J. Resour. Ecol. 2020 11(5): 508-515
DOI: 10.5814/j.issn.1674-764x.2020.05.008
www.jorae.cn

Spatial Distribution of Surface Soil Organic Carbon Density and Related Factors along an Urbanization Gradient in Beijing

TIAN Yuhong*, LIU Fenghua, WANG Tiantian

State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

Abstract: Urban surface soil has a unique set of structures and processes that affect surface soil organic carbon density ($SOC_{density}$) and its spatial variations. Using Beijing as a case study, and assisted by field investigations and experiments, we analyzed the spatial distribution of $SOC_{density}$ in different land use types and functional regions, and assessed associated factors such as urbanization level, the physiochemical properties of soil and plant configurations. The present study aims to provide useful information about the mechanisms driving soil organic carbon and climate change in developing and developed areas in urbanized regions like Beijing. Results indicate that P is the main factor positively influencing $SOC_{density}$ in most regions. Because of the specific interference directly related to human beings in urban areas, with decreases in the urbanization level, more physiochemical factors of soil can influence $SOC_{density}$. $SOC_{density}$ under grasses is not significantly different from that under other plant compositions. Urbanization processes decrease the heterogeneity of the spatial pattern of $SOC_{density}$ in most land use types, but increased its contents when the area reached a developed level in Beijing. More factors related to human interference and spatial variation of surface soil carbon storage, especially under impervious land in urban areas, should be considered in future studies.

Key words: soil organic carbon density; urbanization; soil physiochemical properties; plant configuration

1 Introduction

Soil is the largest carbon sink in terrestrial ecosystems and plays a major role in the global carbon cycle (Piao et al., 2009). Changes in soil organic carbon density are mainly related to the following factors: variation of biomass, soil temperature and humidity of ground and below-ground soils, the decomposition rate of plant residues caused by the difference in the carbon to nitrogen ratio and lignin, and changes influenced by farmland plowing, soil aggregation, protection of soil organic matter, and soil erosion. These factors are directly or indirectly determined by the physiochemical characteristics of the soil, human interference, aboveground plant configurations and land use patterns. For example, differences in carbon sequestration are known to exist between urban green spaces and rural plant communities because of plant configurations (Pouyat et al., 2002; Golubiewski, 2006). The contents of soil organic carbon in coniferous forest were significantly lower than that in broadleaf forest in Changsha, China (Xiao and Liu, 2014). Soil carbon storage and carbon density ($SOC_{density}$) in forest and grassland were much higher than those in farmland in Yunnan, China (Duan et al., 2014). Soil pH, the carbon/nitrogen ratio (C/N) and the contents of clay have also been proven to influence the contents and stability of soil carbon stock (Xiao and Liu, 2014).

Urban land uses can result in greater soil organic carbon storage than found in agricultural land and some natural land types such as deserts, grasslands, and even forests

---

Received: 2019-05-23 **Accepted:** 2020-03-20
Foundation: The Key Projects of National Natural Science Foundation of China (41530747); The State Key Laboratory of Earth Surface Processes and Resources Ecology (2017-FX-01(1)).

***Corresponding author:** TIAN Yuhong, E-mail: tianyuhong@bnu.edu.cn

Citation: TIAN Yuhong, LIU Fenghua, WANG Tiantian. 2020. Spatial Distribution of Surface Soil Organic Carbon Density and Related Factors along an Urbanization Gradient in Beijing. *Journal of Resources and Ecology*, 11(5): 508–515.

(Koerner and Klopatek, 2010; Raciti et al., 2011). Analyzing the impact of urbanization on soil carbon storage has been a hot topic in the current research on urban soil (Seto et al., 2012). Luo et al. (2014) compared soil carbon stocks in urban and suburban topsoil in Beijing and concluded that the accumulation of soil organic carbon in the topsoil of green spaces is the result of the conversion of agricultural land to urban land during the urbanization process. The urbanization process has transformed farmland and forest soil into urban soil by simultaneously changing land use and management, and influencing the soil carbon stock to a great extent (Pouyat et al., 2007). For example, land use changes during urbanization processes, such as deforestation and farmland abandonment, are determinants to the regional carbon balance as indicated in central Germany (Schaldach and Alcamo, 2007). Furthermore, artificial additives, such as urban residential waste and industrial organic waste, are added to urban surface soil during urbanization and may change soil physiochemical characteristics and further alter $\mathrm{SOC}_{\mathrm{density}}$ (Tong and Dong, 2007). Many studies support the belief that urbanization can increase soil carbon sequestration. For example, urbanization-induced nitrogen deposition and elevated carbon dioxide concentration can increase forest soil carbon sequestration (Pouyat et al., 2002; Jastrow et al., 2005; Hyvonen et al., 2008; Pregitzer et al., 2010). However, Chen et al. (2013) analyzed changes in soil carbon sequestration in *Pinus massoniana* forests along an urbanization gradient in Guangzhou and concluded that urbanization negatively influences forest soil carbon. This result has also been tested in other cities as mentioned by Yesilonis and Pouyat (2012). Thus, factors influencing urban surface soil organic carbon storage and its spatial variations may be diverse because of the unique characteristics of structures and processes in urban ecosystems such as soil sealing, functional zoning, and settlement history (Vasevev et al., 2013). These factors should be elucidated to explain the diverse responses of soil organic carbon storage to the urbanization process. It is generally recognized that anthropogenic activities are the dominant drivers of soil organic carbon storage. However, few studies have considered the impacts of soil physiochemical properties and plant configuration on $\mathrm{SOC}_{\mathrm{density}}$, especially along an urbanization gradient in a large metropolitan area such as Beijing.

Using Beijing as a case study, this paper analyzes the spatial patterns of topsoil $\mathrm{SOC}_{\mathrm{density}}$ along an urbanization gradient. Correlation analyses were used to assess relationships between land use patterns, soil physiochemical properties and plant configurations. The study will provide useful information to explore the mechanisms driving urban surface $\mathrm{SOC}_{\mathrm{density}}$ and estimate the regional soil carbon budget. It will also provide information that can help in the construction of a low-carbon city, which is considered a main concern for future development by the Beijing government (Chen and Zhu, 2009).

2 Study area

2.1 General information

Beijing is located in the northwest of the North China Plain, which has a temperate continental monsoon climate. The main climatic characteristics are winds with droughts in spring, heat and rain in summer, sun in autumn, and cold and dry in winter. The distribution of seasonal rainfall is uneven. The average annual temperature is 8–12°C. The main communities of vegetation are temperate deciduous broadleaf forest and coniferous forest. The dominant species are *Quercus wutaishansea* and *Pinus tabulaeformis*. The main soil type is cinnamon soil, which occupies 64.95% of the total area, followed by fluvo-aquic soil. A total of eight districts were included in the study area. They were further divided into four functional regions with different urbanization levels in terms of population, industrial structure and stage of economic development as indicated by the government in 2005 (Fig. 1). The four regions are: capital function core area (CFCA: Dongcheng and Xicheng districts), urban function expansion zone (UFEZ: Chaoyang, Haidian and Shijingshan districts), urban development new zone (UDNZ: Shunyi district) and ecological conservation area (ECA: Mentougou and Huairou districts). Table 1 lists population, population density, industry structure and industrialization stages divided by GDP per capita and industrial output structure (Chenery et al., 1986). It can be inferred from Table 1 that: 1) CFCA has the highest proportion of tertiary industry area and is in a developed economy stage. It represents developed regions with the highest urbanization level. 2) UFEZ has the highest proportion of secondary industry; the population growth rate in UFEZ increased in 1982–2000 and slowed after 2000. It is experiencing rapid urbanization and has a medium urbanization level. 3) UDNZ has a

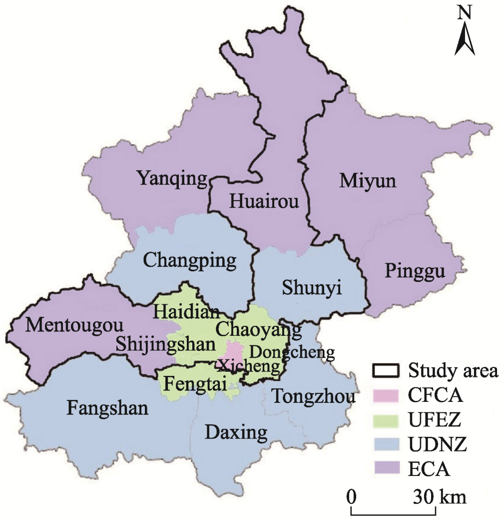

Fig. 1 Location of study area

Note: CFCA, capital function core area; UFEZ, urban function expansion zone; UDNZ, urban development new zone; ECA, ecological conservation area.

Table 1 Population, GDP and industry structure in different functional regions

Items		CFCA	UFEZ	UDNZ	ECA
Population ($\times10^6$)	1982	241.70	283.99	143.57	49.36
	1990	233.64	398.90	167.44	53.17
	2000	229.43	638.86	198.17	56.25
	2012	226.90	1012.72	362.40	70.82
Population density (person km^{-2})	2012	24232.46	7742.29	1226.40	199.71
Total area (km^2)		91.99	1275.61	6299.22	8743.73
GDP ($\times10^8$ Yuan)	2009	2791	5140	1590	478
GDP per capita (Yuan)	2009	27668	72205	5709	3653
Economy density ($\times10^8$ Yuan km^{-2})	2009	29.99	3.99	0.25	0.05
Industry structure (%)	Primary	0	0.10	5.76	9.21
	Second	7.95	26.55	52.36	44.91
	Third	92.05	73.36	41.88	45.89

Note: CFCA: Capital function core area; UFEZ: Urban function expansion zone; UDNZ: Urban development new zone; ECA: Ecological conservation area; GDP: Gross domestic product.

comparatively higher proportion of primary industry and lower population density. It is ready for further development and has a comparatively low urbanization level. 4) ECA has the lowest population density and GDP per capita and the highest proportion of primary industry. It has a limited urbanization level with restricted development because of government policy promoting environmental protection and pollution abatement.

3 Methods

Field investigations were carried out in green spaces from 15 July to 15 August 2013 along the urbanization gradient. Green spaces were divided into nine types according to land use: plantations, roadside, parks, residential, suburban woodland, farmland including plantations, and other lands such as administrative government, cultural and educational, and hospital areas. Overall, 140 surface soil samples at 0–20 cm were collected (Fig. 2). These were randomly distributed among different land-use types in the four functional regions. Table 2 shows the number of soil samples of each type from each region. The sample numbers were roughly set based on the area of each land use type along the urbanization gradient. In mountainous areas of ECAs, samples were selected for typical forest types including white birch (*Betula platyphylla*), oak (*Quercus palustris*) and Chinese pine (*Pinus tabuliformis*).

According to the vegetation compositions of the above soil samples, plant configurations were divided into five types: grass, tree, tree+grass, shrub+grass, and tree+shrub+grass.

Soil samples were air-dried and rubbed with impurities removed. Soil particle composition was then obtained by passing samples through sieves. The commonly accepted international standard was used to classify the samples by particle size as gravel (>2 mm), coarse sand (2–0.2 mm), fine sand (0.2–0.002 mm), silt (0.02–0.002 mm), or clay (<0.002 mm) (Baver et al., 1972). The other physiochemical properties were obtained by the methods mentioned in Table 3.

Table 2 Sample numbers of different green space types in different functional regions

Functional region	Park	Roadside	Residential	Farmland/plantation	Woodland	Others	Total
CFCA	4	16	6			3	29
UFEZ	3	14	7	2	3	8	37
UDNZ	1	14	4	4	7	2	32
ECA	5	7	5	13	10	2	42
Total	13	51	22	19	20	15	140

Note: The means of the abbreviations see Table 1.

Table 3 Measurement methods of indices for soil physiochemical properties

Observation index	Abbreviation	Measurement method	References
Soil organic carbon	TOC	Walkley–Black method	Bremmer and Mulvaney, 1982
Total carbon	TC	Kjeldahl digestion method	Anderson and Ingram, 1993
pH	pH	pH meter method	Thomas, 1996
Total nitrogen	TN	Kjeldahl digestion method	Anderson and Ingram, 1993
Total phosphorus	P	Ammonium molybdate method	Li et al., 2015
Available potassium	K	NH_4OAc digestion	SCS-USDA, 1972
Content of gravel	Gravel	Pipette method	Baver et al., 1972
Content of coarse sand	CS	Pipette method	Baver et al., 1972
Content of fine sand	FS	Pipette method	Baver et al., 1972
Content of silt	Silt	Pipette method	Baver et al., 1972
Content of clay	Clay	Pipette method	Baver et al., 1972
Water content		Oven drying method	
Bulk density		Ring blade method	

Population density, economic density and urbanization rate were selected to represent the urbanization level of the study area. Population data were obtained from the Sixth National Population Census Data conducted in 2010 (The Census Office of the State Council of China, 2010). Economic density was calculated by dividing the GDP in 2012 by the area of the given district. Urbanization rate was calculated according to the characteristics of the population in different industries:

$$U = \frac{I_u}{I_t} = \frac{I_2 + I_3 + I_4}{I_1 + I_2 + I_3 + I_4 + I_5} \tag{1}$$

where U is the urbanization rate; I_u is the total population living in urban areas; I_t is the total population in the study area; I_1, I_2, I_3 are the number of employees in primary, secondary and tertiary industries; I_4 is the population living in urban areas but not employed in secondary and tertiary industries. This latter group consists mainly of people not of working age, unemployed, retired or employed by the army or government. I_5 is the population living in the countryside but not employed by primary industry; these are mainly people not of working age or not able to work.

$\mathrm{SOC}_{\mathrm{density}}$ was calculated as (Freyerová and Šefrna, 2014):

$$SOC_{\mathrm{density}} = TOC \times D \times BD \times (1 - \delta)/100 \tag{2}$$

where SOC_{density} is soil organic carbon density, the unit is kg m^{-2}, TOC is the content of soil organic carbon (g kg^{-1}), D is the soil layer depth (cm) with an average value of 0.1 m, BD is bulk density (g cm^{-3}), and δ is the volume percentage of gravel (diameter > 2 mm) content (%), which was neglected because of the extremely low content of gravel in Beijing soils.

4 Results

4.1 Spatial distributions of $\mathrm{SOC}_{\mathrm{density}}$ in different functional regions

The soil surface TOC ranged from 0.42 to 20.16 g kg^{-1} with a mean value of 4.99 g kg^{-1}. The values of $\mathrm{SOC}_{\mathrm{density}}$ ranged from 2.16 to 3.19 kg m^{-2} with a mean value of 2.56 kg m^{-2} and a strong variation coefficient of 83.80% (Table 4). The values of TOC and $\mathrm{SOC}_{\mathrm{density}}$ in UFEZ were significantly lower with a stronger variation coefficient of 93.64% than in other functional regions. Thus, the distribution of $\mathrm{SOC}_{\mathrm{density}}$ was comparatively uneven in UFEZ and even in UDNZ, with a weak variation coefficient of 35.11%.

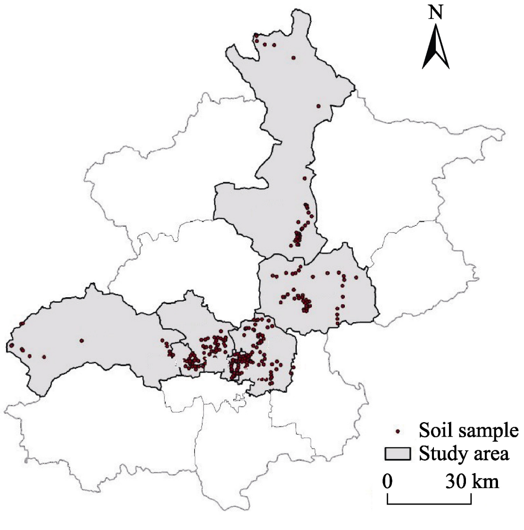

Fig. 2 Sample distribution of the field survey

4.2 Spatial distributions of $\mathrm{SOC}_{\mathrm{density}}$ by land-use patterns

Table 5 displays the results of Duncan's multiple comparison (ANOVA) of $\mathrm{SOC}_{\mathrm{density}}$ in different land uses by functional regions. Fig. 3 shows the box plots of $\mathrm{SOC}_{\mathrm{density}}$ in different functional regions by land use. It can be inferred from Table 5 and Fig. 3 that, compared to those in other functional regions, $\mathrm{SOC}_{\mathrm{density}}$ was comparatively lower in all land uses in UFEZ, higher in residential green spaces in CFCA, higher in park, roadside green spaces and farmland in ECA, and higher in woodland and other green spaces in UDNZ. Overall, compared to other land uses, woodland had a higher mean $\mathrm{SOC}_{\mathrm{density}}$, followed by farmland, while other green space had the lowest. However, the differences in $\mathrm{SOC}_{\mathrm{density}}$ were always insignificant in different land uses in all functional regions and in the whole study area.

Fig. 3 shows the box plots of $\mathrm{SOC}_{\mathrm{density}}$ in different functional regions by land uses. It can be inferred from Fig. 3 that, compared to other regions, $\mathrm{SOC}_{\mathrm{density}}$ was usually slightly higher in ECA in parks, roadside green spaces and farmland and lower in UFEZ in all land uses; CFCA had a slightly higher $\mathrm{SOC}_{\mathrm{density}}$ in residential green spaces and

Table 4 Duncan's multiple comparison of TOC and $\mathrm{SOC}_{\mathrm{density}}$ in different functional regions

Functional region	TOC (g kg^{-1})	$\mathrm{SOC}_{\mathrm{density}}$ (kg m^{-2})	Variation coefficient of $\mathrm{SOC}_{\mathrm{density}}$ (%)
CFCA	5.74b	0.82b	68.11
UFEZ	1.87a	0.29a	93.64
UDNZ	7.01b	0.92b	35.11
ECA	5.33b	0.88b	69.29
Total	4.99	0.77	83.80

Note: a/b mean the class group induced by Duncan's multiple comparison.

Table 5 Duncan's multiple comparison of $\mathrm{SOC}_{\mathrm{density}}$ in different functional regions by land uses

Functional region	Park	Road-side	Residential	Farmland	Woodland	Other
CFCA	0.57a	0.82a	1.06a			0.67a
UFEZ	0.24	0.31a	0.35a	0.21	0.79	0.18a
UDNZ	0.76	0.94a	0.50a	0.63a	1.07a	1.16a
ECA	0.81a	1.11a	0.86a	0.91a	0.87a	0.84a
Total	0.65a	0.79a	0.72a	0.80a	0.94a	0.54a

Note: Horizontal comparison of $\mathrm{SOC}_{\mathrm{density}}$ in different land uses. a/b mean the class group induced by Duncan's multiple comparison.

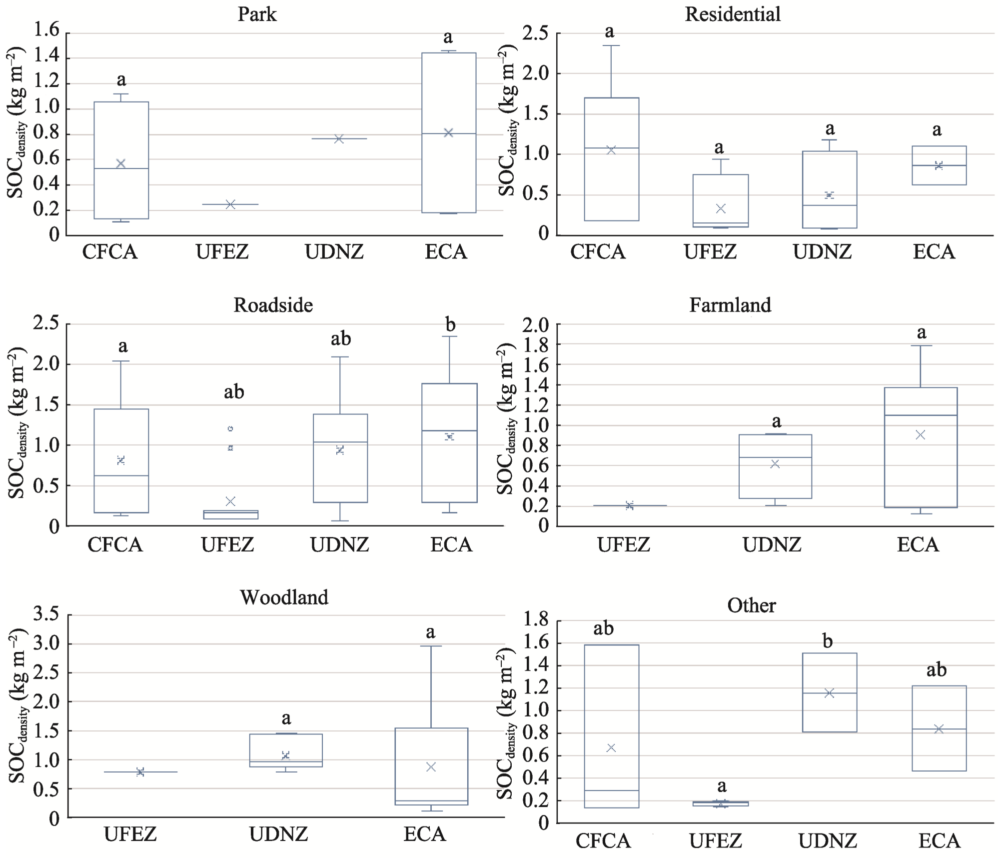

Fig. 3 Box plots of $\mathrm{SOC}_{\mathrm{density}}$ in functional regions by land use

Note: a/b displays whether the values significantly differ from others, which was calculated using Duncan's multiple comparison test in ANOVA in SPSS 19.0.

UDNZ had a higher $\mathrm{SOC}_{\mathrm{density}}$ in woodland and other green spaces, followed by ECA. $\mathrm{SOC}_{\mathrm{density}}$ in roadside green spaces in CFCA was significantly lower than that in ECA. $\mathrm{SOC}_{\mathrm{density}}$ in other green spaces in UFEZ was significantly lower than that in UDNZ. In other land uses, $\mathrm{SOC}_{\mathrm{density}}$ always had insignificant differences by different functional regions.

4.3 Factors influencing the spatial pattern of $\mathrm{SOC}_{\mathrm{density}}$

4.3.1 Impacts of soil physiochemical characteristics and urbanization indicators

Tables 6 and 7 show the Pearson correlation coefficients between $\mathrm{SOC}_{\mathrm{density}}$ and soil physiochemical properties and urbanization indicators. It can be inferred from Table 5 that the content of clay played an insignificant role in $\mathrm{SOC}_{\mathrm{density}}$ in all regions. In the whole study area, $\mathrm{SOC}_{\mathrm{density}}$ was positively and moderately influenced by available phosphorus (P) and negatively and weakly influenced by water content. With the decrease of urbanization level, more factors had an effect on $\mathrm{SOC}_{\mathrm{density}}$ in different regions. In the developed region of CFCA, only two factors, P and pH, played significant roles in $\mathrm{SOC}_{\mathrm{density}}$, positive and negative, respectively. In UFEZ, three factors and silt played moderate positive (C/N and CS) and negative (content of silt) roles in $\mathrm{SOC}_{\mathrm{density}}$. In UDNZ, four factors played positive strong,

Table 6 The Pearson correlation coefficients between $\mathrm{SOC}_{\mathrm{density}}$ and soil physiochemical properties

Region	TC (%)	TN (g kg^{-1})	C/N	P (mg kg^{-1})	K (mg kg^{-1})	pH	CS (%)	FS (%)	Silt (%)	Clay (%)	Water content (%)
CFCA	0.22	0.15	0.04	0.55**	0.05	–0.65**	0.29	–0.36	–0.26	0.05	–0.26
UFEZ	0.19	–0.35	–0.41*	0.23	–0.10	–0.37	–0.49*	0.35	0.42*	0.30	–0.03
UDNZ	0.32*	0.44*	–0.09	0.75**	0.39*	–0.21	–0.07	0.11	–0.26	–0.15	–0.28
ECA	–0.33*	–0.07	–0.27	0.42**	0.27	–0.37*	0.31*	–0.53**	–0.15	0.19	0.05
Total	–0.02	0.12	–0.13	0.49**	0.18*	–0.11	0.10	–0.18*	–0.15	0.01	–0.22*

Note: BD: bulk density; TC: total carbon; TN: total nitrogen; P: available phosphorus; K: available potassium; C/N is the ratio of TC and TN; CS: coarse sand; FS: fine sand; * means correlation is significant at the 0.05 level (two-tailed); ** means correlation is significant at the 0.01 level (two-tailed).

Table 7 The Pearson correlation coefficients between $SOC_{density}$ and urbanization indicators

Urbanization indicator	Population density	Economic density	Urbanization rate
$SOC_{density}$	–0.15	0.11	0.43**

Note: ** means correlation is significant at the 0.01 level (two-tailed).

moderate (TN) and weak (TC and K) roles in $SOC_{density}$. In ECA, five factors significantly influenced $SOC_{density}$. Where TC, pH, and content of fine sand played positively weak and moderate roles, P and content of coarse sand played negatively moderate or weak roles. P played positively moderate or strong roles in $SOC_{density}$ in most regions and the whole study area. Most roles of other factors in $SOC_{density}$ were weak or moderate. Table 7 shows that only urbanization rate significantly and moderately influenced $SOC_{density}$ in the whole study area. Population density and economic density played an insignificant role in $SOC_{density}$.

4.3.2 Impacts of plant configurations

Table 8 displays the results of Duncan's multiple comparison (ANOVA) of $SOC_{density}$ in different plant configurations. It can be inferred from Table 5 that $SOC_{density}$ was significantly lower under shrub + grass than under tree + grass and tree + shrub + grass. Unusually, in a natural environment with no or little human interference, the value of $SOC_{density}$ under grass in this study was insignificantly different from those under other plant configurations, even trees.

5 Discussion

Out results were not supported by Luo et al. (2014), who concluded that $SOC_{density}$ of urban topsoil under green spaces was higher than that of rural green space and farmland in Beijing. The actual situation is more complex when considering green space types and urbanization levels. Of the four regions in Beijing, the lowest $SOC_{density}$ with the strongest variation coefficient appeared in rapidly developing areas of UFEZ in most land uses, followed by the developed areas of CFCA. In CFCA, with a decrease in urbanization level, $SOC_{density}$ usually increased in park, roadside green spaces and farmland. CFCA even had a higher value of $SOC_{density}$ in residential green spaces compared to the four other regions. Thus as the urbanization level decreased, the values of soil organic carbon density decreased in most land uses. However, when an area reached a developed level, soil organic carbon density increased in most land uses as the urbanization level increased. This result is also different from that of Chen et al. (2013), who argued that urbanization-induced environmental changes may have a negative effect on urban forest soil carbon in Guangzhou, China. Our research also concluded that urbanization increased spatial heterogeneity, with highly urbanized regions having higher variation coefficients of $SOC_{density}$ than regions with a low or limited urbanization level. This is also supported by Vasenev et al. (2013). However, outside of CFCA, the highest value of variation coefficients of $SOC_{density}$ appeared in the developing regions of UFEZ. Thus, the distribution of $SOC_{density}$ was homogenous within a developed region in an urban area.

Table 8 Duncan's multiple comparison of $SOC_{density}$ in different plant configurations

Plant configuration	Grass	Shrub+ grass	Tree	Tree+ grass	Tree+shrub+ grass
$SOC_{density}$	2.42ab	1.72a	2.50b	2.65b	2.84b

Note: a/b mean the class group induced by Duncan's multiple comparison.

Earlier studies have indicated that, with an increased silt content and decreased pH and water content, $SOC_{density}$ is usually increased (Jin et al., 2000; Li et al., 2001). This study also obtained these results in most regions and the whole study area. However, different regions have different factors that influence $SOC_{density}$. Of the soil physiochemical properties, P is the main positive factor affecting $SOC_{density}$ in most regions. This verified that in urban surface soil, an increase of P content contributes to the accumulation of soil organic carbon storage, just as an earlier study showed that it did in croplands (Huang et al., 2009). As the urbanization level decreases, more soil physiochemical factors begin to influence $SOC_{density}$. The reason for this may be the significant positive influence of urbanization rate on $SOC_{density}$ (Table 4).

The main source of soil organic carbon is residual root with a slow carbon decomposition rate under grasses. Soil organic carbon under trees or woodland is mainly from litter, which may decompose quickly above ground or in shallow soil (Bouwman, 1990). Furthermore, litter is always collected by municipal workers in urban areas and does not contribute to soil carbon storage. Thus, $SOC_{density}$ under grasses is insignificantly different from that under other plant composition as mentioned in this study. However, this result is not consistent with that of Pouyat and Yesilonis (2008), who argue that in a natural environment without human interference, soil organic carbon content under grasses is significantly lower than it is under trees. This explained the main difference between natural and artificial environments. $SOC_{density}$ in farmland is usually considered to be lower than in other land uses because (Bouwman, 1990): 1) Farmers always harvest crop residues; 2) Surface leaching is serious; and 3) Crop residues are always difficult to decompose. However, in this study, there are insignificant differences in $SOC_{density}$ among different land uses. Farmland even has a slightly higher value of $SOC_{density}$ than most other land uses (except woodland) in ECA and the whole study area. Thus, soil organic carbon is poorly stored in urban surface soil in Beijing. Soil organic carbon is vital in providing edaphic ecosystem services and maintaining urban surface soil health. In order to decrease the losses of soil organic carbon induced by human activities, the following measures should be carried out: 1) returning collected litter to green spaces to form compost for fertilizing; 2) reducing or remove debris in green spaces and reduce trampling to improve soil texture and plant growth; 3) applying a suitable amount of phosphate fertilizer to improve carbon accumulation in soil.

6 Conclusions

In this study, we analyzed the impacts of urbanization, soil physiochemical properties and plant configurations on $\mathrm{SOC}_{\mathrm{density}}$. The following issues can be concluded from the research. 1) The distribution of $\mathrm{SOC}_{\mathrm{density}}$ was comparatively uneven in UFEZ and even in UDNZ. 2) Compared to other land uses, woodland had a higher mean $\mathrm{SOC}_{\mathrm{density}}$, followed by farmland, and other green space had the lowest. 3) P played positively moderate or strong roles on $\mathrm{SOC}_{\mathrm{density}}$ in most regions and the whole study area. 4) With the decrease of urbanization level, more factors had an effect on $\mathrm{SOC}_{\mathrm{density}}$ in different regions. 5) Urbanization processes decreased the heterogeneity of the spatial pattern of $\mathrm{SOC}_{\mathrm{density}}$ in most land uses but increased its contents when the area reached a developed level in Beijing. We provide useful information about the factors that influence soil organic carbon in developed and developing areas and identify the driving mechanisms behind the regional carbon cycle. However, the urban surface soil ecosystem is very complex. In future studies, other factors including methods of management, soil sources, settlement histories and compaction should be discussed. Spatial variation of soil carbon storage especially under impervious land in urban area should also be included for further consideration.

References

Anderson J M, Ingram J S I. 1993. Tropical soil biology and fertility: A Handbook of Methods. Wallingford, USA: CAB International.

Baver L D, Gardner W H, Gardner W R. 1972. Soil physics. New York, USA: John Wiley and Sons Press.

Bouwman A F. 1990. Global Distribution of the major soils and land cover types. New York, USA: John Wiley and Sons Press.

Bremmer J M, Mulvaney C S. 1982. Nitrogen total. In: Page A L (ed.). Methods of soil analysis. Part 2. Chemical and microbiological properties. Wisconsin: American Society of Agronomy& Soil Science Society of America, 595–624.

Chen F, Zhu D J. 2009. Theory of research on low-carbon city and Shanghai empirical analysis. *Urban Studies*, 16(10): 71–79. (in Chinese)

Chen H, Zhang W, Gilliam F, et al. 2013. Changes in soil carbon sequestration in *Pinus massoniana* forests along an urban-to-rural gradient of Southern China. *Biogeosciences*, 10: 6609–6616.

Chenery H, Robinson S, Syrquin M. 1986. Industrialization and growth: A comparative study. New York, USA: Oxford University Press, 387.

Duan X W, Rong L, Hu J M, et al. 2014. Soil organic carbon stocks in the Yunnan Plateau, southwest China: Spatial variations and environmental controls. *Journal of Soils & Sediments*, 14: 1643–1658.

Freyerová K, Šefrna L. 2014. Soil organic carbon density and storage in podzols: A case study from Ralsko region (Czech Republic). *AUC Geographica*, 49(2): 65–72.

Golubiewski N E. 2006. Urbanization increases grassland carbon pools: Effects of landscaping in Colorado's front range. *Ecological Application*, 16(2): 555–571.

Huang Q R, Hu F, Huang S, et al. 2009. Effect of long-term fertilization on organic carbon and nitrogen in a subtropical paddy soil. *Pedosphere*, 19(6): 727–734.

Hyvonen R, Persson T, Andersson S, et al. 2008. Impact of long-term nitrogen addition on carbon stocks in trees and soils in northern Europe. *Biogeochemistry*, 89: 121–137.

Jastrow J D, Miller R M, Matamala R, et al. 2005. Elevated atmospheric carbon dioxide increases soil carbon. *Global Change Biology*, 11: 2057–2064.

Jin F, Yang H, Zhao Q G. 2000. Research progress on soil carbon storage and its factors. *Soil*, 32(1): 11–17. (in Chinese)

Koerner A B, Klopatek M J. 2010. Carbon fluxes and nitrogen availability along an urban-rural gradient in a desert landscape. *Urban Ecosystems*, 13: 1–21.

Li Y, Chen L, Wen H. 2015. Changes in the composition and diversity of bacterial communities 13 years after soil reclamation of abandoned mine land in eastern China. *Ecological Research*, 30(2): 357–366.

Li Z, Sun B, Lin X X. 2001. Density of soil organic carbon and the factors controlling its turnover in east China. *Scientia Geographica Sinica*, 21(4): 301–307. (in Chinese)

Luo S, Mao Q, Ma K. 2014. Comparison on soil carbon stocks between urban and suburban topsoil in Beijing, China. *Chinese Geographical Science*, 24(5): 551–561.

Piao S L, Fang J Y, Ciais P, et al. 2009. The carbon balance of terrestrial ecosystems in China. *Nature*, 458: 1009–1013.

Pouyat R V, Groffman P, Yesilonsic I L. 2002. Soil carbon pools and fluxes in urban ecosystems. *Environment Pollution*, 116: 107–118.

Pouyat R V, Yesilonis I D. 2008. A comparison of soil organic carbon stocks between residential turf grass and native soil. *Urban Ecosystem*, 12(1): 45–62.

Pouyat R V, Yesilonis I D, Russellanelli J, et al. 2007. Soil chemical and physical properties that differentiate urban land-use and cover types. *Soilence Society of America Journal*, 71(3): 1010–1019.

Pregitzer K S, Burton A J, Zak D R, et al. 2010. Simulated chronic nitrogen deposition increases carbon storage in Northern Temperate forests. *Global Change Biology*, 14: 142–153.

Raciti S M, Groffman P M, Jenkins H C. 2011. Accumulation of carbon and nitrogen in residential soils with different land-use histories. *Ecosystems*, 14(2): 287–297.

Schaldach R, Alcamo J, 2007. Simulating the effects of urbanization, afforestration and cropland abandonment on a regional carbon balance: A case study for Central Germany. *Regional Environmental Change*, 7: 137–148.

SCS–USDA (Soil Conservation Service–U. S. Department of Agriculture). 1972. National engineering handbook. Washington D C: USDA.

Seto K C, Güneralp B, Hutyra L R. 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences of USA*, 109(40): 16083–16088.

The Census Office of the State Council of China. 2010. Tabulation on the 2010 Population Census of the People's Republic of China. Beijing, China: Chinese Statistics Press. (in Chinese)

Thomas G W. 1996. Soil pH and soil acidity. In: Sparks D L (ed.). Methods of soil analysis. Part 3. Chemical methods. Madison, USA: Soil Science Society of America, 475–490.

Tong C, Dong Y. 2007. Characteristics of soil carbon pool in urban ecosystem. *Chinese Journal of Ecology*, 26(10): 1616–1621. (in Chinese)

Vasenev V I, Stoorvogel J J, Vasenev I I. 2013. Urban soil organic carbon and its spatial heterogeneity in comparison with natural and agricultural areas in the Moscow region. *Catena*, 107(4): 96–102.

Xiao Y, Liu S H. 2014. SOC content and its spatial distribution characteristics in urban forest ecosystems of Changsha in China. *Information Technology and Agricultural Engineering*, 134: 95–106.

Yesilonis I D, Pouyat R V. 2012. Carbon stocks in urban forest remnants: Atlanta and Baltimore as case studies, In: Lai R, Agustin B (eds.). Carbon sequestration in urban ecosystems. Dordrecht, the Netherlands: Springer Press, 102–112.

北京城市化梯度带上表层土壤有机碳密度空间分布及影响因素研究

田育红，刘凤花，王甜甜

北京师范大学地理科学学部，地表过程与资源生态国家重点实验室，北京 100875

摘　要：城市表层土壤具有独特的结构和过程，影响着表层土壤有机碳密度（$\mathrm{SOC}_{\mathrm{density}}$）及其空间变化。本研究以北京为例，借助实地调查和室内试验分析了沿着城市化梯度带不同功能区不同土地利用下 $\mathrm{SOC}_{\mathrm{density}}$ 的空间分布特征，并探讨了其对城市化水平、土壤理化属性和植物配置等因素的响应。本研究旨在为像北京这样的快速发展的城市中土壤有机碳驱动机制及相应的气候变化分析提供参考。研究结果发现：（1）在快速发展的区域 $\mathrm{SOC}_{\mathrm{density}}$ 的空间异质性最高；（2）林地的 $\mathrm{SOC}_{\mathrm{density}}$ 含量最高，其次是农田，而其他绿地类型中 $\mathrm{SOC}_{\mathrm{density}}$ 含量最低，但各土地利用和功能区中 $\mathrm{SOC}_{\mathrm{density}}$ 含量的差异并不显著；（3）在大部分区域土壤有效磷（P）是 $\mathrm{SOC}_{\mathrm{density}}$ 主要的正面影响因素；（4）由于城市区域人类独特的干扰活动，随着城市化水平的降低，影响 $\mathrm{SOC}_{\mathrm{density}}$ 的土壤理化指标越多。在整个研究区，城市化率显著提高 $\mathrm{SOC}_{\mathrm{density}}$；（5）草本植物与其他植物配置下的 $\mathrm{SOC}_{\mathrm{density}}$ 并没有显著的差异；（6）在大多数土地利用下城市过程降低了 $\mathrm{SOC}_{\mathrm{density}}$ 的空间异质性，但在发达区域 $\mathrm{SOC}_{\mathrm{density}}$ 的值要比其他地区高。为避免因为人类干扰而造成土壤表层有机碳损失，需要做到以下几点：（1）将凋落物作为肥料归还给绿地；（2）移除绿地中的垃圾、杂质等人为干扰物；（3）施用合适的磷肥以增加土壤表层有机碳的积累。在以后的研究中需要进一步考虑城市不透水层下与人类干扰有关的影响地表土壤碳储量变化的因子。

关键词：土壤有机碳密度；城市化；土壤理化属性；植物配置