Study on Soil Organic Carbon Storage and Its Spatiotemporal Changes in Shandong Province

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Abstract [**Objectives**] This study was conducted to investigate the spatial distribution and variation patterns of soil carbon storage. [**Methods**] Using highdensity, highprecision soil carbon data obtained at two depths from the multipurpose regional geochemical survey of Shandong Province (2013), the soil carbon density and storage for the 0 - 20, 0 - 100, and 0 - 160 cm layers in the province were estimated. The spatiotemporal evolution of SOC density and storage and the carbon sequestration potential were further examined. [**Results**] (1) The SOC densities for the three soil layers (0 - 20, 0 - 100, and 0 - 160 cm) in Shandong Province were 2.22, 7.64, and 10.09 kg/m^2, respectively, with all layers showing significantly lower SOC densities than the national average. (2) The spatial distribution of topsoil SOC density generally exhibits a pattern of low values in coastal areas, moderate values in the northwestern plain and eastern hilly regions, and relatively high values in the central and southern mountainous areas. (3) Compared with the data from the Second National Soil Survey conducted 18 years ago (1985), the topsoil SOC density increased from 1.43 to 2.22 kg/m^2, and the storage increased from 226.41 to 350.65 Mt, a net increase of 124.24 Mt. SOC has accumulated in the soil at an average rate of 0.044 $kg/(m^2 \cdot a)$, exhibiting an overall "carbon sink" effect. [**Conclusions**] This study provides a scientific basis for China's strategic planning of CO_2 emission reduction and global carbon cycle research.

Key words Soil carbon density; Soil carbon storage; Spatiotemporal change; Carbon sequestration potential; Shandong Province

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In recent years, global change and the carbon cycle have attracted more and more attention from governments, the scientific community, and the public worldwide. The soil carbon pool is a major component of the terrestrial ecosystem carbon pool, with an estimated soil carbon storage of approximately 1 400 - 1 500 Pg[1-2], accounting for three-quarters of the entire terrestrial ecosystem, about twice the atmospheric carbon pool, and three times the vegetation carbon pool[3]. Therefore, even a small change in the soil carbon pool can lead to significant alterations in atmospheric CO_2 and other greenhouse gas concentrations, thereby affecting the Earth's climate system. Some researchers suggest that a 0.1% change in the soil carbon pool would result in a 1 mg/L change in atmospheric CO_2 concentration[4-5]. The soil carbon pool consists of an organic carbon pool and an inorganic carbon pool. Among them, the organic carbon pool stores a vast amount of carbon, and approximately two-thirds of the CO_2 exchanged between terrestrial ecosystems and the atmosphere comes from the decomposition of soil organic matter[6]. Therefore, the soil organic carbon pool can be regarded as a major source and sink of atmospheric CO_2. A 10% change in global soil organic carbon would release more CO_2 than the total emissions from human activities over 30 years[6]. Thus, the soil organic carbon pool plays a crucial role in the study of the carbon cycle, carbon balance, and global change.

Based on the survey data, in this study, the soil carbon density and storage in Shandong Province were estimated, and their spatial distribution characteristics and the composition of the carbon pool were analyzed. Meanwhile, using the data from the Second National Soil Survey of Shandong Province in 1985, a comparative study was conducted to analyze the spatiotemporal changes in soil organic carbon storage over the past 18 years. This study provides a new approach for exploring the spatial distribution and variation patterns of soil carbon storage, and offers a scientific basis for China's strategic planning of CO_2 emission reduction and global carbon cycle research.

Data Sources and Carbon Storage Calculation Methods

Data sources and processing

(1) Shandong Province initiated a multipurpose regional geochemical survey in 2010 and completed the collection of soil samples in the entire land area of the province by 2013. A total of 158 900 topsoil samples and 39 700 deep soil samples were collected. Total soil carbon and soil organic carbon were determined using the ammonium ferrous sulfate volumetric method after digestion with potassium dichromate and sulfuric acid. The detection limit was 0.02%, and the accuracy and precision pass rates both reached 100%. Sample collection, analysis, and quality control were strictly carried out in accordance with the *Specifications for Multipurpose Regional Geochemical Survey* (DD200501), ensuring the reliability of sample collection and analysis quality.

(2) Organic matter content data of 879 topsoil samples from the Second National Soil Survey conducted in the mid-1980s

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(1980 – 1985) were collected.

Using MapGIS software, the collected organic matter content data from 879 samples of the Second Soil Survey period were mapped at a 0.015% content interval, generating a soil organic matter geochemical map with 57 content intervals. Through spatial analysis, the multi-purpose data were intersected with this "new map" to extract the soil organic matter content data from the Second Soil Survey period at the same sampling points as the multi-purpose survey. These values were then divided by 1.724 (the Bemmelen factor) to obtain the soil organic carbon content data.

Calculation method of soil carbon storage

The soil organic carbon density (SOCD) was calculated using the following formula[8]:

$$SOCD = D \times \rho \times TOC \times 10 \quad (1)$$

$$TOC = \frac{(TOC_1 - TOC_2) \cdot [(d_1 - D) + D \cdot (\ln D - \ln d_2)]}{D \cdot (\ln d_1 - \ln d_2)} + TOC_2 \times \frac{d_2}{D} \quad (2)$$

The soil inorganic carbon density (SICD) was calculated using the following formula:

$$SICD = D \times \rho \times TIC \times 10 \quad (3)$$

$$TIC = [TIC_1 + (TIC_2 \times \frac{D}{d_2} + TIC_1 \times \frac{d_2 - D}{d_2})] \div 2 \quad (4)$$

In formulas (1) – (4), *SOCD* and *SICD* represent the organic carbon density and inorganic carbon density (kg/m^2) within a certain soil depth, respectively. *TOC* and *TIC* denote the average content (%) of soil organic carbon and inorganic carbon, respectively. TOC_1 and TOC_2 are the measured organic carbon contents (%) in topsoil and deep soil, respectively, obtained by subtracting organic carbon from total soil carbon. d_1 is the sampling depth of topsoil (0.1 m); d_2 is the sampling depth of deep soil (1.2 – 1.8 m); *D* is taken as 0.2 m, 1.0 m, and 1.6 m; 10 is the conversion coefficient; and ρ is the soil bulk density (g/cm^3), sourced from *Soils in Shandong*.

Soil Carbon Density and Storage

Characteristics of soil carbon density

According to formulas (1) – (4), the soil carbon densities and storages for the three different soil layers (0 – 20, 0 – 100, and 0 – 160 cm) in Shandong Province are shown in Table 1.

Table 1 Soil carbon density and carbon storage at different depths

Depth//cm	Carbon density//kg/m^2			Carbon storage//Mt			(*SOCR/SCR*)	(*SICR/SCR*)
	SOCD	*SICD*	*TCD*	*SOCR*	*SICR*	*SCR*	%	%
0 – 20	2.22	1.30	3.51	350.65	205.12	555.77	63.09	36.91
0 – 100	7.46	6.86	14.32	1 180.23	1 086.27	2 266.5	52.07	47.93
0 – 160	10.09	12.32	22.41	1 597.49	1 950.35	3 547.84	45.03	54.97

As shown in Table 1, the SIC densities for the three soil layers were 1.30, 6.86, and 12.32 kg/m^2, respectively, while the SOC densities were 2.22, 7.64, and 10.09 kg/m^2, respectively. In typical regions of China[9], the SOC densities were 3.19, 11.64, and 15.34 kg/m^2, which are 1.44, 1.56, and 1.52 times higher than those in the corresponding soil layers of Shandong Province. The SOC densities in all layers of Shandong were lower than the national average. Shandong Province accounts for 1.64% of China's total land area, while its SOC storage in the 0 – 100 cm layer (1 180.23 Mt) accounts for only 0.64% of the national SOC storage in the same layer (185.7 Pg)[10], indicating that there is still substantial potential for soil carbon sequestration in the province.

In terms of carbon storage in different soil layers, the SOC storage in the 0 – 20 cm layer accounted for 22.00% of the SOC storage in the 0 – 160 cm layer. It is comparable to those in most provinces such as Hebei (21.30%), Hunan (21.84%), and Jilin (23.74%), but is lower than that in a few regions rich in topsoil SOC, such as Inner Mongolia (35.56%) and Tibet (57.00%)[9]. The SOC storage in the 0 – 100 cm layer accounted for 73.93% of the SOC storage in the 0 – 160 cm layer, indicating that SOC is primarily concentrated within the 0 – 100 cm depth, while the storage in the 100 – 160 cm range is limited. In contrast to the distribution of SOC storage, the SIC storage in the 0 – 100 cm layer accounted for 55.68% of that in the 0 – 160 cm layer, suggesting that SIC is mainly distributed in deeper soil layers, with limited storage in the topsoil.

Spatial distribution characteristics of topsoil organic carbon storage

The spatial distribution of topsoil SOC density in Shandong Province is shown in Fig. 1. In the vast plains of western and northern Shandong, the SOC density was generally low, with most areas ranging from 1.51 to 1.70 kg/m^2, classified as moderately low. In the central and southern low-mountain and hilly areas of Shandong, as well as the eastern mountainous and hilly regions, the SOC density was relatively high. Additionally, the area west of the Nansi Lake also exhibited a relatively high SOC density, ranging from 2.56 to 19.71 kg/m^2. The lowest SOC density (0.03 – 1.51 kg/m^2) occurred in the Dongying – Binzhou Yellow River Delta and the eastern coastal zone of Shandong. In the remaining areas, the SOC density ranged from 1.70 to 2.56 kg/m^2, at a medium level.

Spatiotemporal changes in soil organic carbon storage

Fig. 2 shows the frequency histogram of SOC content. The topsoil SOC storage and annual change rates for different soil types were calculated, and the results are presented in Table 2.

types were calculated, and the results are presented in Table 2. A comparison was made in terms of SOC content, density, and storage between the Second National Soil Survey (starting in 1985) and the multi-purpose regional geochemical survey (starting in 2003).

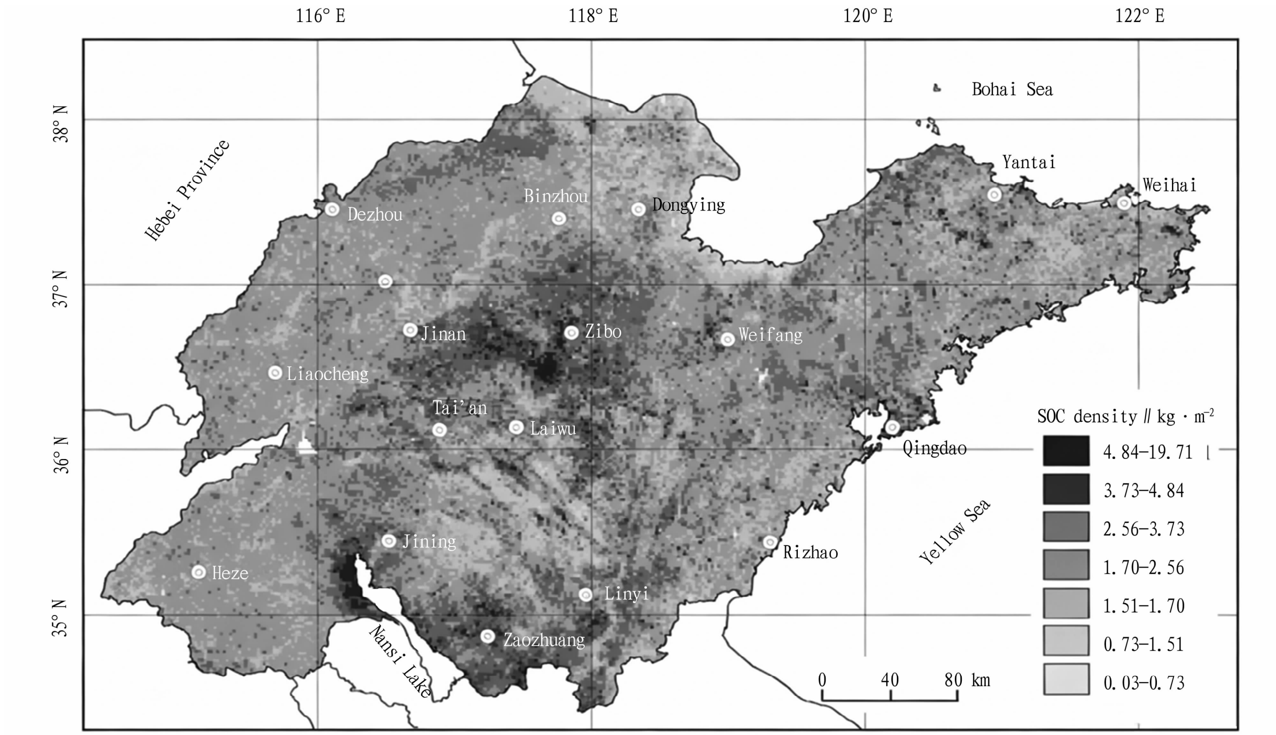

Fig. 1 Spatial distribution of SOC density of top soil (0 – 20 cm) in Shandong Province

As shown in Fig. 2, from the Second National Soil Survey to the multi-purpose geochemical survey, the SOC content in Shandong Province shifted from being mainly concentrated in the range of 0.25% – 0.50% to a concentration in the range of 0.75% – 1.00%. The proportion of SOC content above 0.75% increased from 11.49% to 55.15%, while the proportion below 0.5% decreased from 49.94% to 10.28%. Overall, the average SOC content increased from 0.53% to 0.83%, indicating that after 18 years, the SOC content in Shandong showed a general rising trend.

In terms of annual change rate, paddy soil and lithosol exhibited the fastest increases in TOC, with rates of 0.105 and 0.064 kg/(m^2 · a), respectively. The topsoil in the entire province increased its organic carbon at an average annual rate of 0.044 kg/(m^2 · a). It indicates that over the 18 year period, the topsoil in Shandong Province continuously absorbed carbon from the environment, exhibiting an overall "carbon sink" effect. As shown in Table 2, the topsoil SOC storage increased from 226.41 to 350.65 Mt, with a net increase of 124.24 Mt. Using the spatial analysis function of MapGIS, the total "carbon source" was calculated to be 6.76 Mt, and the total "carbon sink" was 131.00 Mt.

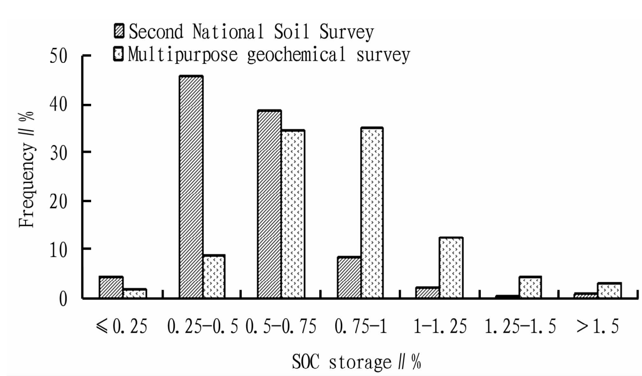

Fig. 2 Comparison of SOC storage in different periods in shandong Province

Table 2 Changes of SOC density and storage of top soil in Shandong Province

Soil type	Area // km^2	Second National Soil Survey		Multipurpose survey		△SOC		Annual change rate
		SOC density kg/m^2	SOC storage Mt	SOC density kg/m^2	SOC storage Mt	Storage // Mt	Change // %	kg/(m^2 · a)
Coastal saline soil	8 848	1.60	14.20	1.52	13.46	–0.74	–5.21	–0.005
Fluvo-aquic soil	61 560	1.36	83.44	2.07	127.5	44.06	52.80	0.040
Skeletal soil	24 948	1.36	33.81	2.28	56.81	23.00	68.03	0.051

(Continued)

(Table 2)

Soil type	Area//km²	Second National Soil Survey SOC density kg/m²	Second National Soil Survey SOC storage Mt	Multipurpose survey SOC density kg/m²	Multipurpose survey SOC storage Mt	△SOC Storage//Mt	△SOC Change//%	Annual change rate kg/(m² · a)
Aeolian sandy soil	728	1.23	0.90	1.68	1.23	0.33	36.67	0.025
Cinnamon soil	22 068	1.67	36.87	2.72	60.11	23.24	63.03	0.059
Red clay soil	232	1.75	0.41	2.89	0.67	0.26	63.41	0.062
Alkaline soil	20	1.20	0.02	2.14	0.04	0.02	100.00	0.056
Shajiang black soil	7 388	1.74	12.87	2.86	21.16	8.29	64.41	0.062
Lithic soil	1 940	1.34	2.59	2.50	4.84	2.25	86.87	0.064
Paddy soil	1 416	1.99	2.82	3.89	5.5	2.68	95.04	0.105
Newly accumulated alluvial soil	1 624	1.22	1.97	1.51	2.45	0.48	24.37	0.016
Saline soil	808	1.51	1.22	2.09	1.69	0.47	38.52	0.032
Brown soil	26 704	1.32	35.28	2.07	55.18	19.90	56.41	0.041
Total	158 284	1.43	226.41	2.22	350.65	124.24	54.87	0.044

Conclusions and Discussion

The SOC densities of the three soil layers (0 – 20, 0 – 100, and 0 – 160 cm) in Shandong Province were 2.22, 7.64, and 10.09 kg/m², respectively. Compared with the national SOC density, the SOC density of each layer in Shandong was significantly lower. The spatial distribution of topsoil SOC density generally showed a pattern of low values in coastal areas, moderate values in the northwestern plain and eastern hilly regions, and relatively high values in the central and southern mountainous areas.

Using the data from the Second National Soil Survey of Shandong Province in the 1980s and the data from this multipurpose geochemical survey, the "carbon source/sink" effect of the region can be quantitatively and qualitatively estimated. The two surveys were conducted 18 years apart (1985 – 2003). Over the 18 year period, the topsoil SOC content increased from 0.53% to 0.83%, and the storage increased from 226.41 to 350.65 Mt, a net increase of 124.24 Mt. In the storage, the the amount of "carbon source" was 6.76 Mt, and that of "carbon sink" was 131.00 Mt. SOC accumulated in the soil at an average rate of 0.044 kg/(m² · a), with the fastest accumulation occurring in paddy soil [0.105 kg/(m² · a)] and lithosol [0.064 kg/(m² · a)]. The results of this study provide a new approach for exploring the spatial distribution and variation patterns of soil carbon storage.

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