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Views & Comments

Soil Organic Carbon Changes in City Areas of China Over the Past Three Decades: Implications for Achieving Carbon Neutrality

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The substantial amount of greenhouse gas emissions from anthropogenic activities has caused the global mean surface temperature to increase by 0.99 °C since the industrial revolution [1]. China is committed to achieving carbon neutrality by 2060 in response to climate change [2]. Soil stores approximately 2344–3000 Pg (10^{15} g) of carbon at depths of 0–100 cm in terrestrial ecosystems, an amount approximately equivalent to twice the amount in the atmospheric carbon pool and three times that in the terrestrial biomass; therefore, even a small change in soil carbon stocks will exert significant impacts on atmospheric CO_2 concentrations [3].

Over 50% of the world population lives in cities; in China, the population living in cities has increased from 26% to 64% (from 301 to 848 million) over the past three decades [4]. Human activities can substantially change land uses in cities, leading to soil organic carbon (SOC) changes [5]. Cities consist of urban and suburban areas; urban areas are characterized by high population densities, automobile transportation, and large areas of impervious surfaces; other areas are considered suburban areas [6]. The soils in cities can be classified into sealed and open soils. The SOC of sealed soils may be stable because sealing can inhibit soil microbial activity, while the SOC in open soils is affected by human activity, climate change, and vegetation [7]. Open soils are mainly distributed in gardens in urban areas and in croplands in suburban areas of China, and garden areas account for approximately 40%–60% of the total urban area [6]. Therefore, SOC changes in cities depend on the changes in open soils based on these two land use types.

China has undergone rapid urbanization since 1978; however, cities in China are at different levels of urbanization because of imbalanced development in different regions [8]. Based on location, population, transportation system, international affairs influences, and their role in world economic networks, cities in China can be divided into high and low levels of urbanization, which are listed in Globalization and World Cities (GaWC) Research Networks 2020. Human activities vary according to different levels of urbanization, leading to diverse influences on SOC changes. Therefore, it is necessary to study SOC changes and their influencing factors in cities based on different levels of urbanization, as this information can provide recommendations for achieving carbon neutrality in China.

1. Data source

To analyze SOC changes in Chinese cities over the past 30 years, we collected published data on SOC in urban and suburban areas of cities in the 1980s and 2010s. In the 1980s, a comprehensive soil survey called the Second State Soil Survey was undertaken in China. This nationwide effort generated the most comprehensive and detailed data that were available at the time for extracting historical information on the soil properties of China. These detailed data have been compiled into an online database by the China Soil Science Data Center[†]. The database recorded detailed information, including each sampling site's geographic location and soil organic matter content, which could be converted into SOC content by the Bemmelen index of 0.58 [9]. Then, we collected published SOC data for the 2010s. Peer-reviewed publications that reported SOC content in suburban and urban areas of China were collected by searching the Web of Science and China National Knowledge Infrastructure (CNKI) using the following criteria: ① Sampling sites should match those in the Second State Soil Survey (based on geographic location) and belong to urban or suburban regions, and ② SOC should be analyzed by potassium-dichromate oxidation, which was consistent with the Second State Soil Survey. Following a series of screenings and verifications, comparable data from 322 matched sites in 60 cities in China were collected, and each data point represented the average of at least 20 subsamples for each site. These 60 cities across the country were divided into different groups according to location and level of urbanization; detailed information is shown in Table S1 in Appendix A. Furthermore, the urban areas of cities with high levels of urbanization in place for decades and with 2019 per capita income higher than 8000 CNY·month^{-1} were considered to be in the developed stage of urbanization [10]. Suburban areas of cities with high levels of urbanization and both urban and suburban areas of cities with low levels of urbanization, all with 2019 per capita

† http://vdb3.soil.csdb.cn/.

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income lower than 8000 CNY·month^{-1}, were considered to be in the developing stage of urbanization [10].

Moreover, to explore the mechanisms of SOC changes, we further collected data on mean annual temperature (MAT), mean annual precipitation (MAP), normalized difference vegetation index (NDVI), and aboveground net primary productivity (ANPP) for each sampling site based on geographic coordinates. MAT and MAP data were taken from National Aeronautics and Space Administration (NASA) Power[†] for the period 1987–2018. NDVI data were acquired from the website of the National Oceanic and Atmospheric Administration[‡] for the period 1987–2018. ANPP data were collected from the National Earth System Science Data Center[††] over the period 1986–2018.

2. SOC changes in Chinese cities

In southern parts of China, the average SOC content in topsoil (0–30 cm, excluded residue) declined slightly ($p > 0.05$) in both suburban and urban areas (from 19.79 to 17.14 g·kg^{-1} and from 14.10 to 13.91 g·kg^{-1}, respectively) in cities with low levels of urbanization over the past three decades. For the cities with high levels of urbanization, the average SOC content in topsoil decreased significantly from 19.84 to 16.92 g·kg^{-1} ($p < 0.05$) in suburban areas but increased significantly from 12.97 to 19.51 g·kg^{-1} ($p < 0.05$) in urban areas over the past 30 years (Fig. 1). Such results indicated that in southern parts of China, the SOC content decreased in city areas in the developing stage of urbanization but increased in city areas in the developed stage of urbanization.

However, in the northern parts of China, there was no relationship between SOC changes and urbanization stages. Regardless of urbanization levels, the SOC content in topsoil increased in both suburban and urban areas during the past three decades. The average SOC content increased significantly from 10.09 to 21.33 g·kg^{-1} ($p < 0.05$) in suburban areas and from 10.34 to 20.02 g·kg^{-1} ($p < 0.05$) in urban areas of cities with high levels of urbanization and increased significantly from 9.48 to 18.43 g·kg^{-1} ($p < 0.05$) in suburban areas and from 11.69 to 20.66 g·kg^{-1} ($p < 0.05$) in urban areas of cities with low levels of urbanization over the past 30 years (Fig. 1).

3. Causes of SOC changes in Chinese cities

SOC changes in cities control the balance of carbon input and output, which is further affected by vegetation, climate, and human activities [11]. The input of plant carbon is beneficial for SOC accumulation [6]. Climate change has both negative and positive effects on SOC content. On the one hand, warming and high precipitation are regarded as favorable climates for plant growth, which can increase SOC content by elevating plant-carbon inputs. On the other hand, warming and high precipitation can stimulate microbial activities, which can accelerate SOC decomposition [11,12]. Human activities can increase or decrease vegetation, which further affect SOC content [6,13].

The temperature and precipitation have increased in the city areas in both the developed and developing stages of urbanization in China (Fig. 2). However, the SOC content decreased in city areas in the developing stage of urbanization but increased in city areas in the developed stage of urbanization in southern parts of China (Fig. 3), which is not consistent with the changes in temperature and precipitation, implying that climate may not be the primary influencing factor for SOC changes.

The trends in SOC changes in topsoil over the past three decades were in line with the changing trend in vegetation in city areas of China, and there were significant positive correlations between SOC changes in topsoil and changes in NDVI and ANPP ($p < 0.01$, Fig. 3). In southern parts of China, over the past three decades, NDVI and ANPP declined in city areas in the developing stage of urbanization, while they increased in city areas in the developed stage of urbanization (Fig. 3). Human activities (such as industrialization and intensified agricultural activities) and related land-use changes have intensified due to economic growth, which could reduce vegetation richness and SOC content [5]. Such a phenomenon occurred in city areas in the developing stage of urbanization. After decades of development, some city areas have transformed from the developing stage to the developed stage of urbanization, as indicated by a significant increase in economic income. During this stage, residents have a strong desire to pursue a high quality of life, and vegetation is replanted in open soil to improve their living environment. The Chinese government has carried out

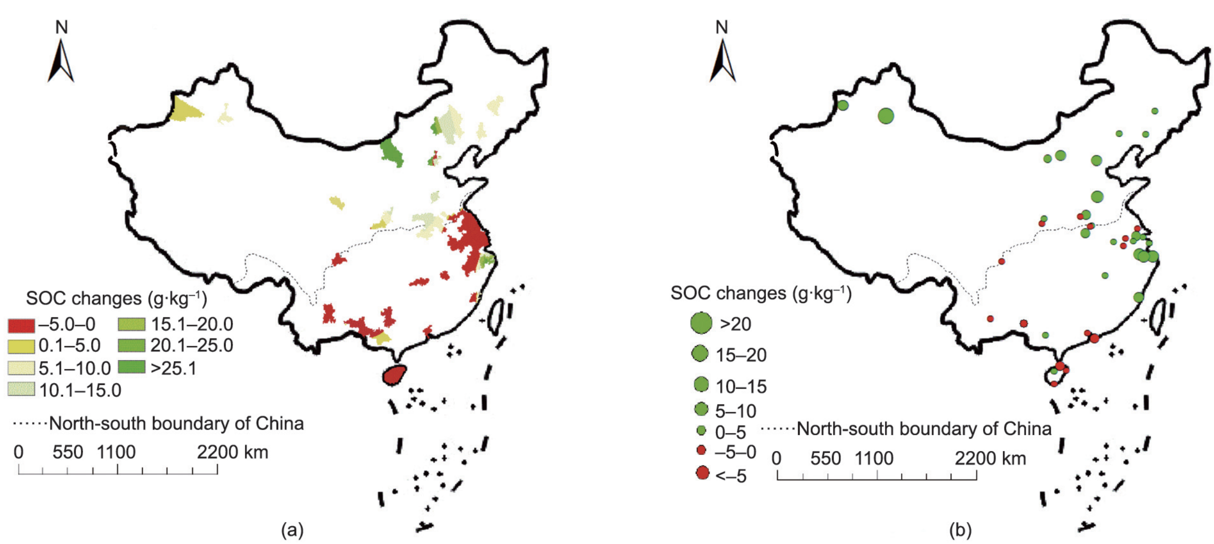

Fig. 1. Topsoil (0–30 cm) SOC changes (g·kg^{-1}) in (a) suburban and (b) urban areas of cities in China over the past three decades. Green and red represent the increase and decrease in SOC content, respectively.

† https://power.larc.nasa.gov.
‡ https://www.noaa.gov.
†† https://www.geodata.cn.

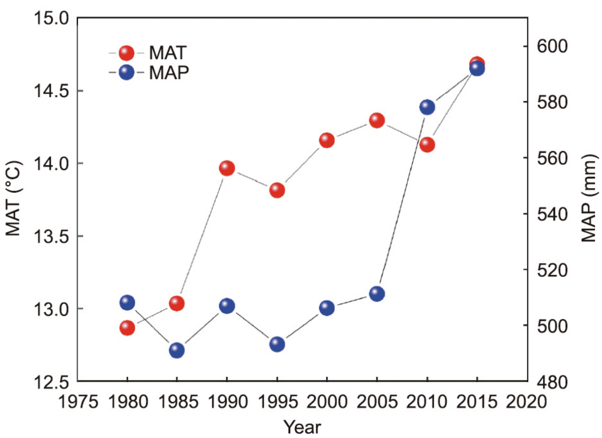

Fig. 2. Mean annual temperature (MAT) and mean annual precipitation (MAP) in suburban and urban areas of the studied cities in China from 1980 to 2015.

ecological city construction since 2002 [14]. In addition to the ecological construction proposed by the national government, local governments have also carried out some replanting programs, such as the "Ecological Priority" policy and "Country Parks Circle Projects" in Shanghai [15]. The implementation of these programs has led to an increase in vegetation coverage and the introduction of some exotic species to improve the scenic value of the areas. Greening, another human activity that can enhance the inputs of plant carbon, has been widely implemented in city areas in the developed stage of urbanization [16]. Such a phenomenon has occurred in city areas in the developed stage of urbanization. Moreover, there is growing evidence that vegetation grows faster in city areas in the developed stage of urbanization [8,17,18]. This outcome may be attributed to the "urban heat island" and diffusive light effects, which can advance the start and delay the end of the growing season [8]. Therefore, different human activities in city areas at different stages of urbanization have led to diverse SOC changes.

SOC changes in topsoil in northern parts of China were not related to the stages of urbanization, which could be attributed to the implementation of ecological protection and restoration projects. Since the late 1970s, China has implemented several national key restoration projects and constructed national key ecological function zones to protect its environment and restore degraded ecosystems, such as the Three-North Shelter Forest Program, the Returning Grazing Land to Grassland Project, the Beijing–Tianjin Sand Source Control Project, and the Yangtze River Shelter Forest Project. These projects have mainly been implemented in northern parts of China (Fig. 4). A previous study reported that the increased carbon in Asian terrestrial ecosystems (including forests, grasslands, and croplands) can primarily be attributed to considerable afforestation and reforestation, especially those implemented under China's national ecological restoration projects [13]. The implementation of ecological protection and restoration projects in northern parts of China has also led to an increase in vegetation coverage and productivity in suburban and urban areas of cities (Figs. 3(a) and (c)).

4. City areas in the developed stage of urbanization acting as carbon sinks

Because of ecological city construction, approximately 40% of the city areas in the developed stage of urbanization are covered by vegetation; this percentage is the largest to date [19]. Based on GaWC, 36 cities in China are regarded as cities with high levels of urbanization; over the past three decades, the total garden area has increased from 809.86 to 2969.69 km^2 in city areas in the

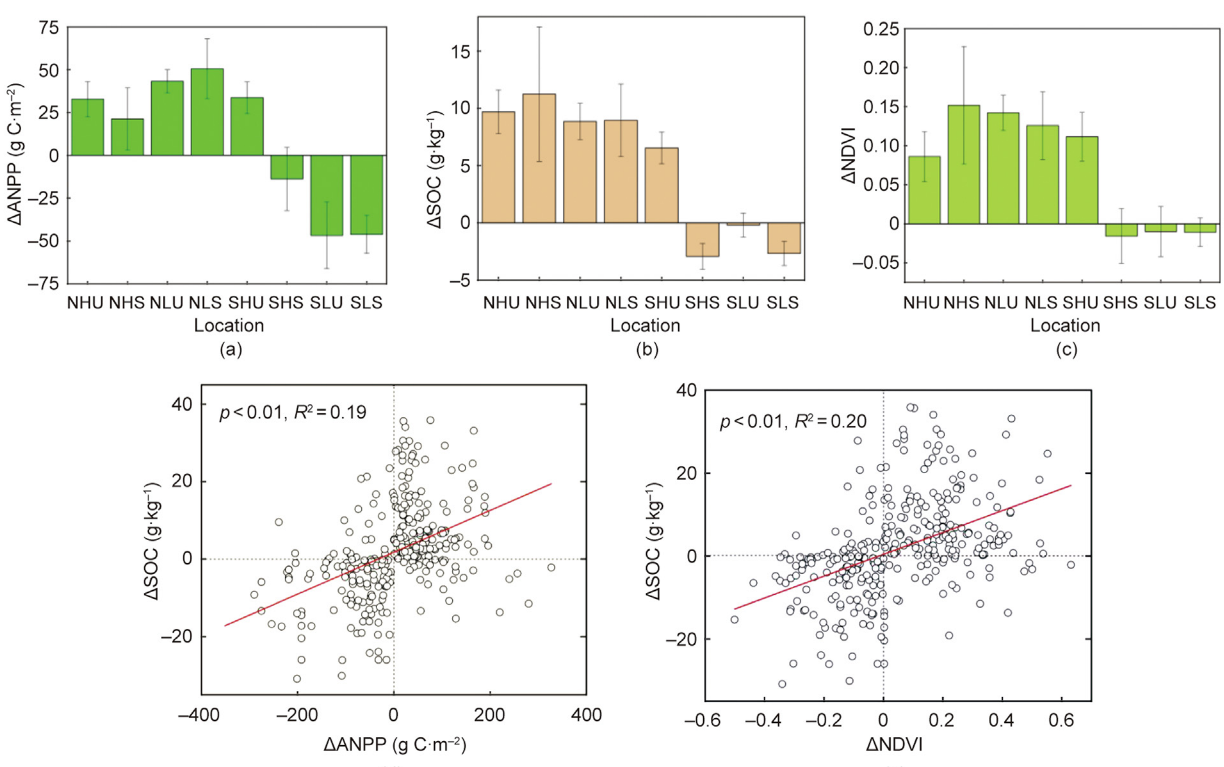

Fig. 3. Changes in (a) ANPP, (b) SOC content, and (c) NDVI and the relationship between SOC changes and (d) ANPP changes and (e) NDVI changes across the country over the past three decades. NHU and NHS represent urban and suburban areas of cities with high levels of urbanization in northern parts of China; NLU and NLS represent urban and suburban areas of cities with low levels of urbanization in northern parts of China; SHU and SHS represent urban and suburban areas of cities with high levels of urbanization in southern parts of China; and SLU and SLS represent urban and suburban areas of cities with low levels of urbanization in southern parts of China, respectively.

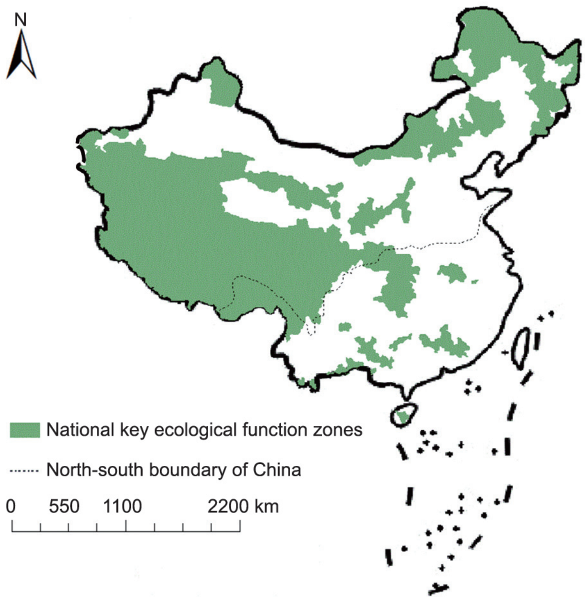

Fig. 4. Spatial distribution of national key ecological function zones in China (which were constructed to protect China's environment).

developed stage in China [10]. The SOC density in urban areas in the developed stage, based on the cities studied, has increased by 3.02 kg C·m^{-2} during the past three decades (22 cities, Table S1). As a result, the SOC stock has increased by 6.53 Tg C in city areas in the developed stage in China over the past three decades, which has offset approximately 0.41% of China's CO_2 emissions from the combustion of fossil fuels that increased from 0.92 to 2.52 Pg C from 1990 to 2017 [20]. Here, we used the SOC changes in 22 studied cities to estimate the change in SOC stock in 36 cities with high levels of urbanization in China. Due to geographic bias, the increase in SOC stock estimated in this study may have some uncertainties. However, the results still indicate that the topsoil in city areas in the developed stage of urbanization has acted as a carbon sink. Meanwhile, although the SOC content has decreased in city areas in the developing stage of urbanization in southern parts of China over the past three decades, the total area of gardens has increased in some city areas (especially in urban areas of cities with low levels of urbanization) [10]. Some cities with low levels of urbanization will convert to cities with high levels of urbanization by 2060, and these cities will be able to absorb more CO_2 and store more carbon in the future.

5. Implications for carbon neutrality via city management

Although urban areas account for less than 3% of the Earth's land area, rapid urbanization can change vegetation cover and land use types and therefore affect the global carbon cycle [6]. Trade-offs between urban expansion and ecological protection are a substantial challenge for sustainable development in China and other developing countries. Urbanization is a dynamic process from the developing stage to the developed stage. The sustainable management of green areas and increasing areas of gardens and parks in cities can not only offset SOC losses caused by urbanization but also improve the resilience of cities to climate change. A previous study has found that an increase in urban vegetation can also reduce surface temperature and mitigate the effect of urban heat islands [6]. For city areas in the developed stage of urbanization, local governments should carry out continuous replanting programs, manage urban gardens effectively, and introduce other kinds of vegetation to enhance both the growth and diversity of soil carbon storage. For city areas in the developing stage of urbanization, ecological construction should be strengthened to increase vegetation coverage and plant-carbon inputs to offset the CO_2 emissions caused by human activities and changes in land use due to economic growth. These measures are beneficial for achieving the goal of carbon neutrality.

Our results indicate that the role of soil in carbon budgets for city areas is related to the stage of urbanization. SOC changes in city areas are positively related to the changes in vegetation coverage and growth, which are affected by human activities and climate change. Cities contain not only soil and vegetation, but also rivers and lakes (Fig. 5). These inland city waters receive organic carbon and other nutrients from soils and can also release a large amount of greenhouse gases, including carbon dioxide, methane, and nitrous oxide [21,22]. More research should be conducted to investigate the effect of urbanization processes on greenhouse gas emissions from inland city waters. In addition to soil and waters, greenhouse gas production by other human activities, such as fossil fuel combustion and landfills, should be taken into consideration to reduce greenhouse gas emissions (Fig. 5) and achieve the goal of carbon neutrality.

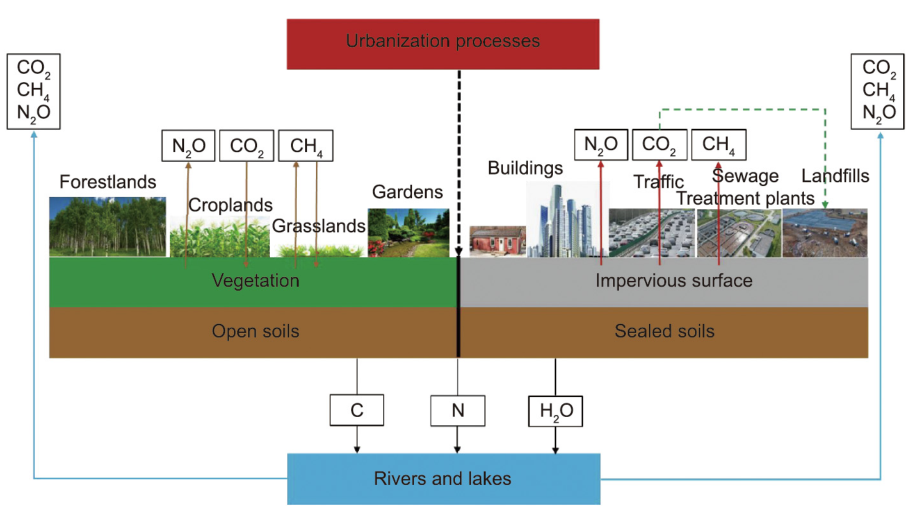

Fig. 5. Schematic of greenhouse gas emissions in city areas.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2022.04.014.

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