Distribution and storage of soil organic and inorganic carbon under different ecological zones in Xinjiang, China

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Abstract: The objective of this study was to quantify both soil organic carbon (SOC) and soil inorganic carbon (SIC) stocks in different ecological zones in Xinjiang Region, the largest arid and semi-arid region in northwest China. The specific focus was on the vertical distributions of 641 typical soil profiles (0-100 cm). The study region covered five ecological zones: I–Altai/west Junggar; II–Junggar basin; III–Tianshan mountain; IV–Tarim basin; and V–Kunlun-Altun mountains. The zones are categorized by their specific geographical locations from north to south with terrains derived from mountains to basins. The data used in the study were obtained from the first (1960s) and the second (1980s) National Soil Surveys and partially from the field survey of this study conducted in 2013. The results suggest that there are 11.74 Pg SOC and 26.71 Pg SIC total stocks in the 0-100 cm surface soil over the entire study region. The distributions of SOC and SIC were found to be non-uniform. The Tianshan mountain zone has the highest SOC stock, followed by the Tarim basin, Kunlun-Altun mountains, Altai and west Junggar (Altai/west Junggar), and Junggar basin zones. In contrast, the Tarim basin zone had the highest SIC stock, followed by the Tianshan mountain, Kunlun-Altun mountains, Junggar basin, and Altai/west Junggar zones. The SOC content decreases gradually from northwest to southeast and from mountains to deserts; while the SIC content decreases gradually from south to north. The SOC and SIC contents also change with soil depth. Within a given ecological zone, the SOC content increased with increasing soil depth, peaked at about 20-40 cm, then it decreased with the bigger depths below 40 cm. The SIC contents increased gradually from 0 to 40 cm, and then decreased gradually with increasing soil depth over the 40-100 cm depth in all ecological zones except for the Tianshan mountain area.

Keywords: ecological zones, soil organic carbon, soil inorganic carbon, carbon storage, vertical distribution
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1 Introduction

Soil carbon pool comprises of two components: soil organic carbon (SOC) and soil inorganic carbon (SIC)[1,2]. Arid ecosystems, including arid regions, semi-arid regions and arid–semi-humid regions[3], account for 47% of total land area of the Earth[4]. Recent studies have shown that deserts may become a relatively large carbon sequestration pool, and global arid soils may have a significant influence on global carbon balance and carbon cycle in terrestrial ecosystems[5,6]. Considerable attention has been paid to soil carbon in these areas in recent years[7] .

Ecosystems in arid regions are very sensitive to global change[8]. Although arid ecosystems cover a very large area of the world and potentially have a great contribution to global biogeochemical cycle, very little effort has been devoted to examining carbon balance in these ecosystems[9,10]. Compared with many studies mainly focus on SOC in arid regions, very little attention has been paid to SIC[11-14], although the SIC content may have a significant effect on the soil carbon storage and carbon cycle in arid regions[6,15]. For example, the SIC pool in northwestern China is approximately five times larger than the corresponding SOC pool, which accounts for over 60% of the total SIC pool in whole China[16]. The magnitude of the atmospheric carbon intercepted and stored in the form of carbonates in northwestern China is about 1.5 Tg/a[16,17].

The Xinjiang Autonomous Region is the far northwestern province of China, is a typical semi-arid to arid ecological region in the northwest China, it covers approximately 17% of the total area of China. Previous researches on the soil carbon storage in the Xinjiang region mainly focused on small spatial scales, such as farmland scale[18,19], landscape scale[6,20,21], and catchment scale[22,23]. Very few studies have quantified the SOC and SIC contents across the entire Xinjiang region. There are also previous studies that estimated the storages of SOC and SIC in Xinjiang on a national scale[17,24,25]. However, it is still unclear how carbon distribution characteristics are affected by different ecological zones in Xinjiang. A detailed study on soil carbon sequestration in Xinjiang would address a critical gap in

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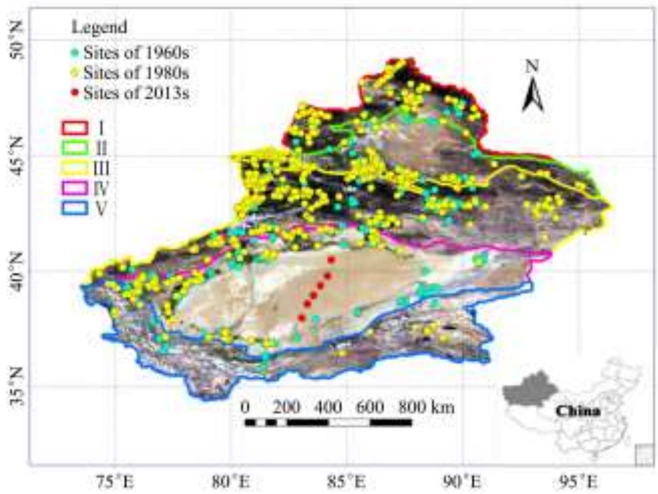
understanding the carbon cycle and climate change, suitability of agricultural land use, and associated ecosystem issues in the arid Central Asia region.

The specific objectives of this study are: (1) to analyze the spatial distributions of SOC and SIC across the entire Xinjiang region; (2) to compare SOC versus SIC contents for different Xinjiang ecological zones, and (3) to estimate the total stored SOC and SIC in the region.

2 Materials and methods

2.1 Overview of Xinjiang region and sampling

The Xinjiang Autonomous Region is located at the center (73°40′-96°23′E; 34°25′-49°10′N) of continental Asia and is the largest province in China (1.66 million km^2), accounting for about 17% of the total area of the country. The Xinjiang region stretches about 1500 km in the south to north direction and 1900 km in the east to west direction, exhibits a "two huge basins interposed by three great mountains" geomorphologic pattern[26]. The three mountain ranges are (from north to south) the Altai (north), Tianshan and Kunlun. The Tianshan range divides the Xinjiang region into two parts (Figure 1) consisting of: (1) the northern Xinjiang sub-region, which is dominated by the Junggar Basin, and (2) the southern Xinjiang sub-region, which is dominated by the Tarim Basin. As a result, the Xinjiang region exhibits a basic landscape pattern of a mountain-oasis-desert system with a diverse ecosystem[27]. In addition, the Xinjiang region has a typical continental arid climate characterized by aridness and little rain, with an average annual precipitation of 167.1 mm (239.9 mm in northern Xinjiang and only 71.0 mm in southern Xinjiang) over 1991 to 2011. The mean annual temperature is 10.0 ℃, ranging from 7.6 ℃ in the north to 12.9 ℃ in the south[28]. The vegetation coverage is only 1.68% due to the majority of the Xinjiang region being classified as desert or bare land[29,30].



Note: I: Altai/west Junggar zone, II: Junggar basin zone, III: Tianshan mountain zone, IV: Tarim basin zone, and V: Kunlun-Altun mountains zone.

Figure 1 Location of sampling points and the five ecological zones in Xinjiang, China

2.2 Ecological zoning

According to the geomorphologic features, temperature, humidity and main ecosystem types, Xinjiang could be divided into five main ecological zones[31]: (I) Altai and the west Junggar (Altai/west Junggar), (II) Junggar basin, (III) Tianshan mountain, (IV) Tarim basin, and (V) Kunlun-Altun mountains (Figure 1). The main characteristics of these ecological zones are listed in Table 1. The precipitation and temperature data from the year 1961 to 2010 were provided by the Meteorological Bureau of Xinjiang Autonomous Region, the topographic data were derived from 1:1,000,000 digital elevation model (DEM) of Xinjiang[32,33], and the main soil types were classified by the Chinese Soil Taxonomy[34].

Table 1 The main natural features of the five ecological zones in Xinjiang, China

Zones	Annual mean temperature/ ℃	Annual mean precipitation/mm	Mean altitude/m	Main soil types
I	3.25	225	1315	Isohumosols, Cambosols
II	6.48	173	663	Aridosols, Primosols
III	5.85	202	1867	Aridosols, Cambosols
IV	11.26	42	1163	Primosols, Gleyosols, Halosols
V	3.63	207	4328	Aridosols

Note: I: Altai/west Junggar zone, II: Junggar basin zone, III: Tianshan mountain zone, IV: Tarim basin zone, and V: Kunlun-Altun mountains zone.

2.3 Sources of data and methods of calculation

Existing SOC/SIC content data for the Xinjiang region were reported mainly in the first (1960s) and the second (1980s) National Soil Surveys (NSS). The 1960s survey provides SOC data for 186 soil profiles and SICS data for 191 soil profiles. In contrast, the 1980s survey reports SOC data for 437 soil profiles and SIC data for 444 soil profiles. In both NSS, soil samples were collected according to soil genetic horizons. The SIC content was determined using the gasometric method[35], while the soil organic matter (SOM) was determined using the potassium dichromate-wet combustion method[36]. The SOC content was obtained by multiplying the soil organic matter (SOM) content by 0.58, whereas the SIC content was expressed as the molar fraction (0.12) of carbon in calcium carbonate[37].

It might not be convenient to study the distribution and storage of soil carbon throughout the Xinjiang region due to a lack of additional soil surveys being performed during the same time period that the two NSS were conducted. Therefore, it is assumed that the basic spatial pattern of carbon content in the five ecological zones and the vertical carbon distribution characteristics in the 1960s did not change much from those in the 1980s. Hence the combined previously and recently collected data and comparison between the five ecological zones in the last two decades are thus regarded as reasonable, because the industrialization in the region over the two decades was not significant.

Soil profiles were taken over a depth of 0-100 cm, which is consistent with the NSS. The use of 0-100 cm soil profiles also facilitates the comparison of this work with previous literature results[26,38]. The SOC content was measured at depths of 0-10 cm, 10-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm in each soil profile using the weight method[39].

Six soil profiles were also sampled along the desert highway in Xinjiang during August 2013 (Figure 1) to complement the soil profiles obtained from the two surveys in the central desert area of the Tarim Basin. Soil samples were taken from six genetic horizons as described previously, and then air-dried, ground and passed through a 0.15 mm sieve. The SOC and SIC content were determined using the same methods as described above.

2.4 Soil carbon storage estimation

Accurate estimation of SOC storage requires reliable soil bulk density measurements. Due to the lack of complete soil bulk density data for all the soil profiles of the NSS, soil bulk density was estimated using the pedotransfer function established by Manrique and Jones[40], which provides an estimate of soil bulk density as a function of SOM by:

$$\rho = 1.66 - 0.308\sqrt{SOM \times 0.58} \quad (1)$$

where, ρ is the soil bulk density, g/cm^3; SOM is the soil organic matter, %. The soil bulk densities of different horizons were calculated using the Kriging method at all observed positions.

The mean SOC and SIC contents in the soil profile (0-100 cm) were calculated using a thickness weighted mean method[39] based on the following equations:

$$SOC = \frac{\sum_{i=1}^{n} \frac{SOM_i}{100} \times 0.58 \times T_i}{\sum_{i=1}^{n} T_i} \quad (2)$$

$$SIC = \frac{\sum_{i=1}^{n} \frac{CA_i}{100} \times 0.12 \times T_i}{\sum_{i=1}^{n} T_i} \quad (3)$$

where, SOC and SIC are the mean SOC and SIC contents (g/kg) in the soil profile (0-100 cm), respectively; T_i is the soil thickness at i_{th} horizon, cm; n is the number of soil horizons in the soil profile; SOM_i is the soil organic matter content in the i_{th} horizon, %; and CA_i is the carbonate content in the i_{th} horizon of the soil profile, %.

The soil carbon storage was mainly estimated according to the following two steps. First, the mean SOC density (SOCD) and SIC density (SICD) of each soil profile was calculated based on the organic matter and carbonate contents recorded in the national soil survey[41] as:

$$SOCD = \sum_{i=1}^{n} (1-\theta_i\%) \times \rho_i \times \frac{SOM_i}{100} \times 0.58 \times T_i \div 10 \quad (4)$$

$$SICD = \sum_{i=1}^{n} (1-\theta_i\%) \times \rho_i \times \frac{CA_i}{100} \times 0.58 \times T_i \div 10 \quad (5)$$

where, $SOCD$ is the SOC density in the soil profile, kg/m^2; $SICD$ is the SIC density in the soil profile, kg/m^2; θ_i is the gravel (>2 mm) content in the i_{th} horizon, %; ρ_i is the bulk density in the i_{th} horizon, g/cm^3; SOM_i is the SOM content in the i_{th} horizon, %; CA_i is the carbonate content in the i_{th} horizon of the soil profile, %; T_i is the soil thickness in the i_{th} horizon, cm; n is the number of soil horizons in the soil profile, and the factor 10 is a conversion from g/cm^2 to kg/m^2.

Second, the mean SOCD and SICD for each ecological zone were calculated using polygon areas in a Xinjiang 1:1,000,000 soil type map from the Second NSS according to Equations (6) and (7):

$$SOCS = \sum_{j=1}^{m} area_j \times SOCD_j \quad (6)$$

$$SICS = \sum_{j=1}^{m} area_j \times SICD_j \quad (7)$$

where, m is the number of ecological zone types; $SOCD_j$ is the SOC density (kg/m^2) over a 1 m-soil depth in the j_{th} ecological zone; $SICD_j$ is the mean SIC density (kg/m^2) over the 1 m soil depth in the j_{th} ecological zone; $area_j$ is the area of the j_{th} soil type in Xinjiang, m^2; and SOCS and SICS represent the SOC storage and SIC storage (kg), respectively.

All data were analyzed using a SPSS software package. Multiple comparisons and analysis of variance (ANOVA) were used to determine the significance of differences among different ecological zones and different horizons[42]. An effect is considered significant at $p \leq 0.05$.

3 Results

3.1 SOC and SIC contents and their distribution characteristics

The SOC and SIC contents in various soil profile horizons for different Xinjiang ecological zones are shown in Table 2. The maximum SOC content occurred in or near the surface horizon (0-10 cm or 10-20 cm) of each profile in all ecological zones. However, the maximum SIC content occurred at a depth of ≥60 cm below the surface (Table 2). The minimum SOC content in the soil profile of all the ecological zones was zero in a horizon deeper than 40 cm, and zones III and IV have shown zeroes at all horizons. However, the minimum SOC content in the surface horizon of Kunlun-Altun mountains zone was higher than those in other ecological zones. The mean and median SOC contents decrease gradually with increasing depth in different ecological zones, however, the mean and median SIC contents first increased with increasing depth to the depth of 20-40 cm or 40-60 cm and then decreased with deeper horizons.

Based on the coefficient of variation (CV), the variation of soil properties can be divided into three categories: weak variation (CV < 0.1), moderate variation (CV = 0.1-1) and strong variation (CV > 1) [43] . As shown in Table 2, the SOC CVs within 0-100 cm depths are almost all greater than 1 in all five ecological zones, indicating a high level of variability. However, the SIC CVs are only >1 in all horizons in the Altai/west Junggar zone, the bottom horizon (60-100 cm) of the Junggar basin and Kunlun-Altun mountains zones, and between 0.36 and 1 in all of the horizons for the other ecological zones, suggesting a more moderate degree of variability.

Figure 2 shows the spatial distributions of the mean SOC and SIC contents in the 0-100 cm soil profile across the Xinjiang region. The SOC content in the profile is high in the Altai/west Junggar and Tianshan mountain zones, with a mean content of 20-120 g/kg, but relatively low in the Junggar basin, Tarim basin and Kunlun-Altun mountains zones, with a mean content below 20 g/kg. In addition, the SOC content is greater in the mountainous areas compared to the basin sub-regions except Kunlun-Altun Mountains where SOC was quite low, and decreases gradually from northwest to southeast and from mountainous areas to desert conditions. The SIC content is high in southwestern Xinjiang with a mean content of 20-60 g/kg, versus lower levels in the northern Xinjiang sub-region with a mean content of below 10 g/kg. The SIC levels show a gradual decreasing trend from south to north within the Xinjiang region.

3.2 Vertical distribution characteristics of SOC density in different ecological zones

Figure 3 shows the vertical distribution of SOC density in the soil profile in Xinjiang. The SOC densities in all of the horizons of the different ecological zones are generally within 0-4 kg/m^2, with frequencies of occurrence over 60% and the maximum frequency in the horizon of 10-20 cm. At different ecological zones, more than 80% of the soils at the 60-100 cm depth have a SOC density ranging at 0-3 kg/m^2, indicating a lower SOC density in the bottom soil than that in the surface soil (Figure 4).

At different ecological zones, the SOC density in the subsoil (10-20 cm) is lower than that in the topsoil (0-10 cm). The SOC has the highest value in the horizon of 20-40 cm, gradually decreasing with depth to above 40 cm below the surface (Figure 4). In addition, the SOC densities in Altai/west Junggar zone and the Tianshan mountain zone are higher than that in other ecological zones, showing a significant difference from that in the surface soil. The SOC density in the depth of 20-100 cm shows a significant higher value in the Tianshan mountain zone than in the other ecological zones; the SOC density in the depth of 0-80 cm in the Tarim basin zone is lower than that in the other ecological zones (Figure 4). Furthermore, the frequencies of occurrence of the low SOC density (0-3 kg/m^2) over 60% are mainly in the Junggar basin and Tarim basin zones (Figure 3).

Table 2 Statistics of SOC and SIC in soil profiles (0-100 cm) of the five ecological zones in Xinjiang, China

Zones	Depth/cm	No. of samples		Minimum/g·kg^{-1}		Maximum/g·kg^{-1}		Mean/g·kg^{-1}		Median/g·kg^{-1}		Std/g·kg^{-1}		CV	
		SOC	SIC	SOC	SIC	SOC	SIC	SOC	SIC	SOC	SIC	SOC	SIC	SOC	SIC
I	0-10	78	75	1.89	0.00	252.76	32.23	42.44	3.76	13.85	1.30	59.09	5.66	1.39	1.50
	10-20	78	75	1.39	0.00	106.14	36.24	17.99	4.48	10.70	2.34	19.75	6.11	1.10	1.37
	20-40	78	75	0.24	0.00	65.83	43.15	11.41	6.72	8.19	4.44	12.07	8.10	1.06	1.21
	40-60	78	75	0.00	0.00	39.73	45.31	6.80	8.87	4.74	6.06	8.37	9.43	1.23	1.06
	60-80	78	75	0.00	0.00	46.52	59.88	3.90	7.87	2.84	2.31	6.74	11.04	1.73	1.40
	80-100	78	75	0.00	0.00	12.82	53.04	1.52	5.73	0.00	0.19	2.40	9.36	1.58	1.63
II	0-10	126	127	0.87	0.85	104.36	41.39	9.59	9.96	5.78	9.24	12.60	5.57	1.31	0.56
	10-20	126	127	0.23	0.85	38.34	50.84	7.80	10.20	5.12	9.53	7.96	6.69	1.02	0.66
	20-40	126	127	0.00	0.88	27.65	58.01	5.89	10.39	3.95	9.62	5.59	7.83	0.95	0.75
	40-60	126	127	0.00	0.00	26.27	74.97	4.22	10.23	2.73	8.88	4.53	9.56	1.07	0.93
	60-80	126	127	0.00	0.00	22.46	75.91	3.02	8.96	1.83	8.45	3.78	9.52	1.25	1.06
	80-100	126	127	0.00	0.00	12.47	60.76	2.10	7.48	1.19	7.29	2.80	8.79	1.34	1.18
III	0-10	229	238	0.00	0.00	249.92	31.36	30.19	9.92	12.47	9.44	40.08	7.78	1.33	0.78
	10-20	229	238	0.00	0.00	249.92	35.40	24.26	10.33	12.12	9.68	30.83	7.95	1.27	0.77
	20-40	229	238	0.00	0.00	146.17	42.51	15.57	12.48	8.74	12.08	19.54	8.66	1.25	0.69
	40-60	229	238	0.00	0.00	148.31	40.08	9.99	13.51	5.68	13.04	14.46	9.05	1.45	0.67
	60-80	229	238	0.00	0.00	69.85	91.45	6.62	14.61	4.23	14.83	9.64	10.97	1.46	0.75
	80-100	229	238	0.00	0.00	61.78	91.45	3.80	12.78	2.20	12.95	6.23	11.46	1.64	0.90
IV	0-10	173	179	0.00	0.00	75.41	44.71	7.82	16.41	5.32	16.44	9.85	6.87	1.26	0.42
	10-20	173	179	0.00	0.37	76.26	42.69	6.53	17.05	4.70	16.81	8.98	6.92	1.37	0.41
	20-40	173	179	0.00	0.22	73.43	41.62	4.85	17.97	3.61	17.88	7.75	6.64	1.60	0.37
	40-60	173	179	0.00	0.00	32.77	40.14	3.31	17.70	2.61	18.05	4.45	7.50	1.35	0.42
	60-80	173	179	0.00	0.00	19.60	38.39	2.36	16.55	1.94	17.47	2.95	8.13	1.25	0.49
	80-100	173	179	0.00	0.00	20.74	51.99	1.85	15.38	1.02	16.92	2.80	9.17	1.52	0.60
V	0-10	23	22	2.02	4.82	64.38	24.71	12.58	15.50	8.50	16.19	14.29	5.54	1.14	0.36
	10-20	23	22	1.71	6.12	67.89	24.04	11.12	15.69	7.80	16.51	14.14	5.73	1.27	0.37
	20-40	23	22	0.00	5.52	61.67	29.24	8.37	16.59	5.41	17.25	12.35	5.97	1.48	0.36
	40-60	23	22	0.00	0.00	32.48	26.72	4.95	13.85	4.47	16.16	6.57	7.34	1.33	0.53
	60-80	23	22	0.00	0.00	22.97	32.62	2.72	11.57	1.04	10.55	4.92	9.26	1.81	0.80
	80-100	23	22	0.00	0.00	10.09	38.52	1.53	8.87	0.00	4.57	2.64	10.68	1.73	1.20

Note: I: Altai/ west Junggar zone, II: Junggar basin zone, III: Tianshan mountain zone, IV: Tarim basin zone, and V: Kunlun-Altun mountains zone. Minimum, maximum, mean and median in the table all refers to the values at specific horizons within a specific ecological zones.

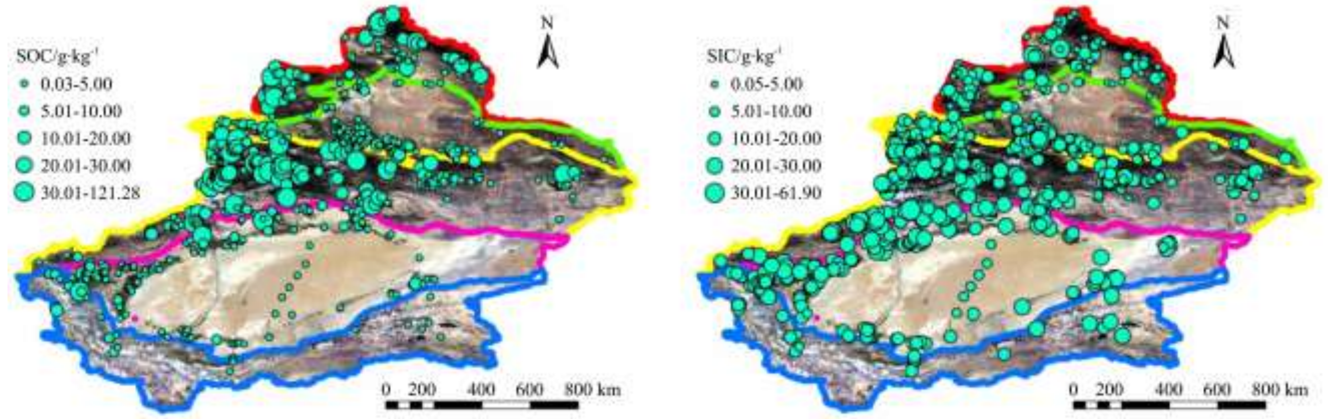
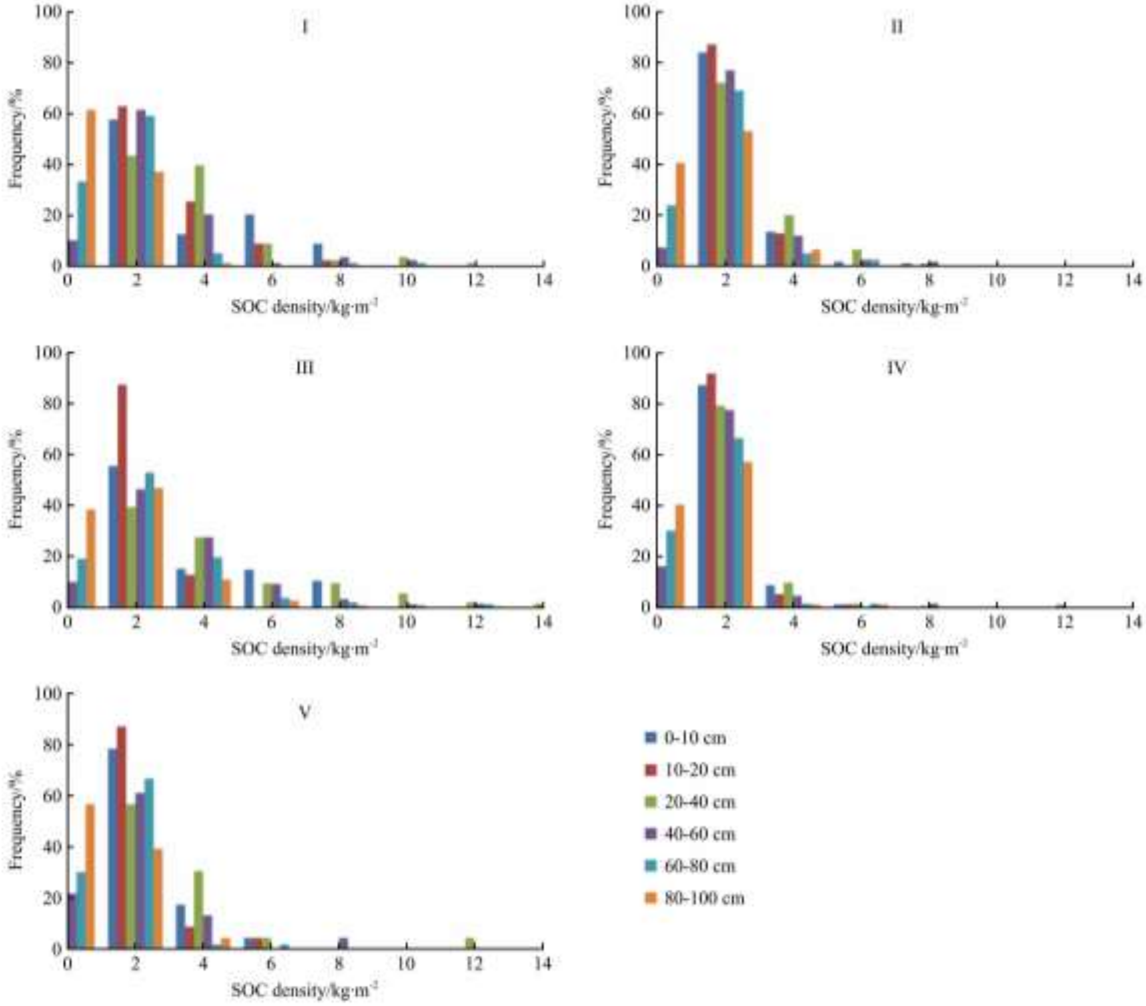
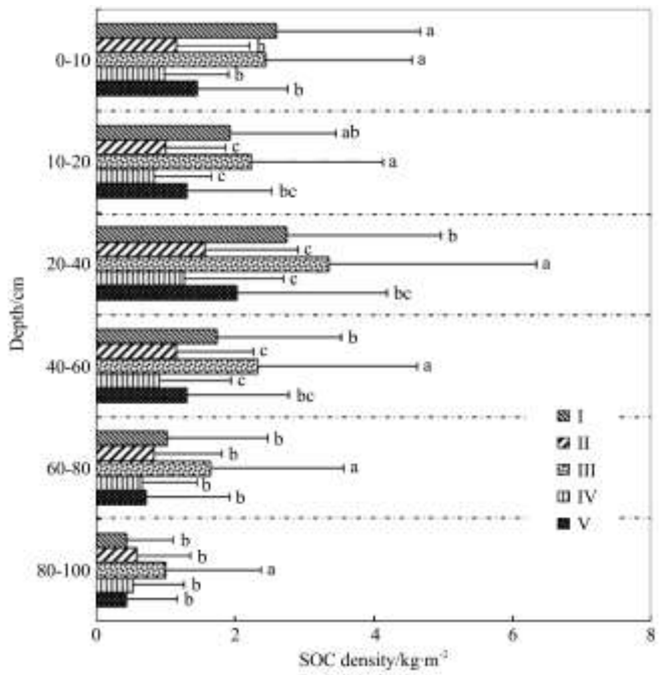


Figure 2 Spatial distributions of SOC and SIC average contents for 0-100 cm soil profiles in Xinjiang, China



Note: I: Altai/west Junggar zone, II: Junggar basin zone, III: Tianshan mountain zone, IV: Tarim basin zone, and V: Kunlun-Altun mountains zone.

Figure 3 Histograms of SOC density for soil profiles (0-100 cm) located in five ecological zones in Xinjiang, China



Note: I: Altai/west Junggar zone, II: Junggar basin zone, III: Tianshan mountain zone, IV: Tarim basin zone, and V: Kunlun-Altun mountains zone. The different lower case letters within the same depth indicates significant difference at $p<0.05$.

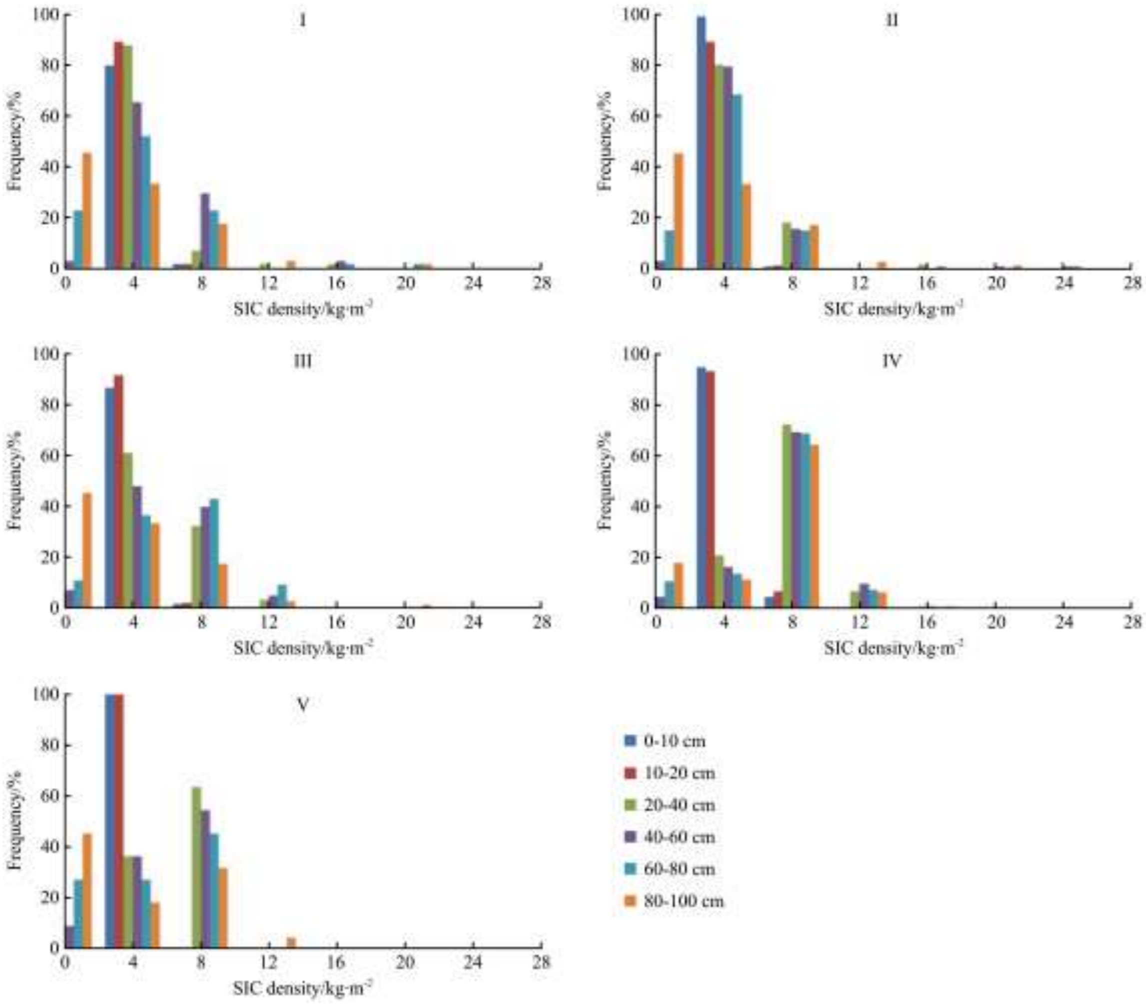
Figure 4 Vertical distribution of SOC density for soil profiles (0-100 cm) located in five ecological zones in Xinjiang, China

3.3 Vertical distribution characteristics of SIC density in different ecological zones

Figure 5 shows the vertical distribution of SIC density in all of the horizons for each of the ecological zones. The frequency of SIC density below 4 kg/m^2 is over 80%, and approaches 100% in the Tarim basin and Kunlun-Altun mountains zones. In contrast, the frequency of SIC density that exceeds 8 kg/m^2 in the bottom horizon is over 20%, indicating a relatively low SIC density in the surface soil and a high SIC density near the bottom of the soil profile for the different ecological zones. This is consistent with the vertical SIC distribution pattern shown in Figure 6. The SIC density in all of the ecological zones generally exhibits an increasing trend firstly in the upper soil horizons, followed by a peak and then a decrease in the lower soil horizons (Figure 6). The inflexion points of the SIC density occurs in the horizons of 40-60 cm and 60-80 cm in Altai/west Junggar zone and Tianshan mountain zone, respectively, and is deeper in other ecological zones. The SIC density lies mainly in the range of 2-6 kg/m^2, with a few in the range of 7-9 kg/m^2 for the Tarim Basin zone (Figures 5 and 6). The frequency of the SIC density of 7-9 kg/m^2 is around 40%-60% (Figure 6).

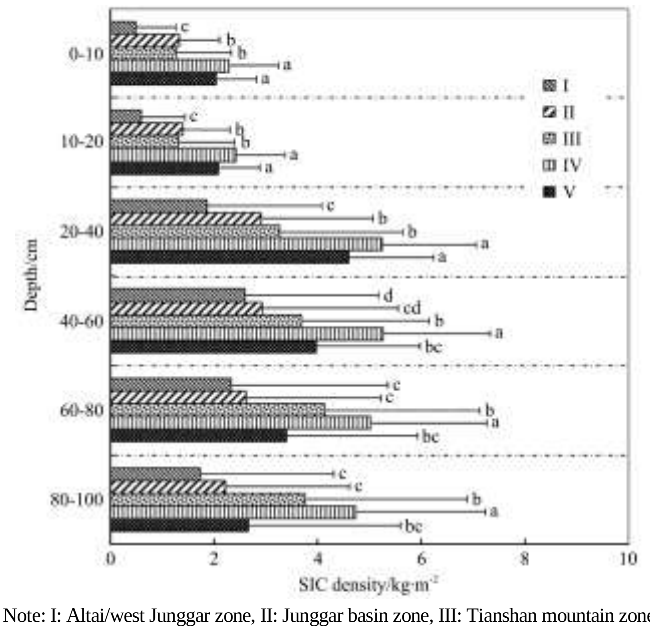
The vertical distribution of the SIC density consistently differs from that of the SOC density (Figure 6) in different ecological zones. The SIC density in the Tarim basin zone is higher than that in other ecological zones, becoming significant at a depth over 40 cm. The SIC density is also significantly higher at the 0-

100 cm depth in the Tarim basin zone than that in the Juggar basin zone−a desert zone. These results indicate that the soil in Tarim basin zone, especially at the 20-100 cm depth, has the largest contribution to the SIC pool in Xinjiang.



Note: I: Altai/west Junggar zone, II: Junggar basin zone, III: Tianshan mountain zone, IV: Tarim basin zone, and V: Kunlun-Altun mountains zone.

Figure 5 Histograms of SIC density for soil profiles (0-100 cm) located in five ecological zones in Xinjiang, China



Note: I: Altai/west Junggar zone, II: Junggar basin zone, III: Tianshan mountain zone, IV: Tarim basin zone, and V: Kunlun-Altun mountains zone. The different lower case letters within the same depth indicates significantly different at $p<0.05$.

Figure 6 Vertical distribution of SIC density for soil profiles (0-100 cm) located in five ecological zones in Xinjiang, China

3.4 Soil carbon storages in different ecological zones

The distributions of the SOC and SIC storages (Table 3) were obtained through statistical analysis according to the polygon areas of each soil type (excluding glaciers with snow cover, rivers, and lakes, as well as oases and islands in rivers and lakes) in different ecological zones, taking into account their mean SOC and SIC densities in the soil profiles. The results indicate that the SOC and SIC storages for the entire Xinjiang region in the 100 cm soil profile are 11.74 Pg and 26.71 Pg, respectively, accounting respectively for 14.01% of the total SOC storage (83.8 Pg) and 34.29% of the total SIC storage (77.9 Pg) in China[17] (Table 4). The SOC stocks in the five ecological zones are ranked in descending order as Tianshan mountain, Tarim basin, Kunlun-Altun mountains, Altai/west Junggar, and Junggar basin. The SIC stocks are ranked for the zones in descending order as Tarim basin, Tianshan mountain, Kunlun-Altun mountains, Junggar basin, and Altai/west Junggar. In the Kunlun-Altun mountains, Juggar basin and Tarim basin zones, the SIC stocks are 2.34, 2.64 and 3.54 times greater than the respective SOC stocks. The differences between the SOC stocks and the SIC stocks in Altai/west Junggar and Tianshan mountain zones are both insignificant.

Table 3 The SOC and SIC storages of the five ecological zones in Xinjiang, China

Zones	Area /×10^5 km^2	Percentage of total area /%	SOC /Pg	Percentage of total SOC/%	SIC /Pg	Percentage of total SIC /%
I	1.31	8.11	1.55±0.94	13.20	1.88±1.36	7.04
II	1.89	11.68	1.02±0.83	8.69	2.70±1.65	10.11
III	4.37	26.98	4.19±2.26	35.69	6.99±4.50	26.17
IV	5.58	34.48	2.90±1.64	24.70	10.27±5.83	38.45
V	3.04	18.76	2.08±1.15	17.72	4.87±1.57	18.23
Total	16.20	100.00	11.74	100.00	26.71	100.00

Note: I: Altai/ west Junggar zone, II: Junggar basin zone, III: Tianshan mountain zone, IV: Tarim basin zone, and V: Kunlun-Altun mountains zone.

Table 4 Summary of previous estimates of SOC and SIC stocks in Xinjiang

Cited studies	SOC stocks /Pg	SIC stocks /Pg	Type of study
Pan and Guo[16]			Analyses of soils in northwest China
Li et al.[17]	8.5	19.76	National survey of China
Xie et al.[24]	8.6	-	National survey of China
Yu et al.[25]	11.6	-	National survey of China

4 Discussion

4.1 Influencing factors of the SOC density

The SOC densities measured across the Xinjiang region in the bottom horizons (60-100 cm) are relatively low compared with the SOC levels in the surface horizons (Figure 3), which is consistent with the vertical SOC profiles measured in other regions of the globe[44-46]. The SOC density in different ecological zones exhibits a gradually decreasing trend, starting at depths below 20-40 cm horizon (Figure 4). This is consistent with the vertical distribution of SOC in different landscape patterns in Xinjiang reported by Wang[20]. Previous results show that the vertical distribution of SOC is mainly affected by leaching[47], microbial activity[20], and mechanical soil disturbance[48]. The horizontal distribution characteristics of the SOC on the global scale is primarily affected by climate factors, but the vertical distribution of the SOC in the soil profile varies significantly with vegetation type[49]. The SOC pool is influenced significantly by the rainfall and temperature[50], and the SOC in natural ecosystems decreases exponentially with increasing temperature. In this study, the ecosystems of the Altai/west Junggar and Tianshan mountain zones are characterized by: (1) an annual rainfall of 300-400 mm, (2) mountainous steppe, meadow and forest, (3) relatively high vegetation coverage, and (4) a large input of organic matter. There are two major deserts, i.e., the Gurbantunggut desert and the Taklimakan desert, distributed across the Junggar and the Tarim basin zones, which have a temperate–warm temperate desert climate, with perennial aridness, little rainfall (annual rainfall below 100 mm), high soil surface evaporation (mean annual precipitation is 2000-4000 mm), sparse surface vegetation coverage, and a relatively little accumulated organic matter, leading to a relatively low SOC density. In addition, the land use, the land cover changes (LUCC) and other human activities also affect the spatial and vertical distribution of the SOC[19,51].

The Altai/west Junggar, Tianshan mountain and Kunlun-Altun mountains zones are located at the margins of the Junggar and the Tarim Basins, with a relatively high altitude. Post has shown that with an increase in the altitude, the temperature decreases gradually, leading to a gradual increasing trend in the SOC content[52]. This is considered to be the reason that SOC contents are high in these high altitude areas. In addition, the clay content in the soil is regarded as another important factor influencing SOC accumulation[45,46,53]. The clay contents in the Altai/west Junggar and Tianshan mountain zones are obviously higher than that in the Juggar and Tarim basin zone, resulting in similar SOC content variation trends (Table 1). The SOC for fine textured soils is higher than soils with a coarse texture, because finely grained soils can be easily aggregated to protect the SOC from decomposition[54]. In the Kunlun-Altun mountains zone, the SOC density decreases with increasing soil depth below 40 cm, which is consistent with the observations in other alpine cold regions[55,56]. Although the studies also show that deep-seated carbon pools are generally stable and would not respond to climate change, some management practices, such as cultivation operations and the use of drought resistant crops with a large root systems, may increase fresh carbon in the soil profile, which should be avoided as all of them would stimulate the loss of such ancient and buried underground carbon[57].

4.2 Influencing factors of the SIC density

Pan and Zhang reported that the mean carbonate content in the arid soil of the northwest China was 100 g/kg, and if carbonate was converted into SIC, the mean SIC content would be about 12 g/kg[16,58]. In this study, the mean SIC contents in Tarim basin zone, which are the main zones with arid soils distribution, were found to be 15.39-17.95 g/kg, slightly higher than that of the above mentioned studies. Mi et al.[37] analyzed the distribution patterns of the SIC storage across all of China and pointed out that in the western China, with a mean annual rainfall below 200 mm, the $CaCO_3$ content was generally around 40-90 g/kg. They further stated that if the $CaCO_3$ was converted into SIC, the SIC content would be roughly 4.8-10.8 g/kg, which agreed with our estimates of 7.48-10.39 g/kg in the Junggar basin zone.

The SIC density is relatively low in the surface soil, but relatively high in the bottom soil (Figures 5 and 6). In general, a relative decalcification phenomenon exists in the near-surface soil, and carbonate solution migrates downwards and deposits gradually[59], forming a feature that the SIC content is relatively low in the surface layer but higher in the deeper layers (Figure 6). In the 0-100 cm profile, the SIC density decreases gradually over the 40-100 cm depth range in all of the ecological zones except for the Tianshan mountain zone, in which is consistent with previous studies[27,60]. Because the Altai/west Junggar and Tianshan mountain zones have a humid climate, higher rainfall, a relatively high vegetation coverage, intense carbonate dissolution and leaching coefficient in the soil profile, the SIC deposits constantly increase with increasing soil depth. Lal proposed significant effect of vegetation and microbial activity on water infiltration, and subsequently changes to the SIC leaching status and secondary carbonate deposition[61]. The vertical distribution of the SIC is also regarded to be complex due to the effect of leaching process[62], with the carbonate being almost completely leached due to the combined effect of strong rainfall and intense biological activities[20].

Previous studies have revealed that the soil water content status was the basis of $CaCO_3$ deposition. On the one hand, the fluidity of water provides leaching power (decalcification) for the upper soil horizon; on the other hand, water is also an important component participating in the calcium carbonate deposition process or calcium deposition[63]. Precise water content in arid regions is favorable for the formation of $CaCO_3$. This explains why the SIC content in oasis soil of arid regions is higher than that in desert regions (Figure 2). The inflection points of the SIC density change in the soil profile are mostly concentrated in the two horizons of 20-40 cm and 40-60 cm, except for 60-80 cm for Tarim Basin zone, possibly due to the carbon generated from the decomposition of the organic residuals of surface arid soils in the Xinjiang region, which serve as a catalyst in the formation of the newly deposited calcite. The soil water in the horizon of 30-60 cm decreases extremely fast, and the crystallization of calcite is relatively active, promoting the transfer of SOC[16,58] and the formation of SIC. In addition, changes in the SOC could influence the SIC composition[37,64]. For example, dissolvable organic carbon can increase the SOC content in the surface soil, and hence suppress the deposition of carbonate[65]. Therefore, the SOC content is relatively high (Figure 4) and the SIC content is relatively low (Figure 6) in the surface horizons (0-20 cm) that were analyzed in this study.

4.3 Influencing factors of the SOC and SIC storage

Table 3 shows that the total soil carbon pool (0-100 cm) in the Xinjiang region is 38.45 Pg, accounting for about 23.78% of the soil carbon pool in China[17], and the SIC storage in Xinjiang is about 2.28 times of the SOC storage. Therefore, the SIC storage in Xinjiang is large and its effect on the regional carbon cycle should not be neglected. The giant SIC storage pool could play an important role in alleviating climate change and subsequent global environment change[66,67]. A recent study has demonstrated that the SIC dynamics may be even more important than that of the SOC within the terrestrial region[68]. In this study, the SIC storage in arid soils is about 2.64-3.54 times greater than the SOC storage, which is consistent with previous reported results[16,17]. However, the SIC storage is more than 2 times the SOC storage in Kunlun-Altun mountains zone, suggesting that the composition of the SOC pool in this cold alpine region is similar to that in the arid region, which requires the further investigation. The SOC and SIC data were obtained from the first and second National Soil Survey in China. The sample numbers for this study are larger than those reported in previous researches[16,17]. However, the methods used in this study for estimating the SOC and SIC stocks are similar to the methods used by Wu[69]. The SOC and SIC data used in this study might have been obtained from different sampling sites, considering that these data were collected from two different periods. Thus, there are some uncertainty remains regarding the estimation of the SOC and SIC stocks in the Xinjiang region.

The horizontal and vertical distributions of the SOC and SIC can be affected significantly by natural factors such as topography, vegetation and climate, because the Xinjiang region covers a vast area. A previous study showed that SOC was significantly correlated to elevation, slope, compound topographic index, normalized difference vegetation index (NDVI), average annual precipitation, mean annual temperature and evapotranspiration ($p<$ 0.01), but was not correlated to factors such as aspect, plan curvature and profile curvature ($p>$ 0.05)[70]. Yan also found that SIC was significantly correlated to slope, average annual precipitation, mean annual temperature, evapotranspiration and land use comprehensive index ($p<$ 0.01), but not to the aspect, plan curvature, profile curvature, compound topographic index and NDVI[70]. Thus, SOC and SIC were both significantly correlated to slope, annual average rainfall, average temperature and evapotranspiration.

4.4 Dynamic changes of SOC and SIC stocks over time

Soil organic and inorganic carbon stocks will change over time in response to natural conditions and human activities. Reeder reported that in the short grass steppe of the northeastern Colorado, long-term heavy grazing (56 years) resulted in 7.5 Mg/ha more SOC stock relative to the long-term non-grazed treatment, and heavy grazing affected SIC levels more than the SOC stocks[71]. In semiarid regions, the results from three long-term (>20 years) no-till experiments suggested that differences in precipitation input among soils appeared to be the dominant factor influencing no-till impacts on the SOC stock[72]. Li found that exploitation of oases significantly reduced SOC stocks over 25 years in arid regions of central Asia, and that the rate of SOC stock decrease was correlated to the length of exploitation[19]. Grassland restored for 12 years and 20 years was reported to significantly reduce the SIC stock in the surface soil in Ningxia, a region located in north central China[73]. Thus, time and other factors (vegetation, parent, topography and human activities) commonly influence change in SOC and SIC stocks.

5 Conclusions

Distribution and storage of soil organic (SOC) and inorganic carbon (SIC) across five different ecological zones in the Xinjiang Autonomous Region of China was explored in this study. The spatial distribution of the SOC content in the region showed a gradual decreasing trend from northwest to southeast and from mountainous to desert zones, while the SIC content decreased gradually from south to north. In general, the SOC content decreases with increasing soil depth except for that at the 10-20 cm horizon, which is lower than that at the 20-40 cm horizon.

The SOC densities in the Altai/west Junggar and Tianshan mountain zones are relatively high compared with those in the other ecological zones. The SOC density within the 20 to 100 cm horizons of the Tianshan mountain zone is the largest SOC pool in the Xinjiang region. In contrast, the SIC content increases with increasing soil depth except for the Tianshan mountain zone. The SIC density in the Tarim basin zone is greater than that found for the other ecological zones, particularly at a depth deeper than 60 cm, which is the largest SIC pool in the Xinjiang region. The total Xinjiang region SOC pool (0-100 cm) is 38.45 Pg, accounting for about 23.8% of the total SOC pool in China. The Xinjiang region SOC and SIC stocks are 11.74 Pg and 26.71 Pg in the 100 cm soil profile, respectively. These results enhance the understanding of the SOC and SIC storages in the arid regions of northwest China and in the overall central Asia region.

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