

# Urban expanding pattern and soil organic, inorganic carbon distribution in Shanghai, China

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**Abstract** Soil carbon stock changes induced by land-use change play an essential role in the global greenhouse effect and carbon circulation. This paper studies the urban expanding patterns and spatial characteristics of soil organic carbon (SOC) and soil inorganic carbon (SIC) distribution and evolution during the urbanization process of Shanghai, China, based on the data of the regional geochemical survey. Urbanization process in Shanghai, China, has been quickening greatly since the 1980s. The urban area expanded from 193.08 km<sup>2</sup> in 1980 to 1,570.52 km<sup>2</sup> in 2005, or up from 3.05 to 24.77% in the past 25 years, and the urban expansion circled the central city region according to the RS images acquired in the periods of 1980, 2000 and 2005. The urban topsoil is slightly enriched with SOC and SIC, which shows obvious spatial variability. By comparison of SOC and SIC distribution in the central urban area, urbanized area during 1980–2000, 2000–2005 and the suburban area, the SOC obviously accumulates in the central urban area, while SOC density in the urbanized area decreases; similarly, the SIC obviously accumulates in central urban area; furthermore, the SIC density increases with urban land use duration extending and urban ecosystem evolving. This paper provides the characteristics of SOC and SIC distribution and evolution during the course of urbanization, which may be useful for assessing the impact of land use and urban development on SOC and SIC pools in urban ecosystem.

**Keywords** Urban expanding pattern · Soil organic carbon · Soil inorganic carbon · Shanghai, China

## Introduction

Soil carbon stock, including soil organic carbon (SOC) and soil inorganic carbon (SIC) stock, is the largest carbon pool in the terrestrial ecosystem (IPCC 2001; Janzen 2004). Soil carbon stock changes induced by land-use changes play an essential role in the global greenhouse effect and carbon circulation. Globally, net cumulative losses of carbon from soils due to land-use change amounted to about 156 Pg from 1850 to 2000, accounting for 1/3 of anthropogenic emissions, which significantly contributes to the sudden increase in atmospheric CO<sub>2</sub> (Feller and Bernoux 2008; Hutchinson et al. 2007; Janzen 2004). Because of past massive loss of carbon from soils, in theory, this may mean substantive potential to sequester atmospheric CO<sub>2</sub>; thus, soil carbon sequestration is believed to be one of the cost-effective ways to mitigate CO<sub>2</sub> increase and the global greenhouse effect (Janzen 2004).

Urbanization process is an inevitable trend in social and economic development, and urban area has enlarged rapidly in the world, which means urban soils play an increasingly important role in the global carbon circulation. Urbanized territories as a specific component and carbon circulation in urban soils are significantly different from that in natural soils, which is strongly influenced by land use and management activity (Anastasia et al. 2004). The conversion of nature land to urban land leads to changes of soil property, collapse of soil structure and transition of ecosystem type, which may result in soil carbon storage increase or decrease (Anastasia et al. 2004; Pouyat et al.

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2002; Terumasa et al. 2008). Globally, studies on carbon circle in urban soils focus on SOC, and little attention has been paid to SIC (Anastasia et al. 2004; Pouyat et al. 2002; Su et al. 2006; Terumasa et al. 2008). SIC storage changes induced by human activity and climate change are coupled with the global greenhouse effect and carbon circle, which means that it is indispensable to carry out research of SIC (Singh et al. 2007).

China, the largest developing country in the world, has undergone intense land-use changes, evident transition in land structure, and rapid urban expansion since the 1980s (Li et al. 2007; Liu et al. 2002). The total loss of SOC and SIC in China was approximately 7.1 and 1.6 Pg due to extensive land-use changes (Wu et al. 2003, 2009). Overall, studies on SOC distribution and evolution in China are mostly limited to agriculture and forestry soils (Fang et al. 2001; Huang and Sun 2006; Liao et al. 2009; Pan et al. 2003; Zhang et al. 2007); only a minority of the studies on urban surface soils have been carried out, whose results are simple and shallow due to limited sample number (Su et al. 2006; Wang et al. 2009; Zhang and Zhou 2006). This paper conducts research on SOC and SIC distribution and evolution in Shanghai, the typical urbanized metropolitan in China, based on the massive data from regional geochemical survey. The study of SOC and SIC spatial distribution in urbanized territories extends to deep soil profile than any previous research, and research of SIC stock is a new contribution to urban soil also, which may be useful for assessing the impact of land-use and urban development on SOC and SIC pools in urban ecosystem.

## Materials and methods

### Study site

Shanghai, the largest economic city in China, extends between 30°41'–31°50' N latitude and 120°51'–121°45' E longitude with a total area of 6,340.50 km<sup>2</sup>, in the east of Chinese Mainland. The climate of this region is generally described as subtropical monsoon with warm and humid climate. Monthly temperature ranges from 2.0 to 3.5°C in January to 26–28°C in July, with mean annual temperature 14–17°C, respectively (She and Luo 2007). Rainfall is also highly seasonal, with mean annual total of 1,000–1,500 mm, about 60–70% falling in spring and summer (She and Luo 2007). The major soil types in this region include paddy soil, tidal soil, yellow brown soil and coastal saline soil. Shanghai, with the highest urbanization level and land use intensity in China, has undergone rapid urban land expansion since the 1980s (Liu et al. 2002). With urban area expanding rapidly, vegetation types, soil ecological

environment and soil management have changed, which may influence SOC and SIC pools.

### Data sources

Remote sensing, as an advanced earth-observing satellite technology with spatial-temporal continuous coverage, is a shortcut way to acquire information of land-use pattern. This paper studies the urban expanding patterns in Shanghai based on the RS images. The landsat MSS, ETM and China–Brazil earth resources satellite CCD images, which were, respectively, acquired in three periods of 1980, 2000 and 2005 were used to extract urban land-use information. The interpreting key system is established by discriminatory mark in RS images by the aid of field survey, and the identifications of interpretation urban territories are designed based on the image characters.

The soil database consisted of 2,228 field data compiled from regional geochemical surveys during 2004–2005 in Shanghai. Topsoil (0–20 cm) sampling evenly distributed in study area with a sampling density of one sample in a 2 km × 2 km grid, and all samples adding up to 1,801. Deep soil (160–180 cm) sampling evenly distributed with a sampling density of one sample in a 4 km × 4 km grid, and all samples adding up to 427. If the sample point fell on a impervious areas (roads or buildings), it was moved to a nearby open space (park or garden).

SOC contents are determined by potassium dichromate-volumetric method and soil total carbon contents are determined by X ray fluorescence spectrometry analysis, both of which have detection limit of 0.1%. SIC contents are equal to the value of soil total carbon contents minus the corresponding SOC contents. Statistical analysis of the data was done using ARCGIS9.2 and SPSS13.0.

### Methods

#### Calculation of SOC and SIC density

SOC or SIC density of a specific soil unit (SOCD<sub>*i*</sub>, kg m<sup>-2</sup>) including several pedogenic layers is calculated from SOC or SIC content (*C<sub>i</sub>*, g kg<sup>-1</sup>) and bulk density (*ρ<sub>i</sub>*, g cm<sup>-3</sup>) as follows:

$$\text{SOCD}_i = \sum_{i=1}^n (1 - \theta_i\%) \times \rho_i \times C_i \times D_i / 100$$

where *i* stands for the *i*th pedogenic horizons, *n* corresponds to total number of horizons, *D<sub>i</sub>* and *θ<sub>i</sub>* % are the thickness (cm) and volumetric proportion of the fraction (>2 mm) in pedogenic layer *i*, respectively. The thickness of topsoil layer and deep soil layer in this study are both 20 cm.

The soil bulk density was estimated using the regression equation with the SOC content from Xu et al. (2011) as follows:

$$\rho(x) = 1.564 \times e^{-0.085 \times X}$$

where  $\rho(x)$  represents estimated bulk density ( $\text{g cm}^{-3}$ ),  $X$  represents soil organic matter content (%).

*Access to SOC and SIC attributes*

Land use in countryside is mainly for agricultural purposes, such as cultivation land, garden land, forestry land, etc., while land use in urban area is mostly for construction uses, such as commercial use, public building use, residential use, etc. The suburban area is defined as the region around urban area, and the land use in suburban area is both for agriculture and construction. The urbanized territories are mainly transformed from agricultural land.

In order to indicate the characteristics of SOC and SIC distribution and evolution in urban area, we divide the territory into three regions according to urbanized period, which are the central urban area and urbanized area during 1980–2000 and 2000–2005, respectively. The central urban area is urbanized before the year 1980, and the urbanized areas are urbanized territories during the period of 1980–2000 and 2000–2005.

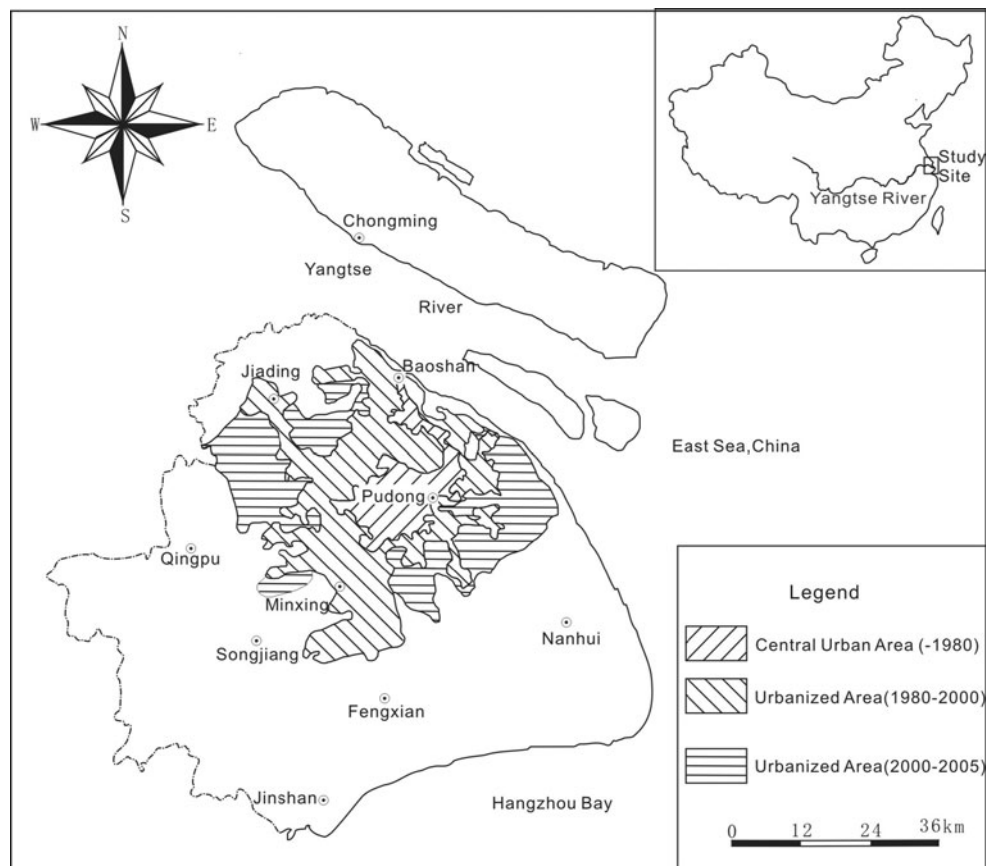
SOC or SIC attributes are the field data including the content, density, bulk density, etc. SOC and SIC attributes in urban, suburban, and countryside area are obtained by spatial overlay analysis between field data and RS interpretation images supported by ARCGIS9.2, which make SOC and SIC status assigned to corresponding land-use patterns. Similarly, we acquired the field data in the central urban area, urbanized area during 1980–2000 and 2000–2005, respectively.

**Results**

**Urban expansion during 1980–2005**

Urban land expansion is a characteristic phenomenon in urbanization process, which means urban area increase. Urbanization process in Shanghai, China, has been quickening greatly since the 1980s, and the urban expansion circled the central urban area according to the RS images acquired in the periods of 1980, 2000 and 2005 (Fig. 1). The urban area increased from 193.08  $\text{km}^2$  in 1980 to 777.55  $\text{km}^2$  in 2000, and the mean urban expanding rate is 38.88  $\text{km}^2 \text{a}^{-1}$  during 1980–2000. Urbanization progress boosted up further since 2000. The urban area increased from 777.55  $\text{km}^2$  in 2000 to 1,570.52  $\text{km}^2$  in 2005, and the mean urban expanding rate is 119.98  $\text{km}^2 \text{a}^{-1}$  during

**Fig. 1** Urban expanding pattern in Shanghai, China during 1980–2005



**Table 1** Sampling distribution and analysis on soil organic and inorganic carbon density in Shanghai, China

Sampling distribution	Tosoil (0–20 cm)						Deep soil (160–180 cm)					
	Soil organic carbon density (kg m <sup>-2</sup> )			Soil inorganic carbon density (kg m <sup>-2</sup> )			Soil organic carbon density (kg m <sup>-2</sup> )			Soil inorganic carbon density (kg m <sup>-2</sup> )		
	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV	Mean	Range	CV
Urban area	3.93	1.47–11.06	0.35	1.12	0.13–3.07	0.57	1.55	0.73–4.29	0.35	1.24	0.09–2.13	0.32
Suburban	3.74	1.24–6.85	0.27	0.73	0–3.11	0.66	1.57	0.82–4.29	0.39	1.07	0.03–2.23	0.49
Countryside	3.13	0.59–8.85	0.34	1.30	0–3.96	0.64	1.58	0.76–4.24	0.36	1.58	0.03–2.73	0.50
Shanghai, China	3.44	0.59–11.06	0.33	1.15	0–3.96	0.66	1.57	0.73–4.29	0.36	1.36	0.03–2.73	0.51

CV coefficient of variation

2000–2005. The urban area increased 1,377.44 km<sup>2</sup>, or up from 3.05 to 24.77% in the past 25 years.

SOC and SIC distribution in urban area

#### SOC distribution

The top SOC densities in urban, suburban and countryside area are  $3.93 \pm 1.38$ ,  $3.74 \pm 1.00$  and  $3.13 \pm 1.06$  kg m<sup>-2</sup>, respectively. The mean SOC density in urban soil is 1.05 times of that in suburban and 1.26 times of that in countryside. The topsoil organic carbon densities decrease gradually along urban–suburban–countryside and the urban topsoil is slightly enriched with SOC, which generally agrees with the results in New York, but the accumulation coefficient of SOC in this study is far below the value in New York (Pouyat et al. 2002). The coefficient of variation (CV) of SOC density in urban area is 0.35, with a range of 1.47–11.06 kg m<sup>-2</sup>, which shows obvious spatial variability. The mean value, range and CV of SOC densities in deep soil do not exhibit significant deviation in urban, suburban and countryside area due to limited human activity (Table 1).

#### SIC distribution

The top SIC densities in urban, suburban and countryside area are  $1.12 \pm 0.64$ ,  $0.73 \pm 0.48$  and  $1.30 \pm 0.83$  kg m<sup>-2</sup>, respectively. The CV of top SIC densities in urban area is 0.57, with a range of 0.13–3.07 kg m<sup>-2</sup>, which shows obvious spatial variability. The SIC densities of deep soil in urban, suburban and countryside area are  $1.24 \pm 0.40$ ,  $1.07 \pm 0.52$  and  $1.58 \pm 0.79$  kg m<sup>-2</sup>, respectively. The CV of SIC density in deep soil in urban area is 0.32, with a range of 0.09–2.13 kg m<sup>-2</sup>. The mean SIC density in urban topsoil and deep soil are 1.53 and 1.16 times of those in suburban, which means that the urban area is obviously enriched with SIC in topsoil, with a slight accumulation in deep soil (Table 1).

SOC and SIC evolution in urbanized territories

#### SOC evolution

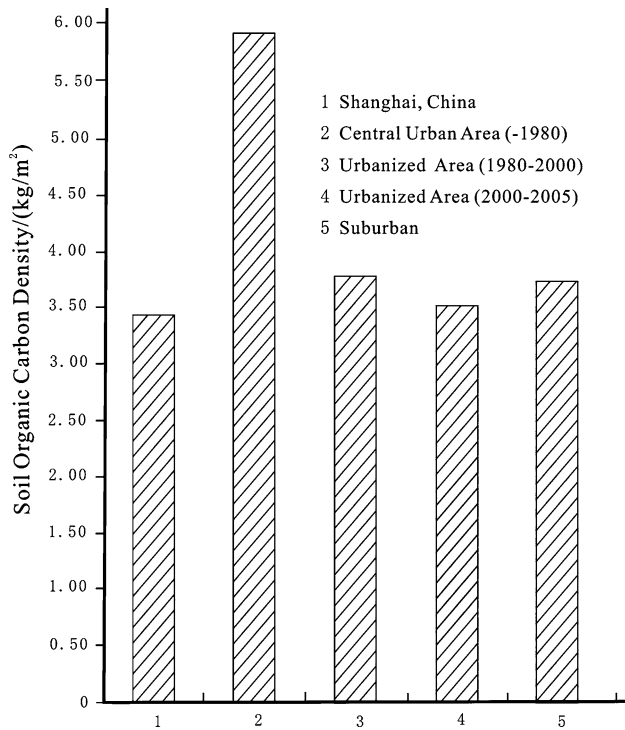
The top SOC densities in central urban area, urbanized area during 1980–2000, 2000–2005 and the suburban area are  $5.58 \pm 2.03$ ,  $3.78 \pm 1.13$ ,  $3.52 \pm 0.91$  and  $3.74 \pm 1.00$  kg m<sup>-2</sup>, which shows obvious SOC accumulation in central urban area. The mean density in central urban area is 47.62, 58.52% higher than that in urbanized area during 1980–2000 and 2000–2005, respectively, and it is 49.20% higher than that in suburban also (Fig. 2). The deep SOC densities in central urban area, urbanized area during 1980–2000, 2000–2005 and suburban area are  $1.75 \pm 0.87$ ,  $1.62 \pm 0.50$ ,  $1.38 \pm 0.41$ ,  $1.57 \pm 0.61$  kg m<sup>-2</sup>, which shows a slight SOC accumulation in deep soil. The SOC density in the urbanized territory during 1980–2005 decreases and the urban soil shows as organic carbon source effect as a whole (Fig. 3). The SOC density increases gradually with urban land use duration extending.

#### SIC evolution

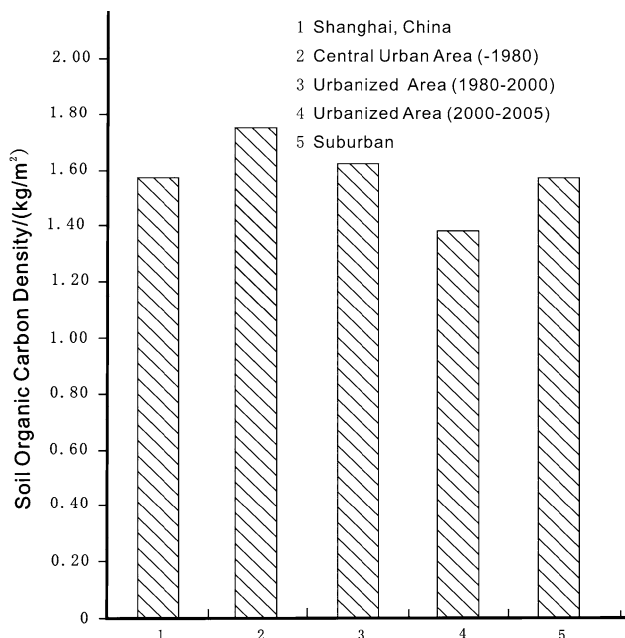
The top SIC densities in central urban area, urbanized area during 1980–2000, 2000–2005 and suburban area are  $1.84 \pm 0.37$ ,  $1.19 \pm 0.67$ ,  $0.78 \pm 0.41$ ,  $0.73 \pm 0.48$  kg m<sup>-2</sup> (Fig. 4), and the counterpart in deep soil are  $1.46 \pm 0.26$ ,  $1.26 \pm 0.36$ ,  $1.10 \pm 0.46$ ,  $1.07 \pm 0.52$  kg m<sup>-2</sup>, respectively. It is shown that the SIC density increases gradually with urban land use duration extending and urban ecosystem evolving (Fig. 5).

### Discussions and conclusions

The SOC and SIC distribution in urban area of Shanghai shows a slight accumulation and obvious spatial variability. The urban soil is enriched with SOC, which generally agrees with the results in New York, Tokyo, Shenyang, etc.

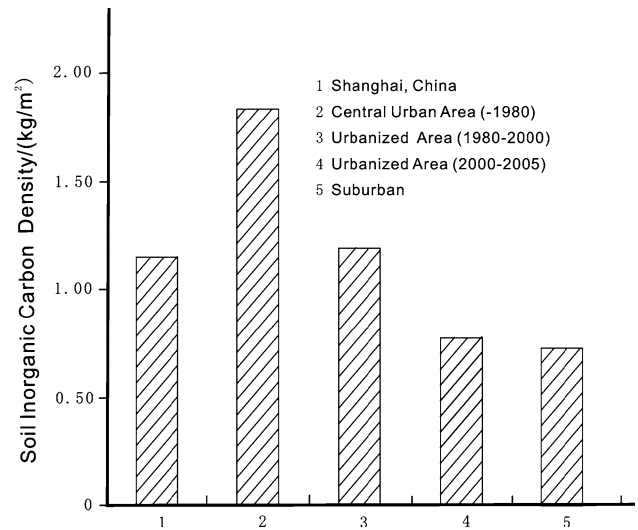


**Fig. 2** Comparison of topsoil (0–20 cm) organic carbon density in Shanghai, China

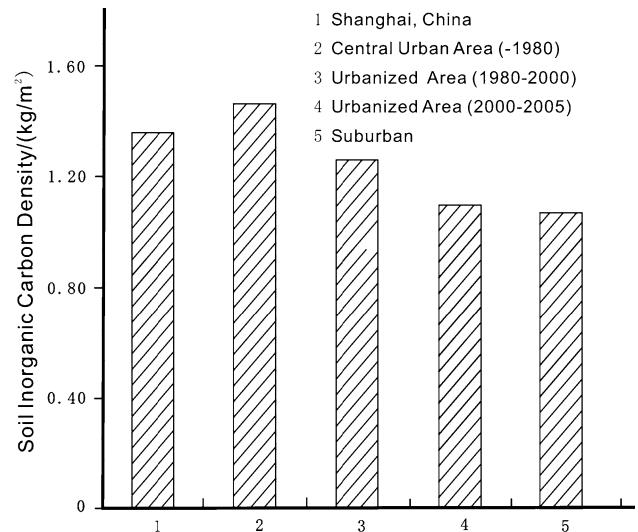


**Fig. 3** Comparison of deep soil (160–180 cm) organic carbon density in Shanghai, China

(He and Zhang 2006; Pouyat et al. 2002; Terumasa et al. 2008; Wang et al. 2009; Zhang and Zhou 2006). Plants are increasingly being expected to act as a carbon sinks, and urban parks are now expected to perform this function (Terumasa et al. 2008). The SOC accumulation may be



**Fig. 4** Comparison of topsoil (0–20 cm) inorganic carbon density in Shanghai, China



**Fig. 5** Comparison of deep soil (160–180 cm) inorganic carbon density in Shanghai, China

coupled with the policy of ecological city construction. With urban area expanding rapidly, the practice of ecological city construction has brought about striking improvements in urban ecological environment. Urban green coverage in Shanghai increased from 23.39 km<sup>2</sup> in 1985 to 288.65 km<sup>2</sup> in 2005, or 9.70–37.00% (Shanghai Bureau of Statistics 2007). SOC in urban soil is primarily derived from organic waste, living organism and plant residue, which contains lower proportion of active carbon and shows more stability, which may be attributed to SOC accumulation in urban soils too (Pouyat et al. 2002; He and Zhang 2006; Wang et al. 2009; Zhang and Zhou 2006).

Irrigation with carbonate and bicarbonate rich water can lead to increase of SIC density in agro-ecosystem (Singh

et al. 2007). The SIC accumulation in urban area may be connected with the exploitation of ground water in large quantities. The hydro-chemical types in Shanghai belong to  $\text{HCO}_3\text{-Ca}$ ,  $\text{HCO}_3\text{-Mg}$  and  $\text{HCO}_3\text{-Na}$  type of water on the whole (Jiang et al. 2008); therefore, the pH in groundwater is neutral or slightly alkaline. Since the 1980s, vast amounts of groundwater have been taken out through engineering drainage and supplied for production and living, the carbonate, bicarbonate dissolved in groundwater deposited in soils, which make soil pH decrease and SIC density increase.

It shows that the SOC and SIC obviously accumulate in central urban area, but SOC density in the urbanized area decreases. In a longer urbanized territory, more stable SOC is accumulated and more SIC in groundwater deposits in central urban area. However, SOC decomposes and releases due to land use changing drastically, which causes SOC density to decrease in the urbanized territories.

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