}} \cdot a_{ki}, \qquad (2)$$

where $\overline{C_{dk}}$ and $\overline{h_k}$ are the average SIC content ($kg\,m^{-3}$) and thickness (m) of subgroup k, respectively. Here, s is the total storage of SIC (kg), a_{ki} is the area of subgroup k ($10^{10}\,m^2$) and p is the number of subgroups. This approach could underestimate SIC storage due to possible soil depth biases. Although some researchers have adopted an empirical relationship between soil depth and C concentration to determine the SOC storage at soil depths to 1 m and greater (Jobbágy & Jackson, 2000; Li & Zhao, 2001), in this study we had to adopt measured soil depth to calculate SIC contents because measured depth of many profiles failed to reach 1 or 2 m, and, therefore, available data were limited. The soil database just lists the content value of $CaCO_3$; hence, we could not distinguish and know the fraction of pedogenic carbonates.

Data from second national soil survey in China were converted from pedogenetic horizons to different depth increments (0–0.1, 0.1–0.3, 0.3–0.5, 0.5–1.0 m). The depth of each horizon was used as a weighting coefficient, so as to derive the average SIC density of the soil profile to a depth of 0.1, 0.3, 0.5 and 1 m (Li & Zhao, 2001; Wang *et al.*, 2004) allowing storage estimates at each depth.

Weighted SIC densities by depth zone (0–0.1, 0.1–0.3, 0.3–0.5, 0.5–1.0 m) were calculated for each soil profile as a product of depth of horizon, concentration of SIC, and bulk density. After weighting, the mean densities for SIC were calculated by soil unit and depth. Area estimates were then calculated. Profiles failing to reach 0.5 and 1.0 m were excluded for the calculation of SIC content in the 0.3–0.5 and 0.5–1.0 m layers.

In order to estimate the content and storage of SIC in different climatic regions, soil profiles were grouped into five MAP classes: 0–200 mm (arid region), 200–400 mm (semiarid region), 400–800 mm (semihumid region), 800–1600 mm (humid region) and >1600 mm (wet region).

Error analysis method

The variance range ($\pm$) of SIC density and soil thickness for each subgroup was computed by using a t-test (Wilding *et al.*, 2001; Wang *et al.*, 2004):

$$Variance = \frac{t \cdot SD}{\sqrt{n}}, \qquad (5)$$

where t is the distribution value at 0.05 significant levels (95% confidence interval), SD is the standard deviation and n is the number of samples.

Correlation analysis

Pearson moment correlation was used to relate the dependant variable of SIC density in the 0–0.1, 0.1–0.3, 0.3–0.5 and 0.5–1.0 m soil depth to independent variables representing characteristics of different land sites: elevation (EV), MAT and MAP. The analysis was restricted to samples for which all the variables as above were available.

Results and discussion

Total SIC stock

Total SIC storage estimates for China is $53.3 \pm 6.3\,Pg\,C$. When fixed depth of 0.1, 0.3, 0.5 and 1.0 m are considered, SIC storage amount 4.6 ± 4.0, 15.2 ± 4.2, 26.3 ± 3.7 and $47.1 \pm 3.3\,Pg\,C$, respectively (8.7%, 28.7%, 49.6% and 88.9% of the total SIC storage, respectively). It can be inferred from the results that there is still $6.2\,Pg\,C$ or more SIC present below 1 m of the soil. The lower limit of carbonate illuviation horizons could reach to a depth of 2.0–3.0 m. Thus, our estimates should be considered as a lower boundary given to this fact (Díaz-Hernández *et al.*, 2003).

The average content of SIC for the whole country of China is $4.29 \pm 0.36\,kg\,C\,m^{-3}$ with the largest values occurring towards the northwest and north of its territory (Fig. 1) and the lowest towards the south and northeast, where MAP is generally high and the continuous
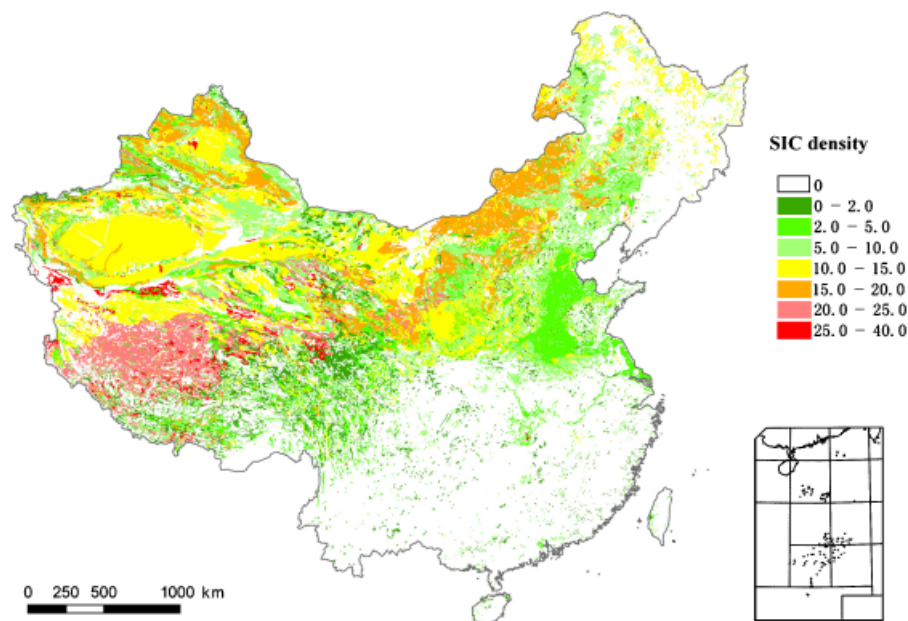
Fig. 1 Spatial pattern of SIC content in China (units $kg\,m^{-3}$). Representation of the average SIC contents of each soil subgroup. In China, the whole number of soil subgroups is 277 according to soil taxonomy; among them the number of soil subgroups with carbonates data is 125 based on soil profile database of second national soil survey.

removal of soluble material from the system and/or high soil acidity prevent SIC accumulation (Eswaran et al., 2000). Content of SIC increased from 2.0–5.0 to 15–20 $kg\,C\,m^{-3}$ from northeastern China to the Mongolia Plateau as a result of the transition from humid zones to semihumid, semiarid and arid zones. The regions where SIC content is largest ($>25\,kg\,C\,m^{-3}$) are deserts around northeastern Tibet, the Kunlun Mountain and the southern part of the Qinghai province in northwestern China.

In China, there are vast areas prone to desertification, covering a total area of 334 000 km^2, mainly in northern China, between 125°E and 75°W and 35°N and 50°N (Feng et al., 2002). Our study also indicates that there is significant spatial variability of SIC stocks (Fig. 1). For example, the desert SIC content was about 10–15 $kg\,C\,m^{-3}$ in the Taklimakan Desert of Xinjiang province in western China and was higher than 15 $kg\,C\,m^{-3}$ in most regions of Inner Mongolia in northern China. We found that MAP is lower than 200 mm for the former and ranges from 200 to 400 mm for the later. And $CaCO_3$ content of soils amounts 40–90 and 50–250 $g\,kg^{-1}$ for the former and the later, respectively, suggesting that climate and parent material are the main controlling factors of SIC contents in the soil.

Climate and SIC content

According to Batjes (1998) and Lal & Kimble (2000), the SIC pool is mainly concentrated in soils of arid and semiarid ecoregions with annual precipitation <500 mm. We found that 84% of the whole SIC pool of China exists in areas with that precipitation level (Table 1). However still, 4.19 Pg C SIC are stored in areas with higher MAP ranging 500–800 mm (Table 1).

The content of SIC showed a positive correlation with elevation and a negative one with MAP for investigated profiles, as well as for each depth increment (excepting 0.5–1.0 m vs. elevation, Table 2). The positive correlation between elevation and SIC content is attributed to the decreasing MAP and MAT with increasing elevation. The results in Table 2 show that the correlation between SIC content and MAT was not significant except the depth of 0.1–0.3 m. Temperature can affect $CaCO_3$ equilibrium directly through its influence on the solubility constant and indirectly through its effects on the partition of precipitation inputs between evapotranspiration and leaching (Lal & Kimble, 2000; Feng et al., 2002). Besides, our results also indicate that the negative correlation between SIC content and MAP is similar with increasing depth (Table 2). In many arid soils, the caliche, or calcic horizons, are deposited at a depth related to the maximum infiltration of rainfall (Schlesinger & Adrienne, 1998). In this study, we used multiyear mean temperature and precipitation to analyze the relationship between SIC and climate and did not consider effects of terrain and other factors on SIC storage.

To further evaluate the effects of climatic parameters on SIC storage, we grouped the soil profiles in climatic

Table 1 Contents and storages of soil inorganic carbon (SIC) and soil organic carbon (SOC) in different climatic regions

Annual mean precipitation (mm)	Area (10^6 ha)	SIC				SOC			
		Content ($kg\,m^{-3}$)	SD ($kg\,m^{-3}$)	Storage (Pg C)	Percent (%)	Content ($kg\,m^{-3}$)	SD ($kg\,m^{-3}$)	Storage (Pg C)	Percent (%)
0–200	237.7	10.37	7.20	20.0	37.5	3.44	4.00	6.8	8.1
200–400	154.3	12.48	8.92	18.3	34.3	9.06	8.80	12.0	14.1
400–500	79.7	7.45	7.21	6.5	12.2	14.39	12.67	10.3	12.2
500–800	194.4	3.54	4.71	7.3	13.7	16.42	12.43	28.3	33.3
800–1600	209.5	0.59	1.86	1.1	2.1	10.98	5.10	20.2	23.8
>1600	70.2	0.06	0.62	0.1	0.2	10.90	2.99	7.2	8.5
Sum	945.8			53.3	100			84.8	100

Table 2 Pearson correlation coefficient between soil inorganic carbon (SIC) density and environment†

Depth (m)		Elevation	Mean annual temperature (MAT)	Mean annual precipitation (MAP)	SIC content
0–0.1	Elevation	1.000			
	MAT	−0.616**	1.000		
	MAP	−0.416**	0.647**	1.000	
	SIC content	0.279**	−0.061	−0.348**	1.000
0.1–0.3	Elevation	1.000			
	MAT	−0.606**	1.000		
	MAP	−0.398**	0.631**	1.000	
	SIC content	0.306**	−0.131*	−0.380**	1.000
0.3–0.5	Elevation	1.000			
	MAT	−0.547**	1.000		
	MAP	−0.280**	0.535**	1.000	
	SIC content	0. 251**	−0.044	−0.317**	1.000
0.5–1.0	Elevation	1.000			
	MAT	−0.801**	1.000		
	MAP	−0.222**	0.506**	1.000	
	SIC content	0.065	−0.097	−0.331**	1.000

†The number of profiles involved in the study for depths 0–0.1, 0.1–0.3, 0.3–0.5, 0.5–1.0 m are $n = 487, 478, 438, 329$, respectively.
*Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level.

ranges. Within each MAT gradient (−10 to 0 °C for cold temperate, 0–10 °C for warm temperate, 10–20 °C for subtropics, 20–30 °C for tropic), MAP was divided into five ranges.

In addition, the correlation between SIC density and climate is prominent when MAP is restricted from 200 to 1600 mm and MAT from 0 to 30 °C. In the four MAT ranges, SIC contents decreased with increasing precipitation (Table 3). In cold and warm temperate zones, SIC contents increased with increasing depth within all precipitation ranges. However, this trend was not seen in subtropical and tropical zones. Moreover, for MAP range of 200–400 and 400–800 mm, SIC contents generally decreased with increasing temperature. The results from Table 3 suggest that MAP has larger influence on SIC formation and spatial distribution than MAT.

Content and vertical distribution of SIC across land cover types

The magnitude of SIC content for different land covers is in the following order of magnitude: desert > grassland > cropland > marsh > shrubland > meadow > forest (Fig. 2). Land cover type has a strong influence on the vertical distribution of roots and SOC (Jobbágy & Jackson, 2000; Lal & Kimble, 2000) and these imprints are likely to affect SIC distribution.

Table 3 The soil inorganic carbon (SIC) contents within mean annual temperature (MAT) and mean annual precipitation (MAP) gradients by depth interval

| MAT (°C)	Depth (m)	Mean SIC content (kg C m^{-3})				
		0–200 mm	200–400 mm	400–800 mm	800–1600 mm	>1600 mm
−10 to 0	0–0.1	–	12.41	1.84	–	–
	0.1–0.3	–	15.88	2.57	–	–
	0.3–0.5	–	22.19	3.37	–	–
	0.5–1.0	–	30.72	–	–	–
0–10	0–0.1	13.08	12.01	3.79	0.24	–
	0.1–0.3	13.67	13.28	4.16	0.30	–
	0.3–0.5	14.55	15.75	5.16	0.50	–
	0.5–1.0	12.34	16.62	6.26	1.08	–
10–20	0–0.1	15.82	6.43	5.53	0.99	–
	0.1–0.3	15.90	2.29	5.02	0.97	–
	0.3–0.5	17.74	1.84	4.86	0.89	0.03
	0.5–1.0	11.82	1.64	4.93	0.99	0.09
20–30	0–0.1	–	–	4.09	0.08	–
	0.1–0.3	–	–	3.63	0.01	–
	0.3–0.5	–	–	2.86	0.08	–
	0.5–1.0	–	–	4.38	0.10	–

Symbol '–' refers to no data.
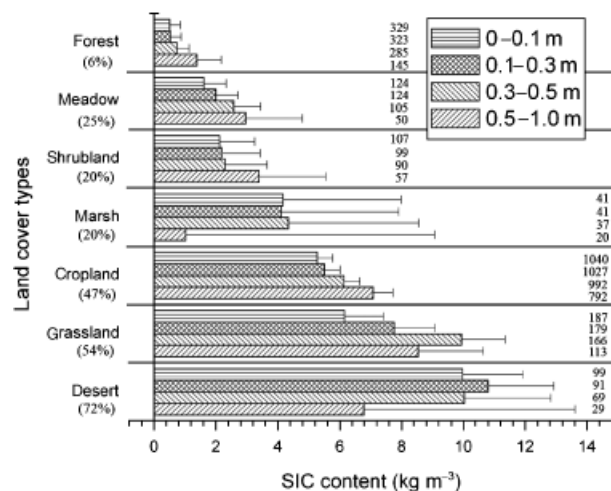
Fig. 2 The vertical distribution of SIC content under different land cover types in China. In each land cover type, profiles that without carbonate were excluded and the magnitude of SIC content in the figure represent the average condition of certain land cover type. The error bars represent the variance range of each SIC content of different land cover types. The number to the right of each error bar is the sample size (*n*) of each soil horizon. The percentage underneath each cover type name represents the percentage of profiles with measurable carbonate for each cover type.

Depending on the vertical characteristic of SIC contents, we classified the tendency of SIC content of seven land cover types into three types: (1) SIC content increases with increasing depth (forest, meadow, shrubland, cropland); (2) SIC content peaking at intermediate depths (grassland, desert); and (3) SIC content showing mixed patterns with increasing depth (marsh). Contents of SIC may increase with depth in forest, meadow, shrubland and cropland as a result of leaching and SOC accumulation. Leaching bicarbonate from the upper layers during the rainy season probably undergoes precipitation as carbonates in the lower layers during the dry hot periods (Pal *et al.*, 2000). In addition, increase in SOC results in increased dissolution and reprecipitation of carbonates as a result of SOC influence on microbial respiration yielding CO_2, as well as Ca^{2+} and Mg^{2+} (Lal & Kimble, 2000; Bronick & Lal, 2005).

Discussion and uncertainties

Table 4 lists the estimates of global and China's SIC and SOC reservoirs. Feng *et al.* (2002) estimated that the desertification-prone lands, mainly in northern China, contain 7.8 Pg of organic carbon and 14.9 Pg of carbonate carbon in the top 1.0 m of the soil. We calculated that China has a SIC storage of 53.3 ± 6.3 Pg C, which is consistent with the estimation of Pan & Guo (2000). The discrepancy between SIC estimates for China's soils is probably due to the inability to differentiate between primary (LIC) and secondary (PIC) carbonate in soils and different data sources of profile and areas. The proportion of SIC to total soil C storage (SIC + SOC)

Table 4 Comparison of estimating soil organic carbon storage in world

Authors	Soil organic carbon (Pg C)	Soil inorganic carbon (Pg C)	Scale
Schlesinger (1982)		780–930	Global
Sombroek *et al.* (1993)	1220	720	Global
Batjes (1996)	1462–1548	695–748	Global
Eswaran *et al.* (2000)	1530	940	Global
Pan & Guo (2000)		60	China
Wang *et al.* (2001, 2004)	83 ± 20		China
Feng *et al.* (2002)	7.84	14.91	Desert in China
This study		53.3 ± 6.3	China

averages 40% in China, being higher then the value of 32–38% reported at the global scale (Table 4).

Soil C stock in China reach 136 ± 26 Pg C including SOC and SIC (Table 4). According to the estimations of Batjes (1996) and Eswaran *et al.* (2000), China's soil C stock is about 5.51–6.11% of global soil C reservoir to a depth of 1 m. Lal (2002, 2004) estimated that the total potential of SOC and SIC sequestration in China was about 105–198 and 7–138 Tg C yr^{-1}, respectively, with effective management practices. It means that there is a potential of C sequestration in China's soil. Further studies are needed to prove this.

In China, 84.0% and 34.4% of SIC and SOC storage distributed in regions with annual precipitation lower than 500 mm, respectively (Table 1), which the content of SIC increased with decreasing precipitation. Compared with SIC distribution, the largest SOC content occurs in the regions where the precipitation is between 500 and 800 mm (see Table 1). Our study suggests that the distribution pattern of SIC and SOC is inverse in China with increasing precipitation (Table 1). The area of regions of MAP <500 mm and MAP >500 mm accounts for 49.87% and 50.13% in China, respectively, but the former occupies about 59.2% of total soil C stock.

Traditionally, the calculation method of soil C reservoir is based on 1 m soil depth. However, this paper adopted the measured soil depth to calculate the SIC content. In fact, many soils are very deep; furthermore, the core stratum of soil has a lot of organic carbon and inorganic carbon (Batjes, 1996; Wang *et al.*, 2001), so the SIC storage should be much higher in China.

Conclusions

The amount and vertical distribution of soil inorganic carbon shows an association to land cover type and climate across China. With a stock of approximately 50 Pg down to 2 m of depth, soil inorganic carbon represents 40% of all the carbon stored by Chinese soils. Efforts to understand the dynamics of this large carbon pool, including its exchange rates with the atmosphere and its responses to climate and land use change, are needed to gain a better picture of global carbon cycling and sequestration possibilities.

References

Batjes NH (1996) Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science*, **47**, 151–163.

Batjes NH (1998) Mitigation of atmospheric CO$_2$ concentrations by increased carbon sequestration in the soil. *Biology and Fertility of Soils*, **27**, 230–235.

Bronick CJ, Lal R (2005) Soil structure and management: a review. *Geoderma*, **124**, 3–22.

Díaz-Hernández JL, Fernández EB, González JL (2003) Organic and inorganic carbon in soils of semiarid regions: a case study from the Guadix-Baza basin (Southeast Spain). *Geoderma*, **114**, 65–80.

Doner HE, Lynn WC (1977) Carbonate, halide, sulfate, and sulfide mineral. In: *Minerals in Soil Environments* (eds Dixon JB, Weed SB), pp. 75–98. Soil Science Society of America, Madison, WI, USA.

Duchaufour P (1976) Dynamics of organic matter in soils of temperate regions: its action on pedogenesis. *Geoderma*, **15**, 31–40.

Eswaran H, Reich PF, Kimble JM (2000) Global carbon stocks. In: *Global Climate Change and Pedogenic Carbonates* (eds Lal R, Kimble JM, Eswaran H, Stewart BA), pp. 15–25. CRC Press, Boca Raton, USA.

Eswaran H, Van den Berg E, Reich PF (1993) Organic carbon in soils of the world. *Soil Science Society of American Journal*, **57**, 192–194.

Feng Q, Endo KN, Cheng G (2002) Soil carbon in desertified land in relation to site characteristics. *Geoderma*, **106**, 21–43.

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

Jobbágy EG, Jackson RB (2003) Patterns and mechanisms of soil acidification in the conversion of grasslands to forests. *Biogeochemistry*, **64**, 205–229.

Lal R (2002) Soil carbon sequestration in China through agricultural intensification, and restoration of degraded and desertified ecosystems. *Land Degradation & Development*, **13**, 469–478.

Lal R (2004) Offsetting China's CO$_2$ emissions by soil carbon sequestration. *Climatic Change*, **65**, 263–275.

Lal R, Kimble JM (2000) Pedogenic carbonate and the global carbon cycle. In: *Global Climate Change and Pedogenic Carbonates*

(eds Lal R, Kimble JM, Eswaran H, Stewart BA), pp. 1–14. CRC Press, Boca Raton, USA.

Landi A, Anderson DW, Mermut AR (2003a) Organic carbon storage and stable isotope composition of soils along a grassland to forest environmental gradient in Saskatchewan. *Canadian Journal of Soil Science*, **83**, 405–414.

Landi A, Mermut AR, Anderson DW (2003b) Origin and rate of pedogenic carbonate accumulation in saskatchewan soils, Canada. *Geoderma*, **117**, 143–156.

Landi A, Mermut AR, Anderson DW (2004) Carbon distribution in a hummocky landscape from saskatchewan, Canada. *Soil Science Society of America Journal*, **68**, 175–184.

Li Z, 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.

Mermut AR, Amundson R, Cerling TE (2000) The use of stable isotopes in studying carbonate dynamics in soils. In: *Global Climate Change and Pedogenic Carbonates* (eds Lal R, Kimble JM, Eswaran H, Stewart BA), pp. 65–85. CRC Press, Boca Raton, USA.

Mielnick P, Dugas WA, Mitchell K, Havstad K (2005) Long-term measurements of CO_2 flux and evapotranspiration in a Chihuahuan desert grassland. *Journal of Arid Environments*, **60**, 423–436.

Monger HC, Gallegos RA (2000) Biotic and abiotic processes and rates of pedogenic carbonate accumulation in the southwestern united states-relationship to atmospheric CO_2 sequestration. In: *Global Climate Change and Pedogenic Carbonates* (eds Lal R, Kimble JM, Eswaran H, Stewart BA), pp. 273–289. CRC Press, Boca Raton, USA.

National Soil Survey Office (1993) *Soil Species of China*, Vol. I. Chinese Agriculture Press, Beijing, China.

National Soil Survey Office (1994a) *Soil Species of China*, Vol. II. Chinese Agriculture Press, Beijing, China.

National Soil Survey Office (1994b) *Soil Species of China*, Vol. III. Chinese Agriculture Press, Beijing, China.

National Soil Survey Office (1995a) *Soil Species of China*, Vol. IV. Chinese Agriculture Press, Beijing, China.

National Soil Survey Office (1995b) *Soil Species of China*, Vol. V. Chinese Agriculture Press, Beijing, China.

National Soil Survey Office (1996) *Soil Species of China*, Vol. VI. Chinese Agriculture Press, Beijing, China.

National Soil Survey Office (1998) *Chinese Soils*. Chinese Agriculture Press, Beijing, China.

Nordt LC, Wilding LP, Drees LR (2000) Pedogenic carbonate transformations in leaching soil system: implications for the global C cycle. In: *Global Climate Change and Pedogenic Carbonates* (eds Lal R, Kimble JM, Eswaran H, Stewart BA), pp. 43–64. CRC Press, Boca Raton, USA.

Pal DK, Dasog GS, Vadivelu S, Ahuja RL, Bhattacharyya T (2000) Secondary calcium carbonate in soils of arid and semiarid regions of India. In: *Global Climate Change and Pedogenic Carbonates* (eds Lal R, Kimble JM, Eswaran H, Stewart BA), pp. 149–186. CRC Press, Boca Raton, USA.

Pan G, Guo T (2000) Pedogenic carbonate of aridic soil in China and its significant in carbon sequestration in terrestrial systems. In: *Global Climate Change and Pedogenic Carbonates* (eds Lal R, Kimble JM, Eswaran H, Stewart BA), pp. 135–148. CRC Press, Boca Raton, USA.

Post WM, Emmanuel WR, Zinke PJ, Stangenberger G (1982) Soil carbon pools and world life zones. *Nature*, **298**, 1586–1589.

Qiu D, Zhuang D, Hu Y, Yao Y (2004) Estimation of carbon sink capacity caused by rock weathering in China. *Earth Science – Journal of China University of Geosciences*, **29**, 177–183 (in Chinese).

Scharpenseel HW, Mtimet A, Freytag J (2000) Soil inorganic carbon and global change. In: *Global Climate Change and Pedogenic Carbonates* (eds Lal R, Kimble JM, Eswaran H, Stewart BA), pp. 27–42. CRC Press, Boca Raton, USA.

Schlesinger WH (1982) Carbon storage in the caliche of the arid world: a case study from Arizona. *Soil Science*, **133**, 247–255.

Schlesinger WH (1997) *Biogeochemistry: An Analysis of Global Change*, 2nd edn. Academic Press, San Diego, USA.

Schlesinger WH, Adrienne MP (1998) Plant-soil interactions in deserts. *Biogeochemistry*, **42**, 169–187.

Sombroek WG, Nachtergale FO, Hebel A (1993) Amounts, dynamics, and sequestration of carbon in tropical and subtropical soils. *AMBIO*, **22**, 417–426.

Wang S, Huang M, Shao X, Mickler RA, Li K, Ji J (2004) Vertical distribution of soil organic carbon in China. *Environment Management*, **33**, S201–S209.

Wang S, Tian H, Liu J, Pan S (2003) Pattern and change of soil organic carbon storage in China: 1960s–1980s. *Tellus*, **55B**, 416–427.

Wang S, Zhou C, Li K, Zhu S, Huang F (2001) Estimation of the soil organic carbon reservoir in China. *Journal of Geographical Sciences*, **11**, 3–13.

West LT, Drees LR, Wilding LP, Rabenhorst MC (1988) Differentiation of pedogenic and lithogenic carbonate forms in Texas. *Geoderma*, **43**, 271–287.

Wilding LP, Drees LR, Nordt LC (2001) Spatial variability: enhancing the mean estimate of organic and inorganic carbon in a sampling unit. In: *Advances in Soil Science: Assessment Methods for Soil Carbon* (eds Lal R, Kimble JM, Stewart BA), pp. 69–104. CRC Press, Boca Raton, FL, USA.

Wilding LP, West LT, Drees LR (1990) Field and laboratory identification of calcic and petrocalcic horizons. In: *Proceedings of the Fourth International Soil Correlation Meeting (ISCOM IV) Characterization, Classification, and Utilization of Aridisols. Part A: Papers* (eds Kimble JM, Nettleton WD), pp. 79–92. US Department of Agriculture-Soil Conservation Service, Lincoln, NE, USA.