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Research paper

The role of urban function on road soil respiration responses

Hong Ye[a,*], Caige Sun[b], Kai Wang[a], Guoqin Zhang[a], Tao Lin[a], Han Yan[b]

[a] Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

Soil plays an important role in carbon storage. Accordingly, urban soil carbon and its storage have great impacts on urban carbon balance and future urban sustainable development. In this study, 151 traffic road soils in five urban functional areas were selected. The discrepancies of field soil respiration, soil physiochemical conditions among urban functional areas were calculated. Factor analysis and the Geographic Detector (GeoD) factor model showed that heavy metals had the most important impacts on soil respiration, followed by organic matter and urban function. Using the geographic detector method, individual factors and their interaction effects on soil respiration were tested. The GeoD interaction model demonstrated that no-linear enhanced interaction exhibited between C and ecological function, between N and residential function, S and industrial function. Moreover, no-linear enhanced interaction existed between Ti and ecological function, between Hg, Zn, Ni and residential function. The GeoD risk detector indicated that Soil temperature, N and Hg in different categories had obvious traffic road soil respiration impacts discrepancy. Overall, the results of this study will be useful for further investigation of urban soil treatment to enable healthy urban functional development.

1. Introduction

Globally, a total of 2500 Pg organic and inorganic carbon is held in soils, which is four times greater than in the biotic pool and about three times greater than in the atmospheric pool. Soil carbon is the last major pool of the carbon cycle, and changes in soil carbon storage can have a large effect on the global carbon budget (Knorr et al., 2005). Soil respiration (SR), including respiration by plant roots, bacteria, fungi and soil animals, is a key ecosystem process that releases carbon from the soil in the form of CO_2 (Kosugi et al., 2007). With rapid urbanization, soil quality and quantity in cities has changed dramatically (Koerner and Klopatek, 2010; Zhang et al., 2012; Li et al., 2017; Wang et al., 2017a,b). In contrast to the carbon emissions from urban soil, a growing number of related studies have quantified the total CO_2 levels in urban environments by calculating the emission inventories from estimates of fossil fuel consumption, evaluating the amount of sequestered carbon in urban vegetation, and studying short-term ambient CO_2 concentrations (Nowak and Crane, 2002; Sharma et al., 2017; Wang et al., 2017a,b; Trammell et al., 2017).

In 1933, the Athens charter declared that the city has four functions; providing habitat, job opportunities, rest and entertainment and commuter. Furthermore, the spatial distribution of city could be established by balancing and connecting these functions. A number of theories and approaches about designing of scientific spatial patterns had been put forward to satisfy the functionality of cities (Fenn et al., 1939). In some studies, urban functions were defined according to the basic social-economic activities, and could be organized at related functional areas such as industrial, residential, commercial, and public facilities and ecological zones.

In order to identity the key soil respiration influential factors, some control experiments or stepwise regression statistical methods had been applied (Raich and Tufekciogul, 2000; Rodeghiero and Cescatti, 2005; Lorenz and Lal, 2009; Beesley, 2014). But the response of soil respiration (SR) to interactions between natural condition and anthropogenic impacts is not well understood, but may increasingly affect future C storage under the combined urbanization impacts of heavy metal deposition, N deposition and climate change (Copeland et al., 2003; Li et al., 2013).

Different urban factions are related to different activities in the specific area, that provides an insight to explore how urbanization impact on soil respiration. Therefore, in this study, by designing field and lab experiments from five contrasting urban function areas, we challenged to investigate how changes and the interactions in physiochemical condition and urbanization regulating SR. Our main purpose was to reveal how soil physiochemical conditions and urban functions jointly influence urban traffic road SR by using statistical and geographical methods. Three main objects were: (1) to explore whether different factors have different significant impacts on SR, (2) to identify

* Corresponding author.
E-mail addresses: hye@iue.ac.cn, yehongg@gmail.com (H. Ye).

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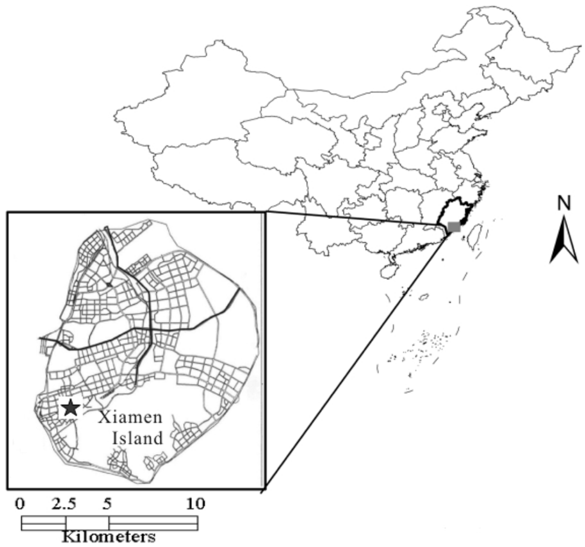

Fig. 1. Study area.

the combined strengths of different impact factors on SR at the group level and (3) to acquire the effect ranges. The results presented herein will facilitate future urban functional organization.

2. Materials and methods

2.1. Study area

Xiamen in southeastern China was selected for this case study. The city is characterized by mild weather, with the annual average temperatures of 22.7 °C, annual precipitation of 19.1 cm and intense solar radiation all year with average sunshine duration of 1877.5 h in 2015. Xiamen had a high urbanization rate of 79.65% in 2015. The city is characterized by rapid population growth with a wide range of both direct and indirect CO_2 sources, such as mobile emissions and land use changes (Fig. 1).

Soil from traffic roads in Xiamen was selected for urban soil representation. Traffic road in Xiamen is developed and characterized by strict traffic discipline. For example, types and running times of the vehicles are strictly arranged in different urban functional areas. Therefore, roads showed discrepancies across urban functional areas.

2.2. Experimental design and field measurements

To identify the effects of urban function on urban SR, 151 traffic soil samples in five typical functional areas of Xiamen were selected (Fig. 2). According to the urban planning discipline combined with 'The Code for Classification of Urban Land Use and Planning Standards of Development' (GB/T 21010-2007) (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2011), urban functional areas including industrial, commercial, residential, ecological and public facility areas were defined in this study and extracted by remote sensing and geographical information system tool (ArcGIS software 10.0).

Soil respiration rate, soil temperature and soil humidity were collected by using a Licor-6400 with a soil chamber. Prior to measurement, grass under the chamber was removed to minimize the effects of vegetation respiration. Following removal of roots, soil samples were oven dried (105 °C), sieved (2 mm) and ground, after which Total C and N were determined by dry combustion (Perkin-Elmer 2400 Series II CHNS/O Analyzer, Perkin-Elmer, Boston, MA, USA). Additionally, inorganic C content was determined by the acetic acid method, and heavy metals were measured by ICP-MASS.

2.3. Factor analysis

For factor analysis, multiple variables are grouped to reduce dimensionality according to the size of the correlation, such that correlation between variables within the same group is higher and the variable correlation between different groups is lower. New factors are formed in each group, and the factors are not related to each other. All variables can be expressed as a linear combination of common factors. Eq. (1) shows the factor analysis model:

$$\begin{aligned} X_1 &= a_{11}F_1 + a_{12}F_2 + \ldots + a_{1m}F_m + \varepsilon_1 \\ X_2 &= a_{21}F_1 + a_{22}F_2 + \ldots + a_{2m}F_m + \varepsilon_2 \\ &\vdots \\ X_p &= a_{11}F_1 + a_{p2}F_2 + \ldots + a_{pm}F_m + \varepsilon_p \end{aligned} \tag{1}$$

where the matrix $A = (a_{ij})$ is the factor load matrix and a_{ij} is the factor loading, which is a correlation coefficient of the common factor F_i and variable X_j. ε represents influencing factors other than the common factors (Lattin et al., 2003). We conducted factor analyses to test how urban traffic road SR varies as a function of soil physiochemical conditions and urban functions.

2.4. Geographic detector model description

The geographical detector model (GeoD) is a spatial analysis model based on the theory of spatial heterogeneity and applied widely in many ecological researches. The model quantitatively detects and identifies various interactions between a geographical attribute and its explanatory factors (Wang et al., 2010). GeoD is composed of risk, factor, ecological, and interactive detectors. The Geographic Detector model is freely available from www.sssampling.org/geogdetector. Assuming that urban functions and certain physiochemical conditions jointly influence SR, the risk detector is used to search for the range in which factors significantly affect SR, while the factor detector is used to explore the impact of different factors on the research target. Additionally, the ecological detector is used to explore whether different factors have different significant impacts and the interactive detector is used to identify the combined strengths of different impact factors on SR. SR was set as the dependent variable in statistical analysis. Multiple physiochemical and urban function factors set as independent variables were input into the GeoD model for simulations.

2.5. Standardization

Different data type exists on physicochemical condition and urbanization functions. For demonstrate impacts on SR from parameters, we standardized the data according to Eq. (2).

$$y_i = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \tag{2}$$

where y_i is the standardized data, x_i is the original data. $x_{\min}$ and $x_{\max}$ represent the minimum and the maximum value of the original data respectively.

3. Results and discussion

3.1. Soil characteristics

The surveyed soil CO_2 emissions ranged from 0.216 μmol m^{-2} s^{-1} to 4.051 μmol m^{-2} s^{-1}, with an average of 1.604 μmol m^{-2} s^{-1}. The SR was lowest in the public facility area, and increased from 0.531 μmol m^{-2} s^{-1} to the highest value of 2.117 μmol m^{-2} s^{-1} in the residential area. Overall, the SR rate in this study was slightly lower than those exhibited in the similar climatic condition area such as Changle, Fujian Province (with 2.26 ± 0.29 μmol m^{-2} s^{-1}) and Taicang, Jiangsu Province (2.33 ± 0.13 μmol m^{-2} s^{-1}) (Jiang et al., 2014). But it was far lower than the other studies reported in Phoenix,

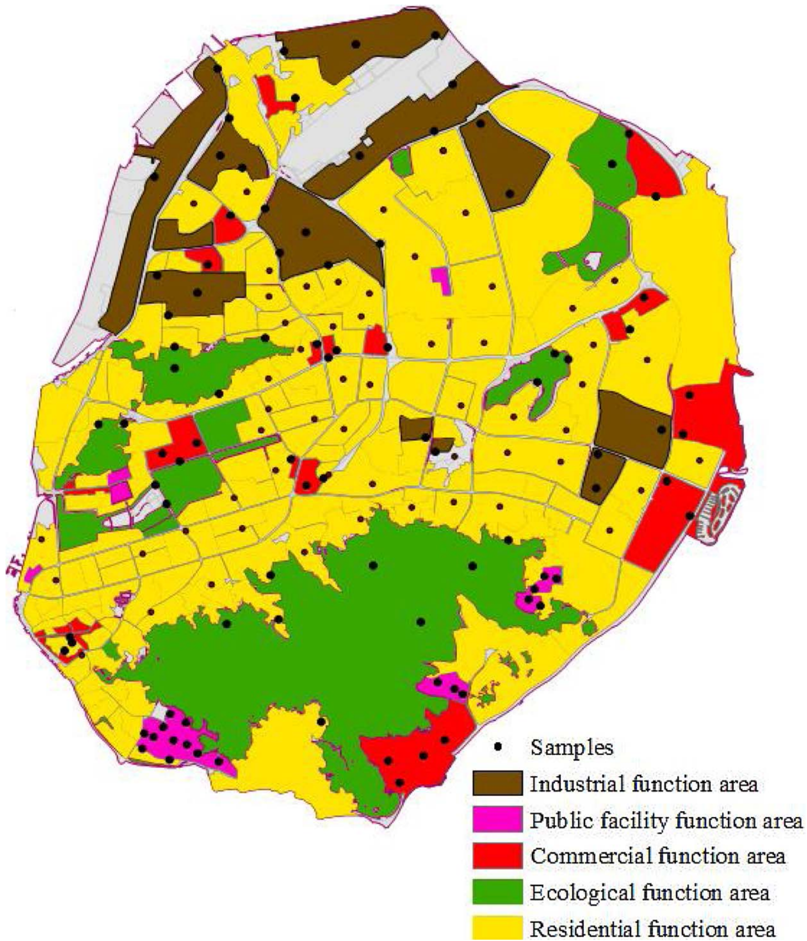

Fig. 2. The spatial distribution of collected samples.

AZ, USA (3.70 μmol m^{-2} s^{-1}) and Fort Collins, CO, USA (7.34 ± 0.72 μmol m^{-2} s^{-1}) (Kaye et al., 2005). Soil relative moisture of the selected samples ranged from 67.25% to 78.47% with an average of 73.44% while the soil temperature was with an average of 29.07 °C, as compared to the highest value of 31.77 °C and the lowest of 26.06 °C. The range of the soil relative moisture and temperature is relatively narrow due to similar climate conditions in a 132.5 km^2 study area. The average soil organic S, N and C was 0.038%, 0.056% and 0.737%, respectively. Spatially, soil organic matter presents a high variability (Fig. 3a). As shown in Fig. 3b), the typical heavy metals found in traffic road soil are Hg, Pb, Zn, Ni, Ti, Cu, Cd at average contents of 97.82 mg/kg, 18.66 mg/kg, 89.98 mg/kg, 26.60 mg/kg, 735.54 mg/kg, 37.78 mg/kg and18.77 mg/kg respectively. The highest soil heavy metals variation was observed in the residential area with standardized value 0.66, followed by that in public facility areas (0.59). The third highest heavy metal concentration was in the commercial area (0.43); However, the third highest total C/N/S was in the ecological area (0.22). The fourth highest heavy metal was in the ecological area (0.36); However, the fourth highest total C/N/S was in the commercial area (0.13) (Fig. 3c).

3.2. Impacts on soil respiration

Factor analysis was conducted to reduce the dimensionality for four groups of 17 influencing factors. Upon factor analysis, the first four characteristic roots, F_1, F_2, F_3, and F_4, exceeded value 1. The cumulative variance contribution rate of the first four common factors was 79.39%, The variance contribution rates of F_1, F_2, F_3, and F_4 were 31.63%, 19.96%, 17.32%, and 10.48%, respectively (Tables 1 and 2).

F_1 had a greater load for the heavy metal factors (Cd, Pb, Zn, Ni, Ti, Hg have the highest value in component 1); therefore, it is taken as the soil pollutant factor (PF). F_2 had a greater load for soil temperature and humidity (soil temperature and humidity have their highest value in component 2). F_3 had a greater load for the three soil organic C/N/S whose highest value located in component 3, which combined with soil temperature and humidity was taken as the overall soil ecological factor (EF). F_4 had a greater load for the five groups of urban function factor (UF) symbolized by their highest value in component 4, and was therefore taken as the overall urban function influential factor.

GeoD factor detector model results indicated that the soil heavy metal was most important to SR ($q = 0.711$), followed by temperature, humidity ($q = 0.596$) and soil organic matter ($q = 0.313$), and then urban function ($q = 0.286$). PFs and EFs were dominant factors that influenced SR. Specifically, heavy metals Hg ($q = 0.698$), Cd ($q = 0.607$), Zn ($q = 0.504$), Ni ($q = 0.220$), Pb ($q = 0.189$), Cu ($q = 0.167$), soil temperature ($q = 0.607$), humidity ($q = 0.187$) and soil S ($q = 0.222$), C ($q = 0.208$), and N ($q = 0.196$) had greater impacts on SR than urban function (Davidson and Janssens, 2006; Chen et al., 2014). These results were consistent with those from factor analysis. Different from rural and natural soil, the heavy metal in urban soil played an important role in traffic road SR. Slight increases in heavy metals introduced via fossil fuels combustion (e.g., Pb) or through friction between the tire and road surface (e.g., Ni, Cd) may accelerate utilization of soil carbon by soil microbes, thereby accelerating carbon turnover rate. Pollutant deposition and heat island effects in response to urbanization land use and land cover change processes would led to carbon dioxide changes evolved by contaminated material (Nwachukwu and Pulford, 2011).

In our experiment, EFs had the second most important effect on SR. Soil carbon decomposition was temperature sensitive, and closely

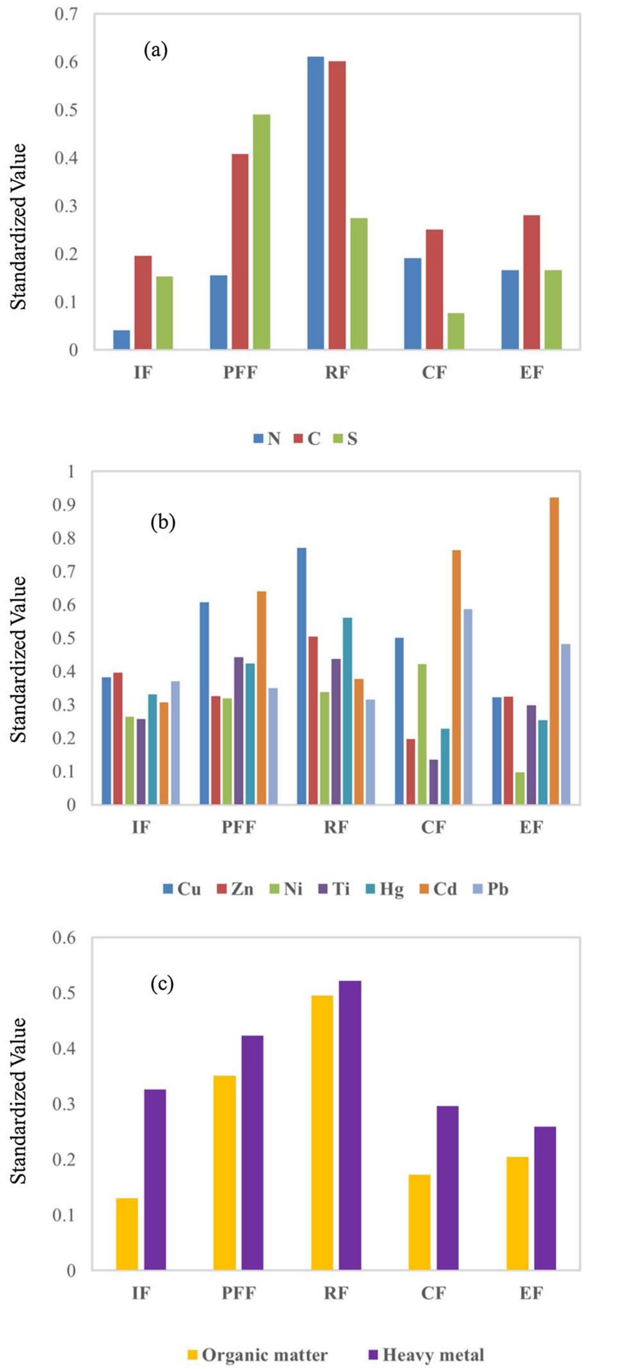

Fig. 3. The characteristics of surveyed soil.
Note: IF, PFF, RF, CF and EF represent Industrial function area, Public facility function area, Residential function area, Commercial function area and Ecological function area respectively.

related to humidity (Fang et al., 2005). Urbanization is likely to result in a greater increase in urban heat absorption than in thermal inertia and therefore, increase diurnal land surface temperature variation (Chen et al., 2017). The temperature sensitive of the soil carbon decomposition could accelerate the metabolic activity of soil organisms and account for the increase in SR.

When compared with soil pollutant conditions and ecological factors, urban function had the third most important effect on SR. Although this effect was relatively weak, the urban function could not be ignored because of its importance to urban planning and ability to facilitate reduced soil carbon emissions.

Table 1
Rotated Component Matrix.

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative%
1	3.163	31.63	31.63
2	1.996	19.958	51.587
3	1.732	17.322	68.909
4	1.048	10.483	79.392
5	0.9	8.999	88.391
6	0.579	5.791	94.182
7	0.312	3.123	97.304
8	0.178	1.779	99.083
9	0.087	0.868	99.951
10	0.005	0.049	100

Table 2
Total Variance Explained by Principal Component Analysis.

	Component			
	1	2	3	4
Residential function	0.501	−0.008	−0.526	0.598
Industrial function	−0.303	−0.371	−0.19	0.536
Commercial function	0.308	−0.224	−0.47	0.718
Public facility function	0.072	0.273	0.26	0.726
Ecological function	−0.26	0.225	0.009	0.605
N	0.376	0.342	0.723	0.024
C	0.212	0.654	0.666	0.109
S	0.341	−0.171	0.689	−0.494
Cd	0.686	0.26	−0.11	0.254
Pb	0.558	0.124	−0.07	−0.475
Zn	0.631	−0.259	0.264	0.261
Ni	0.619	0.169	−0.177	0.122
Ti	0.714	−0.472	0.347	−0.147
Hg	0.802	−0.254	−0.121	0.389
Tsoil	−0.283	0.607	0.487	0.333
Humidity	−0.036	0.656	0.314	0.065

The factor analysis model in the present study showed that increases in SR were a combined result of soil ecological condition, pollutant condition and urban functions. GeoD interaction model was used to reveal the complicated interactions among various factors and their contribution to the heterogeneity of SR.

3.3. Interaction effects on urban soil respiration

3.3.1. Interaction effects on urban soil respiration at the group level

GeoD interaction model demonstrated that nonlinear interactions were observed for all relationships among the three selected group factors: The effect from the interaction of UF with EF (UF∩EF) was greater than that from the two sub-factors individually (UF, EF), as well as a simple combination of them (UF + EF). We used two simple equations, (UF∩EF) > (UF, EF) and (UF∩EF) > (UF + EF) to describe this finding, here '∩' means interaction and '+' means combination. Such model was also applicable to UF and PF, based on the calculation. We found that for factor UF and PF, the relationship between them is similar, that is (UF∩PF) > (UF + PF) or (UF∩PF) > (UF, PF). These findings illustrated that there were strong interaction effects between the dominant factor and urban functions. The UF group, EF group and PF group could contribute to soil respiration by themselves. Meanwhile, the effects on soil respiration would be enhanced when enforcement coming from the UF group interacted with one of the other two groups. UFs are essential of typical city characteristics due to comprehensive factors such as industrial frame and population density. UF could be fulfilled in a specific spatial area, which would lead to discrepancies among urban functional areas. For example, roads in residential areas are different from those in industrial areas in that they are generally more developed, have smaller vehicle capacity, and are present in greater numbers than in industrial regions. Conversely, some ecological areas in Xiamen were constructed for tourist areas and therefore differ from those in residential and industrial areas. Knowledge regarding the interaction between UF and EF or PF will facilitate management of soil carbon respiration.

3.3.2. Single factor and urban function interaction effects

Our results showed nonlinear enhancement exhibited in the interactions between N and public facility areas, between C and ecological areas, and between S and industrial areas. It demonstrated that urbanization had the potential to greatly influence functional area C and N cycles by altering the biotic system through changes in water and energy conditions (Xu et al., 2016). Non-linear interactions enhancement also existed between Hg, Zn, Ni and residential areas, as well as between Ti and ecological areas. Typical vehicle type and operational time in typical urban functional areas led to the presence of unique heavy metals which regulating the response of soil microorganism respiration as well as changed soil organism respiration processes (Zhou et al., 2016).

3.3.3. Effect range detector

In this study, the explanatory factors are the category variables. The GeoD risk detector was used to detect the impacts of explanatory factors between categories. The results showed that geochemical conditions had varying impacts on SR in different category levels. The impacts on SR from Hg increased gradually from level 2 (range, 119 mg/kg–146 mg/kg) to level 3 (range, 154 mg/kg–180 mg/kg) and then level 4 (range, 206 mg/kg–248 mg/kg). While the increasing SR effect exhibited from soil temperature level 1 (range, 25.31 °C–25.81 °C) to level 2 (range, 25.97 °C5–26.84 °C) and to level 4 (range, 27.32 °C–30.04 °C). N in level 5(range, 0.117%–0.173%) and level 2 (range, 0.028%–0.034%) made a greater contribution to SR than level 1(range, 0.0217%–0.0221%). These findings will facilitate scientific urban soil management by detail range physiochemical conditions controlling.

4. Conclusions

Because of the complex interactions between physiochemical and urban environmental factors, it is difficult to isolate the effects of individual factors on SR. This study proposed a novel approach for detection of urban function impacts on SR using combined factor analysis and GeoD analysis based on a study of Xiamen, which is undergoing rapid urbanization.

Variations in SR reflect the synthesis results of physiochemical and urban function influences. For the examined case, heavy metals contributed greatly to SR, whereas the corresponding contributions from temperature/humidity, organic matter and urban function decreased gradually.

In general, soil physiochemical condition had strong capacity for SR, which was nonlinear enhanced when interaction with urban function. These findings demonstrate that urbanization could effectively change soil moisture, temperature, and heavy metal conditions, as well as change the SR environment.

Our interaction study also identified the dominant factors in urban function when considering their integrated effects on SR. Moreover, some physiochemical range levels were accessed with high confidence to reveal that dominant factors in special categories had a high ability to control SR.

During rapid urbanization, urban soil carbon management plays an important role in urban sustainability. Scientific soil carbon management can alleviate CO_2 emitted from soil, improve air quality. Although quantitative interactions between urban function, soil organic matter and heavy metals were not exhibited, the results did suggest that further study investigating the interactions between these factors are warranted to provide a scientific basis for improvement of urban function, and for addressing climate change adaptation policies.

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