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Urban soils as hot spots of anthropogenic carbon accumulation: Review of stocks, mechanisms and driving factors

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Abstract

Urban soils and cultural layers may accumulate C over centuries and consequently large C stocks may be sequestered beneath cities. Processes and mechanisms leading to high C accumulation in urban soils remain unknown. Data on soil organic carbon (SOC), soil inorganic carbon (SIC), black (pyrogenic) carbon (BC), and nitrogen contents and stocks in urban soils were collected from 100 peer-reviewed papers. The database (770 data points for SOC, SIC, and BC stocks from 116 cities worldwide) was analysed considering the effects of climate and urban-specific factors (city size, age, and functional zoning) on C stocks. The processes of C accumulation specific for urban soils were analysed, and C sequestration rates were assessed. For the wide range of climatic conditions, total C content in urban soils was 1.5–3 times higher, and C accumulation was much deeper compared with natural soils, resulting in 3–5 times larger total C stocks. Urban SOC stocks increased with latitude, whereas SIC stocks were less affected by climate. City size and age were the main factors explaining intercity differences in C stocks. The intracity variability of C and N stocks was dominated by functional zoning: Large SOC and N stocks in residential areas and large SIC and BC stocks in industrial zones and roadsides were consistent across all climates and for cities of various sizes and ages. Substantial amounts of SOC, SIC, and N are sequestered in the subsoils, cultural layers, and sealed soils, underlining the importance of these hidden stocks for C assessments. Long-term C input from outside the cities and associated C accumulation coincided with upward soil growth of ~50 cm per century, and continuous accumulation of 15–30 kg C/m^2 per century in urban soils and cultural layers. We conclude that, despite the relatively small area of cities, urban soils are hot spots of long-term soil C sequestration worldwide, and the importance of urban soils will increase in future with global urbanization.

KEYWORDS
carbon accumulation rate, cultural layers, global change, pyrogenic carbon, urbanization processes, xeno-C

1 | INTRODUCTION

1.1 | Urban soils: features, functions, and environmental relevance

Globally, urbanization is progressing rapidly, with more than two thirds of the world population expected to live in cities by 2050 (Food and Agriculture Organization of the United Nations [FAO], 2013; United Nations, 2008). Urbanization coincides with substantial changes of vegetation and soils (Pickett et al., 2011). Urban ecosystems range from seminatural and slightly disturbed (e.g., in green infrastructure and recreational and suburban areas) to completely artificial (e.g., roads and built-up areas). The components of urban ecosystems, including surface water, vegetation, and soils, are dominated by anthropogenic effects (e.g., fragmentation, pollution, and physical disturbance) and therefore differ completely from their natural counterparts.

Urban soils are a key component of urban ecosystems, responsible for multiple functions and services, including water drainage, substrate and support for green infrastructures, habitat for microorganisms, and carbon (C) sequestration (Lorenz & Lal, 2009; Morel, Chenu, & Lorenz, 2014). The role of soils in sustainable development of urban ecosystems and their contribution to the comfort and well-being of city dwellers are widely recognized. For example, soils attenuate air and water pollutants, provide the physical basis for civil engineering and infrastructures, and even conceal and preserve historical artefacts (Blum, 2005; Dominati, Patterson, & Mackay, 2010). Recent studies highlighted the contribution of urban soils to global environmental issues such as climate change mitigation (Decina et al., 2016; Gómez-Baggethun & Barton, 2013; Weissert, Salmond, & Schwendenmann, 2016), but a global assessment of C sequestration in urban soils is absent.

Global estimates of urban areas give approximately 2.5% (Elvidge et al., 2007; Schneider, Friedl, & Potere, 2009; Sharma, Tateishi, Hara, Gharechelou, & Iizuka, 2016), but urban areas can cover up to 10% regionally (Kachan, Rybalsky, Samotesova, & Barsova, 2007). Urbanization affects soils far beyond the settlement boundaries (Svirejeva-Hopkins & Schellnhuber, 2006; Yang & Zhang, 2015). For example, human-influenced and man-made soils would likely be found at private cottage villages, which proliferate around major cities (Argenbright, 2011; Pickett et al., 2011). The environmental relevance of urban soils is much broader than their area and may further increase with ongoing urbanization globally.

1.2 | Urban soils: definitions and classifications in global and regional surveys

'Urban soils' represent a relatively novel direction in ecosystem sciences. Conventional soil surveys have focused on natural and agricultural areas and excluded urban soils. Major international (FAO, 1988, 1998) and national soil classifications (e.g., Egorov, Fridland, Ivanova, & Rosov, 1977; KA5, 2005; Shishov, Tonkonogov, Lebedeva, & Gerasimova, 2004) paid limited attention to urban soils or ignored them completely. The growing importance of urban ecosystems in the last few decades has resulted in consideration of urban soils in recent editions of the World Reference Base (WRB), where new reference groups of Technosols and Anthrosols were included (Rossiter, 2007; WRB, 2014). A broader definition of 'SUITMAs' (Soils of Urban, Industrial, Traffic, Military, and Mining Areas) was proposed to identify a wider range of human-modified soils (Morel & Heinrich, 2008). An 'urban soil' can be identified based on spatial or pedological criteria. The spatial definition is used to designate soils inside urban areas, whereas the pedological definition stresses domination of the anthropogenic factor over the other five factors of soil formation. The pedological definition is more scientifically relevant and is used for field diagnostics and classification purposes (Lehmann & Stahr, 2007). However, its implementation for spatial analysis of urban soil properties is constrained by their high heterogeneity (Rossiter, 2007; Vasenev, Stoorvogel, Vasenev, & Valentini, 2014).

We define urban soils as seminatural four-dimensional bodies at the Earth surface, developed and functioned by a combination of physical, chemical, and biological processes under strong predominance of anthropogenic factors and being an essential part of all urban ecosystems.

Variety and mutual relationships between natural and anthropogenic soil-forming factors result in a unique spatial–temporal heterogeneity of processes, features, and functions of urban soils (Puskás & Farsang, 2009; Sarah, Zhevelev, & Oz, 2015). To deal with the diversity of urban soils, some studies proposed more detailed classification and diagnostics. For example, more than 10 subtypes, including 'culturozems' (soils of recreational areas), 'constructozems' (artificial soil constructions), and 'ekranozems' (soils under sealed surfaces) were proposed for urban soils in Moscow, Russia (Gerasimova, Stroganova, Mozharova, & Prokofieva, 2003; Prokofyeva, Martynenko, & Ivannikov, 2011). 'Man-changed' and 'man-made' soils were distinguished by Lehmann and Stahr (2007) to differentiate between natural soils exposed to anthropogenic effects and completely artificial soils. Four categories were proposed for SUITMAs (Morel et al., 2014) according to their role in urban ecosystems: vegetated pseudonatural, vegetated engineered, dumping sites, and bare soils.

Historically, urbanization and urban soils were related to soil and land degradation, whereas environmental functions of urban soils (e.g., habitat for biota, nutrient storage, decontamination and filtering functions, and carbon sequestration) were ignored as a rule. Land degradation resulting from urbanization includes such processes as contamination, salinization, and overcompaction (McKinney, 2006; Smagin et al., 2006; Stroganova, Myagkova, & Prokofieva, 1997). Consequently, plenty of urban soil studies focus on contamination control (Li, Poon, & Liu, 2001; Manta, Angelone, Bellanca, Neri, & Sprovieri, 2002; B. Wei & Yang, 2010). However, new concepts of sustainable cities were proposed recently to improve the environmental safety and the quality of life for city dwellers (Jansson, 2013; Jim, 2013). These concepts highlight the role of urban soils to provide and support important services, for example, enhancing C and N storage (Lorenz & Lal, 2009; Raciti & Fahey, 2008; Vasenev et al., 2015). Studying C stocks and sequestration in urban soils is becoming increasingly relevant, considering the continuous urbanization.

1.3 | What do we know and what do we not know about C stocks in urban soils?

The urban environment brings with it a very specific set of conditions and processes affecting C accumulation in soil. Of the six factors of soil formation, the anthropogenic factor dominates urban soils' formation and functioning, both directly and indirectly (Lehmann & Stahr, 2007; Lorenz & Lal, 2009). Direct effects include physical alterations (e.g., soil sealing, input, withdrawal, and relocation of topsoil material) and addition of neutral, ballast, or toxic substrates (Table 1). Indirect effects refer to anthropogenic alterations of the urban environment that modify the other five, natural soil-forming factors (i.e., climate, relief, parent material, vegetation, and time). Both direct and indirect factors have various effects on C stocks and fluxes and completely change the natural C cycle and accumulation in urban soils. Different forms of carbon—soil organic carbon (SOC), soil inorganic carbon (SIC) and black or pyrogenic carbon (BC)—differ in sensitivities to anthropogenic effects. In addition, xenobiotic carbon (xeno-C), including wastes of artificial polymers, polycyclic aromatic hydrocarbons, and other organic pollutants, contributes to long-term carbon storage in urban soils (Table 1).

1.3.1 | Direct anthropogenic effects on C stocks in urban soils

Construction of infrastructure (houses, highways, industries, etc.) results in considerable SOC losses through excavation and relocation of the fertile topsoil layer and soil sealing (Kaye, McCulley, & Burke, 2005; Elvidge et al., 2007; Raciti, Hutyra, & Finzi, 2012). Soil sealing, however, can indirectly contribute to C storage by isolating subsoil C and decreasing mineralization, thus reducing CO_2 emission (Z. Wei, Wu, Yan, & Zhou, 2014; Zhao, Zhu, Zhou, Huang, & Werner, 2013). Establishing green infrastructure, in contrast, has clear positive effects on SOC stocks by increasing net primary productivity with urban trees and lawns (Nowak & Crane, 2002; Zirkle, Lal, & Augustin, 2011). Addition of natural organic substrates (e.g., turf, peat, or compost) increases SOC stocks in urban soils. However, intensive decomposition by microorganisms can result in 30–40% loss of C in these materials as CO_2, within just a few years (Shchepeleva et al., 2017; Vasenev, Epikhina, Fatiev, & Prokhorov, 2014). Heating industries and fossil fuel combustion are important BC sources (Preston & Schmidt, 2006; Rawlins et al., 2008). Cement and construction industries increase SIC stocks by input from dust deposition and disposal of construction wastes with high lime contents (Prokof'eva, Kiryushin, Shishkov, & Ivannikov, 2017; Stroganova et al., 1997).

Combustion products and recycling of domestic wastes increase all three of SOC, SIC, and BC stocks in urban soils. The increase results also from the input of materials from outside the city (i.e., rural and suburban areas), their transformation, and deposition in the vicinity of residences or in landfills (Lorenz & Lal, 2009). Besides the input of these natural substances modified by anthropogenic processes, persistent xenobiotics play an important and continuously increasing

TABLE 1 Contribution of direct and indirect anthropogenic effects to accumulation of C stocks in urban soils (ranked based on the literature data and expert assessment)

	Contribution to stocks				Contribution to fluxes		
Anthropogenic effects	Soil organic C	Soil inorganic C	Black C	Xenobiotic C	Inputs	Outputs	In situ changes
Direct							
Soil sealing	−−	+	+	++			*
Removal of topsoil	−−−	−	−			***	
Importing materials (i.e., turf, peat, and composts) to construct urban soils (e.g., for greening purposes)	+++	+	+		***		
Pruning and cutting lawns and ornamental shrubs	++					***	**
Fertilizing and irrigation	++	+			**	***	**
Wood combustion	+	+	+++			***	*
Fossil fuel combustion for industrial and domestic needs and transport	+		+++	+++		**	*
Cement industry or building construction		+++			**	**	**
Chemical industries		+	+	+++	*		*
Waste management	+++	++	++	+++	*	***	**
Overcompaction	++	++	++				**
Contamination or salinization				+++			**
Residential history (accumulation of cultural layers)	+++	++	+++	+		**	***
Indirect (altered soil-forming factors)							
Heat island effect (climate)	−−					**	
Water budget (climate)	++	−					**
Urban vegetation (biota)	+++				***		
Levelling, terracing (relief)	++				**	*	
Urban sediments, cultural layers, and buried horizons of natural soils (parent materials)		++	+	+	***		*
Time factor (young age and usual renovation of urban soils)	+				**	***	**

Note. + = positive contribution (corresponding stocks increase); − = negative contribution (corresponding stocks decrease); +/− = minor contribution; ++/−− = moderate contribution; +++/−−− = strong contribution to the corresponding stocks; * = minor contribution; ** = moderate contribution; *** = strong contribution to the corresponding fluxes. Empty cells refer to negligible contribution.

role in C sequestration, especially in urban soils. These xeno-C stocks include (a) asphalt and bitumen resins used for road construction (Kida & Kawahigashi, 2015); (b) plastics and polymers (i.e., polyethylene, polypropylene, polyisobutene, polyvinyl chloride, Teflon, thermoplastics, and elastomers) used for construction (e.g., tubes and pipes) and food industries (e.g., packaging; Skariyachan et al., 2015; Yabannavar & Bartha, 1993); and (c) polycyclic aromatic hydrocarbons and synthetic rubber, coming from chemical industries and transport (Yang et al., 2016). The xeno-C inputs from construction, industry, services, and transport increase with growing urbanization (Jaward, Farrar, Harner, Sweetman, & Jones, 2004; Lorenz & Lal, 2009). Although many studies focus on these xenobiotics as pollutants (Tang, Tang, Zhu, Zheng, & Miao, 2005; Yang et al., 2016), their contribution to C accumulation in urban soils has never been quantified. Xeno-C stocks are abundant in urban soils as organic pollutants, anthropogenic inclusions (i.e., pieces of rubber, plastic, and asphalt remains), pavements and isolating materials, and underground pipes. An absence of natural decomposition mechanisms for these and other xenobiotics leads to their long-term persistence in soil. Whereas xenobiotic stocks in natural and agricultural soils are irrelevant for C sequestration, their accumulation in urban soils, and especially in landfills, roadsides, and industrial areas, makes them locally relevant for total C stocks.

1.3.2 | Indirect effects of cities on C accumulation in soils

Indirect effects are mainly related to changes in SOC decomposition rates in urban soils. Some factors accelerate decomposition (e.g., higher temperature and enhanced plant biomass growth), and others retard it (e.g., soil sealing and waterlogging) relative to natural soils.

Urban climate is an excellent example of indirect anthropogenic effects on soils. Air temperature in densely urbanized areas is on average 2–4 °C higher than in suburban areas (Savva, Szlavecz, Pouyat, Groffman, & Heisler, 2010). This so-called urban heat island effect (George, Ziska, Bunce, & Quebedeaux, 2007; Oke, 1973) increases the temperature of urban soils (Smagin, Shoba, & Makarov, 2008) and stimulates microbiological activity, which accelerates SOC mineralization and depletes SOC stocks. At the same time, a higher average temperature may increase the growing season of urban vegetation in boreal climates and contributes to additional C input into the soil, with consequences for microbial biomass and SOC stocks (Cadenasso, Pickett, McDonnell, & Pouyat, 2007). Relief is another important soil-forming factor, which is almost completely artificial in urban areas. Levelling and terracing for construction purposes combat soil erosion and decrease C outputs in lateral fluxes (Leake & Haege, 2014).

Temporal dynamics of C stocks in urban soils are also very specific. Permanent anthropogenic disturbances, urban relief modifications, and formation of anthropogenic sediments result in short cycles of soil formation and the ‘young’ age of urban soils (Vasenev et al., 2017). This is partly similar to the formation sequences of Fluvisols (Zielhofer, Recio Espejo, Núnez Granados, & Faust, 2009). The trend of topsoil's upward growth is referred to as ‘synlithogenic’ soil formation, which is rare under natural conditions (Andosols and Fluvisols), but typical for urban soils (Prokof'eva et al., 2017). Consequently, and in contrast to most natural soils, the pedogenic age of urban topsoils is always younger than that of subsoils.

Long-term residential activity contributes substantially to C accumulation in urban subsoil and ‘urbosediments,’ referred to as ‘cultural layers’ (Alexandrovskaya & Alexandrovskiy, 2000; Dolgikh & Aleksandrovskii, 2010). The depth of cultural layers ranges from 0.5 m in recently developed areas to as deep as 10 m in historical centres and relief depressions (e.g., old streams, gullies, and river valleys). Considering that average C content in these sediments can be 3–5% or more (Aleksandrovskii, Aleksandrovskaya, Dolgikh, Zamotaev, & Kurbatova, 2015; Vasenev, Stoorvogel, & Vasenev, 2013), cultural layers are the most significant local SOC stocks in ancient and medieval cities. Other direct and indirect factors accelerating or reducing C accumulation and decomposition of organic matter in urban compared with natural soils are presented in Table S1.

1.3.3 | Gaps of knowledge on C accumulation in urban soils

Most existing information on urban SOC stocks was obtained in temperate to tropical climates of the northern hemisphere (from 30°N to 50°N), where most urban areas are located (Sharma et al., 2016). Much less is known about urban soils in equatorial climates or at high latitudes. Several reviews (e.g., Lorenz & Lal, 2009, 2015; Vodyanitskii, 2015) compared C stocks in urban soils from various countries, but global patterns of urban soil C have never been analysed (at least results have not been published), and the relevance for C accumulation in urban soils has not been presented.

There is a substantial bias in urban soil research towards studying SOC contents and stocks in comparison with other C forms: SIC, BC, and xeno-C. There is also a lack of knowledge about intercity and intracity variability in SOC, SIC, and BC stocks and the factors behind this variability. Various approaches are used to assess spatial variability of C stocks in urban soils, including urban–rural gradients (Kaye, Burke, Mosier, & Guerschman, 2004), proximity to roads (Ghosh, Scharenbroch, & Ow, 2016), percentage of sealed areas (Raciti, Hutyra, Rao, & Finzi, 2012), historical and functional zonality (Vasenev, Prokof'eva, & Makarov, 2013; Vasenev, Stoorvogel, et al., 2014). There are few comprehensive studies that apply similar methods to several cities with different climates, ages, and structures (Madrid et al., 2006; Pouyat et al., 2015; Pouyat, Yesilonis, & Golubiewski, 2009). Datasets representing a wide range of climatic conditions, size and history of cities, management and functional zoning are needed. Information on subsoil C stocks and C stocks in sealed soils is also very limited, and the mechanisms of C accumulation in cultural layers and under impervious surfaces remain unknown.

This review provides a comprehensive analysis of (a) the global pattern of C stocks in urban soils as compared with natural soils under the same climate; (b) factors of intracity and intercity variability of C stocks as related to three main C forms (SOC, SIC, and BC); (c) profile distribution of C forms stored in urban soils, compared with natural soils; and (d) an estimation of C accumulation time in urban soils. Such analysis is necessary to understand the phenomena of urban soil C stocks, to analyse the processes and mechanisms of C accumulation in urban soils, and to assess perspectives of urban soils in sustainable city management.

2 | MATERIALS AND METHODS

2.1 | Basic definitions and terms

The following units and approaches are used in this review to analyse C contents and stocks in urban soils. *Carbon contents* of soils are presented as percentage of C in bulk soil (% dry weight), whereas *C stocks* are the amounts of C per surface area (kg C/m^2). Three forms of C stocks were studied: SOC, SIC, and BC. Throughout the manuscript, the term *C stocks* refers to the total stocks including all the three forms. Considering the global scale of analysis, urban areas and urban soils were identified based on spatial criteria—location within legal city boundaries according to regional and global maps (e.g., ESRI world urban areas). Therefore, any soils located inside urban (city, town, or village) areas were accepted as 'urban.' Additional information on functional zoning, management, or soil profiles was considered, for example, to segregate artificial urban soils from seminatural soils in suburbs. Urban soils were compared with their natural counterparts. Natural soil types based on the Harmonized World Soil Database v 1.2 (Fischer et al., 2008) and dominating in the 10-km buffer surrounding a city were selected as natural counterparts for comparison.

Profile distributions of C stocks in urban soils were analysed and compared with those in natural soils. Urban soil profiles differ from natural soil profiles morphologically (e.g., straight and sharp boundaries between the layers and large amount of artefacts) and genetically (e.g., artificial addition of mineral, organic, or drainage materials). To consider these differences, the term *horizon* will be used for *natural soils*, whereas *layer* will be used for *urban soils*. To compare data between individual studies and to investigate the profile distribution, C stocks were recalculated to standard depths: 0–10, 0–30, 0–50, and 0–100 cm. These depths correspond to the majority of the available studies on C stocks in urban and natural soils. *Topsoil* C stocks refer to the 0–10- or 0–30-cm depth, whereas *subsoil* C stocks refer to 30–100-cm depth, as proposed by many global studies on natural soils (Batjes, 1996, 2009; FAO, 1995). Because C stocks in deep soil layers of medieval and ancient cities may be high (Dolgikh & Aleksandrovskii, 2010; Mazurek, Kowalska, Gasiorek, & Setlak, 2016), C stocks below 100 cm (but not deeper than 200 cm) were calculated and referred to as *cultural layers* (below 100 cm). Therefore, our study included C stocks in topsoil, subsoil, and cultural layers of urban soils.

The C content and stocks in urban soils at 0–10, 0–30, and 0–100 cm were compared with the data for their natural counterparts, extracted and recalculated from the global soil datasets, including Harmonized World Soil Database v 1.2, Digital Soil Map of the World (FAO, 1995), and ISRIC-WISE Harmonized Global Soil Profile Dataset (Batjes, 2009).

2.2 | Literature survey and data collection

A literature search in the Scopus database for the keyword combinations 'urban soil' × 'carbon,' 'urban soil' × 'organic carbon,' 'urban soil' × 'inorganic carbon,' and 'urban soil' × 'black carbon' was performed to obtain an overview of existing information and to evaluate data availability for C stocks, with coverage of various countries and climate zones. The search yielded 1,617 publications, 80% of which were published in the last 10 years. Although data from 40 countries were available, almost half of the sources referred to the United States or China, indicating a significant geographical bias in urban C research. Information on the three C forms in urban soils was also unequally distributed. The major part (almost 78%) of available papers focused on SOC. The SIC and BC stocks were much less investigated, with respectively 13% and 9% of the analysed papers (Figure 1). Most of the publications presented local studies focused on topsoil SOC stocks in comparison with their natural counterparts. Although we have not found separate studies on xeno-C stocks in urban soils, we assume that this C is methodically accounted for within SOC and was not analysed separately. The analytical methods for xeno-C stocks (not for the forms) are the same as for natural SOC (i.e., dry or wet combustion), but their origin, chemical composition, persistence, and effects on microorganisms are completely different. This needs to be considered in future studies.

The collected papers were examined, and those without numerical data on C stocks in urban soils (e.g., papers focused on atmospheric

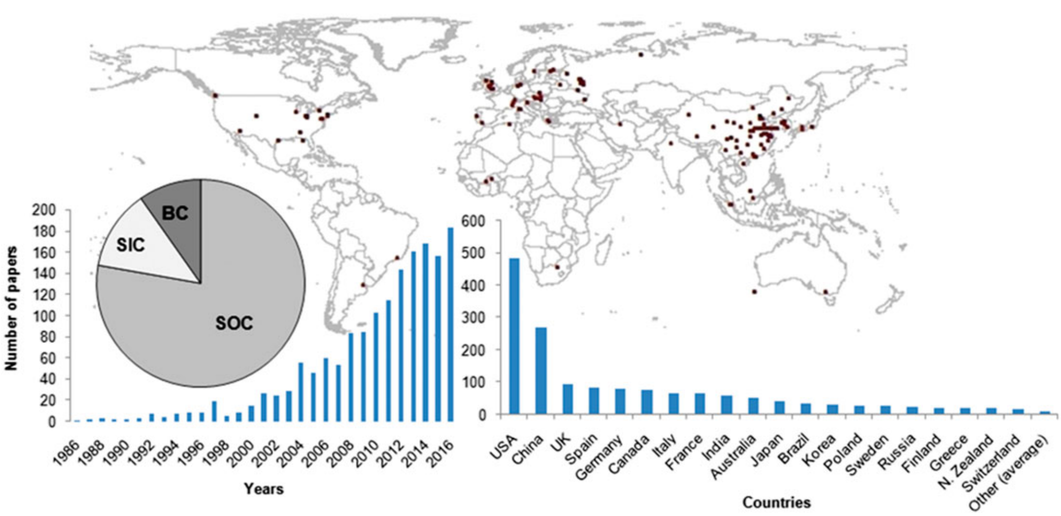

FIGURE 1 Published studies to C stocks in urban soils over the last 30 years for various C forms in various countries (C; based on Scopus review from January 10, 2016, www.scopus.com). BC = black carbon; SIC = soil inorganic carbon; SOC = soil organic carbon [Colour figure can be viewed at wileyonlinelibrary.com]

pollution, C budgeting, or climate mitigation, where C stocks were mentioned but were not measured) were excluded from further analysis. The survey yielded a dataset including 770 values for SOC, SIC, and BC stocks from 116 cities across the globe. The cities represented a wide range of bioclimatic conditions, from the equator (Singapore, 1.09°N, 103.4°E) to the polar circle (Vorkuta, 64.2°N, 67.3°E). The dataset included five data categories: environmental factors, urban-specific factors, C contents and stocks, secondary soil properties, and supplementary information (Figure 2). Köppen climate zones were aggregated to cold (D climates), temperate (C climates), arid (B climates), and tropical (A climates), based on the world map of climate classification (Rubel & Kottek, 2010), considering the temperature of the coolest and warmest months as the main factor. All cities were also stratified into four categories based on the total area, population, age (time since settlement), and population density (Table 2).

2.3 | Data processing and statistics

Normality of the distribution was checked by Shapiro–Wilk's W test, and homogeneity of variances was checked by Levene's test. Significance of differences between mean C stocks in urban and natural soils for 0–10-, 0–30-, and 0–100-cm depths was checked by the t test. The contribution of environmental and urban-specific factors to the total variance of C contents and stocks was tested by factorial analysis of variance (ANOVA). Global C stock patterns were related to latitude (modulus) using linear regression. The predictive power of each statistical model was characterized by the coefficients of determination, R^2 and R^2_{adj}. Statistical analysis was performed in STATISTICA 12.0. All data on C contents and stocks presented in the text, figures, and tables are means ± standard errors.

3 | RESULTS AND DISCUSSION

3.1 | Global comparison of C stocks in urban and natural soils

The C contents and stocks for both urban and natural soils were highly variable, with coefficients of variance of up to 70–80% for the whole dataset. Such variation is common and to be expected from the heterogeneity of bioclimatic, urban, and management conditions. Average SOC contents in urban soils at the 0–10-, 0–30-, and 0–100-cm depths were 3.56 ± 0.20%, 2.25 ± 0.22%, and 1.56 ± 0.13%, respectively, which was more than 1.5 times higher (t test; $p < .05$) than in natural soils at the corresponding depths. Average SOC stocks in 0–10 and 0–100 cm of urban soils were double those of natural soils, whereas average SOC stocks in 0–30 cm were similar for urban and natural soils (Figure 3). The top 10 cm of urban soils usually include composts, litter, and other organic residues used for soil construction and management as well as from urban wastes (Beesley, 2012; Zirkle et al., 2011), whereas layers located at 10–30-cm depths contain more

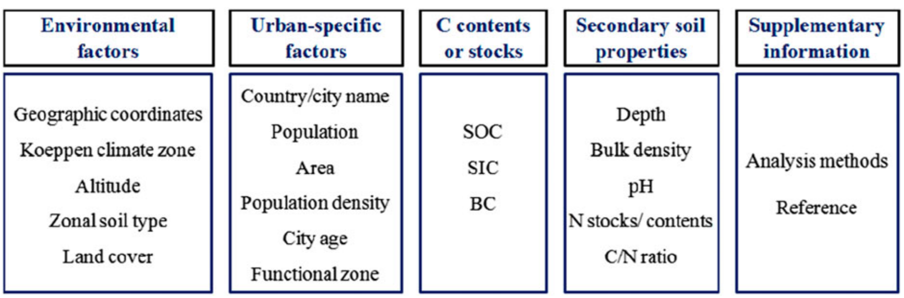

FIGURE 2 Structural blocks of the dataset on C stocks in urban soils. BC = black carbon; SIC = soil inorganic carbon; SOC = soil organic carbon [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Categorizing cities in the dataset on urban C stocks

Category	Population (thousands of citizens)	Extent (km^2)	Age (years)	Population density (citizens/km^2)
Megapolis	>10,000	>1,000		
Big	1,000–10,000	500–1,000		
Medium	100–1,000	100–500		
Small	<100	<100		
Ancient			>1,500	
Medieval			500–1,500	
Old			200–500	
Young			<200	
Overpopulated				>10,000
Dense				4,000–10,000
Moderate				1,000–4,000
Low density				<1,000

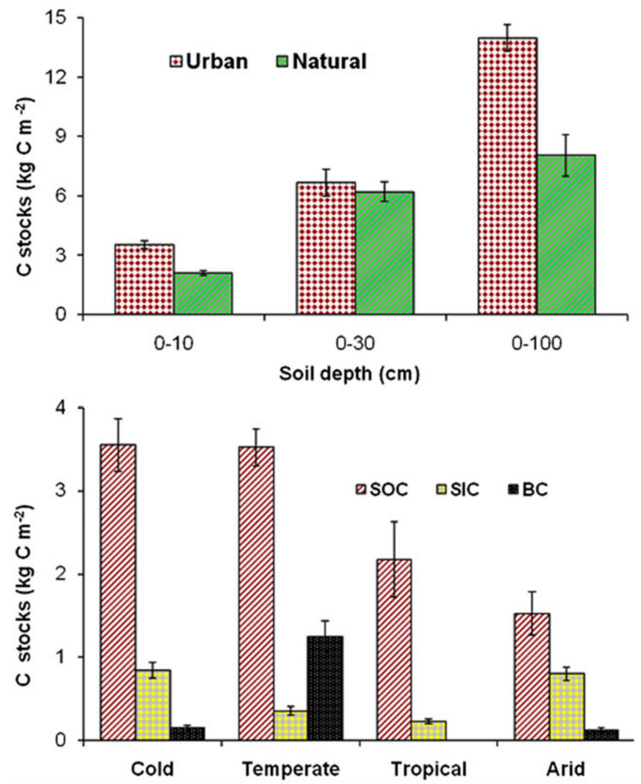

FIGURE 3 Average soil organic carbon (SOC) stocks (kg C/m^2) in urban and natural soils for the 0–10-, 0–30-, and 0–100-cm layers (top) and average 0–10-cm SOC, soil inorganic carbon (SIC), and black carbon (BC) stocks (kg C/m^2) in different Köppen climate zones (bottom) [Colour figure can be viewed at wileyonlinelibrary.com]

artefacts and coarse materials (Puskás & Farsang, 2009), which usually excluded from the common SOC analyses. As a result, stocks in 0–10 cm are larger for urban soils than for natural soils, whereas the difference in SOC stocks in 0–30 cm is negligible. High C stocks in deeper layers result from the contribution of subsoil and cultural layers, which are abundant in historical parts of old cities (Mazurek et al., 2016).

A comparison of SIC contents down to 30 cm, averaged for natural and urban soils of all climates, gave similar results to those for SOC; SIC contents were 4 to 8 times higher in urban soils (0.51 ± 0.05 vs. 0.06 ± 0.01% for 0–10 cm and 0.36 ± 0.07 over 0.09 ± 0.01% for 0–30 cm for urban and natural soils, respectively). However, the opposite was found for 0–100-cm layers, where SIC contents were 2 times lower and SIC stocks 4 times lower than in natural soils (0.42 ± 0.14 vs. 0.98 ± 0.15% and 3.75 ± 1.34 over 14.2 ± 1.8 kg C/m^2). High SIC contents in urban topsoils depend on the input from lime dust, cement, and concrete particles from building sites and cement factories, present in almost all cities (Lorenz & Lal, 2015; Washbourne, Renforth, & Manning, 2012). High subsoil SIC stocks in natural soils are connected to the $CaCO_3$-containing parent materials, which make a substantial contribution to C stocks, especially in semiarid and arid climates (Zamanian, Pustovoytov, & Kuzyakov, 2016). In urban and natural soils, SIC stocks were 3–5 times lower than SOC stocks down to the 30-cm depth. However, SOC stocks at 0–100-cm depths were 2 times higher than SIC stocks in urban soils and 2 times lower than SIC stocks in natural soils.

The analysed global datasets lacked information on BC. The data on N stocks were also limited. Some reviews and individual studies reported higher BC and N stocks in urban compared with adjacent natural soils (Lorenz & Lal, 2009, 2015; J. Yang et al., 2016).

3.2 | Global patterns and intercity variability in urban soil C stocks

High variation of C stocks in urban soils is caused by environmental and urban-specific factors. The contributions of the four most important factors were tested in this review: climate zone, city population, city area, and age. Climate was the main contributor to the variance of SOC stocks in the topsoil, whereas city area and age mainly affected SOC stocks in subsoil and cultural layers. All four factors significantly affected SIC contents and stocks in 0–10-cm layers, with the largest impact from climate (20% of total variance). City age was significant for subsoil SIC (Table S2).

Urban topsoil SOC stocks for cold and temperate zones were similar to each other and significantly higher than in tropical and arid zones (Figure 3). For detailed investigation of the global patterns, we related urban C stocks to latitude using linear regression (Figure 4). SOC stocks significantly increase (r = .61, R^2 = .38, p < .05) in 0–10 cm of urban soils from the tropics (~20°) towards high latitudes (60–70°). The pattern was similar to the SOC distribution in the upper 10 cm of natural soils for the same range of latitudes (ISRIC-WISE Dataset, Batjes, 2008), but the correlation for the natural soils was weaker (r = .46, R^2 = .21, p < .05). Thus, urban topsoil in the tropics and in arid climates (20–30° latitudes) contained less SOC, whereas in temperate and cold climates, SOC contents and stocks were substantially larger compared with those in natural soils (Figure 4).

The increase in urban SOC stocks with latitude (Figure 4) results from a set of climate-related factors. Low temperature is a widely accepted abiotic factor limiting soil respiration, and therefore, mineralization of SOC and litter in cold climates is slower compared with that in warmer conditions (Bond-Lamberty & Thomson, 2010). Considering that urban soils contain such components as turf, peat, and organic composts (Beesley, 2012; Vasenev, Epikhina, et al., 2014), the retarded mineralization increases SOC stocks. Apparently, the

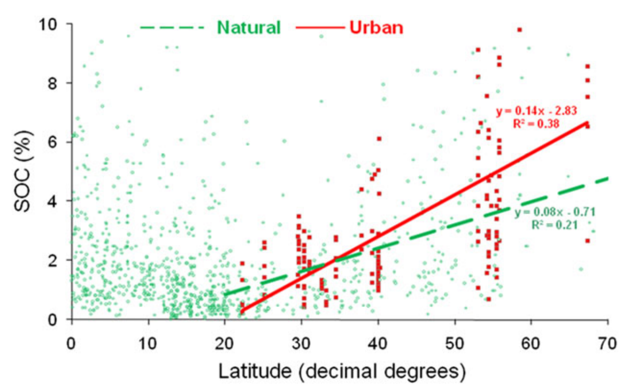

FIGURE 4 Zonal patterns in soil organic carbon of urban and natural topsoil (0–10 cm). The data from Singapore were excluded from the regression analysis as a typical outlier, as it was the only data point in the equatorial and subequatorial zones (latitude <20°) [Colour figure can be viewed at wileyonlinelibrary.com]

difference in climatic conditions between cold and temperate zones is not sufficient to affect the average SOC stocks, whereas distinctly warmer conditions in tropical and arid zones enhance mineralization and decrease average SOC stocks.

The extra BC input from wood and fossil fuel combustion for heating may be another important C source, increasing urban C stocks in cold and temperate climates compared with the tropics. For example, substantial inputs of charcoal and biochar into urban soils were reported for industrial and residential areas in Vorkuta town in the polar region (Dymov, Kaverin, & Gabov, 2013; Lehndorff et al., 2015). However, we have not found straight patterns between BC stocks and climate conditions that might be explained by the predominant effect of nonclimatic factors (e.g., functional zoning) and data limitations for BC compared with other C forms.

Whereas in natural soils SIC stocks decrease from arid to temperate climates (Zamanian et al., 2016), the highest SIC stocks in the investigated urban soils were obtained in arid and cold zones. Likely, the leaching processes are similarly retarded in arid conditions due to water scarcity and in cold conditions due to low temperature and frost penetration. Mainly an anthropogenic origin of urban SIC may be another reason for similar urban SIC stocks in cold and arid climates (Table S3).

Similar to SOC, N stocks in urban soils increased with latitude, and there was no corresponding change in the C-to-N ratio. These main patterns for topsoil SOC, SIC, and BC relationships with climate were similar in the deeper layers, but the robustness of results for depths below 30 cm was constrained by the limited number of data points.

Generally, climate was the dominant factor affecting urban C stocks at 0–10 cm, whereas C stocks in subsoil and cultural layers were also greatly influenced by urban-specific factors. For example, SOC stocks at 0–30 cm were higher in small and medium cities (area < 500 km^2 and population < 1 million citizens) than in big cities and megapolises (Figure 5). This is because small cities are usually dominated by residential zones, with additional C inputs of organic compost and domestic and garden wastes. In contrast, big cities and megapolises usually include vast industrial areas and traffic zones, with low or absent organic C input and with accelerated C outputs (e.g., caused by the heat island effect). The highest subsoil SOC stocks were located in medieval cities, compared with other age categories (Figure 5).

High variability of C stocks was only partly explained by urban-specific factors because of strong interaction by regional and urban-specific effects. For example, most Chinese cities are ancient megapolises, whereas medium medieval cities dominate in Europe, and young megapolises and big cities represent the most typical urban areas in the United States. This overlay limits analysis of individual factors, evident from the ANOVA results, where the contribution of each factor is rather low (5–20%), whereas the model prediction power is high (R^2_{adj} ranged 0.2 to 0.9). Strong intracity variability is another reason for the insignificant contribution of the analysed factors to variance in urban C stocks.

3.3 | Intracity variation of C stocks: the effects of functional zoning, land cover, and management

Intracity variability of C stocks is driven by multiple functional zones and management practices inside the cities. The suburban natural and residential areas stored more SOC at 0–30 cm than at other zones, whereas the highest subsoil (below 50 cm) SOC stocks were found in the residential and public areas (Figure 6). The largest urban topsoil SOC stocks in the least disturbed recreational areas in comparison with other functional zones are explained by higher natural C inputs in the former, including litter, leaves, and plant remains (Bae &

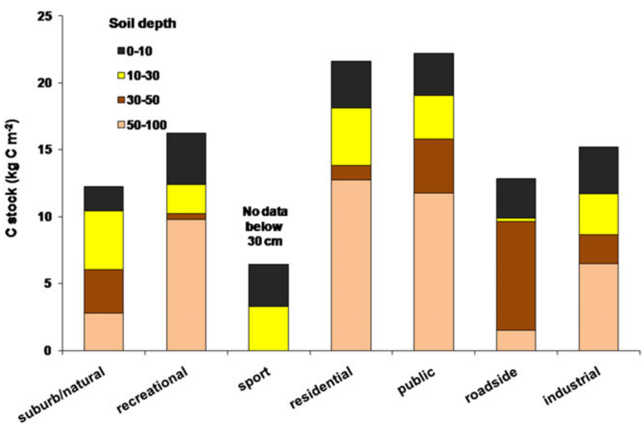

FIGURE 6 Soil organic carbon stocks in different depths of urban soils, located in different functional zones [Colour figure can be viewed at wileyonlinelibrary.com]

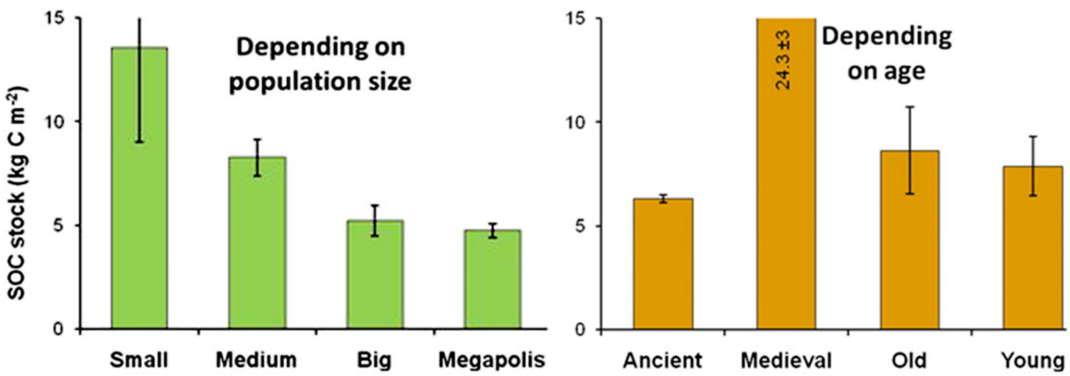

FIGURE 5 Soil organic carbon (SOC) stocks averaged for the 0–30-cm layer in cities of different sizes (left) and for the subsoil layers in cities of different ages (right) [Colour figure can be viewed at wileyonlinelibrary.com]

Ryu, 2015; Svirejeva-Hopkins, Schellnhuber, & Pomaz, 2004). SOC stocks in subsoils and cultural layers are mainly influenced by long-term residential activities. Therefore, the greatest SOC stocks are located in cultural layers of the public and residential areas with the longest history (Dolgikh & Aleksandrovskii, 2010; Mazurek et al., 2016). The subsoil has the highest SOC stocks in 0–100-cm depths in residential and public areas (Figure 6), which were 30–40% higher than those for industrial and roadside sites. The lowest SOC stocks were in the sports areas (but no data for SOC stocks below 50 cm were available; Figure 6).

Functional zoning had a significant impact on SIC stocks, contributing 20–60% to the total variance (main effect ANOVA), and this effect was higher for the subsoil than for the topsoil. SIC stocks increase in subsoil due to concrete rubble or lime gravel, in contrast to the topsoil, where the SIC is deposited mainly by dust (Prokof'eva et al., 2017). The largest BC stocks are located along roadsides and in residential zones (2–3 times more than that in suburban natural areas), corresponding to the main BC sources: fossil fuel and wood combustion (J. Yang et al., 2016).

The largest N stocks are located in soils of residential areas, amounting to 20–30% more N than that of industrial and public zones and 5 to 10 times more than that of suburban and natural areas. The urban environment provides specific sources of N inputs into soil, including (a) deposits from industries and automobile engines; (b) chemical fertilizers for maintaining lawns; and (c) urine and faeces from pets (Kaye, Groffman, Grimm, Baker, & Pouyat, 2006; Lorenz & Lal, 2009). These N inputs are abundant in residential and public zones but limited in natural and suburban areas, which is confirmed by the 2–3 times higher C-to-N ratio in natural areas compared with residential and public zones (Table 3).

The patterns obtained for the functional zones, with large SOC and N stocks in residential areas and large SIC and BC stocks in industrial zones and roadsides, were similar for all climates and for cities of different sizes and ages.

3.4 | Hidden C stocks in urban soils

Approaches to analyse soils were mainly developed for natural soils, and therefore, specific urban characteristics are disregarded. One such characteristic is high C stocks in the deep layers, which are not usually analysed in natural soils. Disregarding these layers leads to substantial underestimation of C stocks due to ‘hidden’ (unobserved) C stocks below 50 or 100 cm, and especially in soils sealed under impervious surfaces. The literature analysis highlighted the existing bias towards studying urban C stocks in topsoil rather than in subsoil and favouring green and residential areas over other functional zones. Studies on C stocks below 50 cm constituted only one tenth of the database, despite the fact that more than half of total C stocks were accumulated below the 50-cm depth. Only very few studies of C stocks in sealed soils were available. As a result of this bias, C stocks in urban soils are mainly judged by their topsoils, ignoring the hidden part in deeper layers.

3.4.1 | C stocks in sealed soils

Soil sealing is traditionally assumed to be the main factor limiting C stocks and fluxes in urban areas. Many regional studies consider sealed soils as ‘carbon neutral’ and even extrapolate this assumption to urban areas as a whole, neglecting C stocks in other urban soils (Schaldach & Alcamo, 2007; Schulp & Verburg, 2009). The Ekranic Technosols (the WRB reference for the sealed soils; WRB, 2014) have recently received increasing attention regarding C stock magnitude and availability (Lorenz & Lal, 2009; Piotrowska-Długosz & Charzyński, 2014). Although data on C stocks in the top 50 cm of sealed soils were not available, these soils contained on average 13.3 ± 0.7 kg C/m^2 of SOC at 50–100 cm, which was 25% less than that under lawns but 10% higher than that under trees and shrubs. Similar patterns were found for N stocks, whereas SIC stocks in sealed soils were 2 times higher than those under lawns as well as 20% higher than those under trees at the same depth. C stocks below 100 cm follow a similar pattern (Figure 7). Data for BC stocks in sealed soils were not available, but individual studies report asphalt layers as an important BC source (Kida & Kawahigashi, 2015).

SOC and SIC below 1 m were 8.8 ± 5.9 and 12.5 ± 4.8 kg C/m^2, contributing respectively 40% and 66% to the total stocks in sealed soils. N stocks at the same depth were 1.1 ± 0.7 kg N/m^2, contributing a similar 63% of the total N stocks in sealed soils. Substantial SIC stocks in deep layers of sealed soils have anthropogenic origin and include lime-containing materials used for road construction (i.e., gravel, cement, and concrete). SOC and N stocks may include both cultural layers and buried horizons of the natural or agricultural soils that dominated the area prior to urbanization. Therefore, soil sealing isolates subsoil C and N stocks but does not deplete them.

3.4.2 | Carbons stocks in cultural layers

Large C stocks in sealed soils illustrate the large contribution of subsoil and cultural layers to total C stocks and illustrate the difference in depth distribution of C stocks between urban and natural soils. To further corroborate this, we compared the depth distribution of C stocks in urban soils with those in three groups of natural soils for boreal, steppe, and tropical bioclimatic zones: Retisols, Chernozems, and Ferralsols, respectively. The data for natural soils were derived from a global assessment of soil C and N (Batjes, 1996) and standardized to 0–30-, 30–50-, 50–100-, and 100–200-cm depths. In urban soils, 50% of total C stocks occur below 100 cm. In contrast, Retisols, Chernozems, and Ferralsols contained only 6%, 36%, and 29% of SOC stocks below 100 cm (Figure 8). SOC stocks deeper than 100 cm in urban areas originated from anthropogenic cultural layers under long-term settlement. They consist mainly of the remains of wooden buildings and roads and may include manure residues, ash, charcoal, domestic, and municipal wastes (Aleksandrovskii et al., 2015). The depth and composition of cultural layers depend on the city age, initial mesorelief, and climate. For example, due to the slower decomposition rate of organic materials, SOC stocks in cultural layers in the boreal regions of Europe, North, and Central Russia are greater and more diverse than those in cities of comparable age located in the tropics (Dolgikh & Aleksandrovskii, 2010).

The anthropogenic origin of SOC in cultural layers is indirectly confirmed by high N stocks at 100–200 cm, which were larger than N stocks in the upper 100 cm. In contrast, the greater part of N stocks in the upper

TABLE 3 Soil inorganic C, black C, and N stocks (kg/m^2) and C/N in urban soils of different functional zones ($M \pm SE$)

Functional zone	Soil inorganic C	Black C	N	C/N
0–10 cm				
Industrial	0.32 ± 0.15	0.15 ± 0.01	0.23 ± 0.04	15 ± 2
Roadside	0.52 ± 0.15	1.73 ± 0.54	0.20 ± 0.01	21 ± 1
Public	1.00 ± 0.15	0.39 ± 0.01	0.37 ± 0.12	8 ± 1
Residential	0.60 ± 0.08	1.31 ± 0.27	0.32 ± 0.06	16 ± 2
Sport	–	–	0.11 ± 0.01	11 ± 1
Recreational	0.31 ± 0.06	0.91 ± 0.28	0.28 ± 0.06	15 ± 1
Suburb or natural	0.32 ± 0.08	0.20 ± 0.13	0.12 ± 0.04	15 ± 6
0–30 cm				
Industrial	1.12 ± 0.38	–	0.71 ± 0.07	10 ± 1
Roadside	0.13 ± 0.01	3.91 ± 0.03	–	–
Public	2.91 ± 1.28	1.02 ± 0.01	0.99 ± 0.32	8 ± 1
Residential	1.67 ± 0.37	0.32 ± 0.01	0.81 ± 0.24	16 ± 2
Sport	–	–	–	–
Recreational	0.59 ± 0.37	2.8 ± 1.21	0.43 ± 0.07	13 ± 1
Suburb or natural	0.42 ± 0.17	0.78 ± 0.01	0.16 ± 0.05	16 ± 6
0–50 cm				
Industrial	1.88 ± 1.74	–	–	–
Roadside	0.24 ± 0.01	–	–	–
Public	1.27 ± 0.26	–	0.10 ± 0.03	11 ± 4
Residential	2.31 ± 0.81	–	0.97 ± 0.41	18 ± 4
Sport	No data	–	–	–
Recreational	0.92 ± 0.51	7.17 ± 0.74	0.69 ± 0.13	13 ± 2
Suburb or natural	0.28 ± 0.01	–	0.11 ± 0.01	33 ± 2
0–100 cm				
Industrial	4.05 ± 3.56	–	1.11 ± 0.09	23 ± 3
Roadside	0.51 ± 0.03	–	–	–
Public	13.29 ± 6.86	–	0.65 ± 0.16	11 ± 3
Residential	3.28 ± 2.03	15.94 ± 1.55	2.36 ± 0.74	21 ± 5
Sport	No data	–	–	–
Recreational	4.47 ± 1.95	18.90 ± 6.24	0.96 ± 0.13	14 ± 1
Suburb or natural	0.61 ± 0.01	–	0.16 ± 0.01	33 ± 2

0–100 cm of Retisols, Chernozems, and Ferralsols occurs in the top 0–50 cm (Figure 9). Similar to SOC, high N stocks in cultural layers were caused by N inputs from household activities in medieval private manors, including straw, wooden chips, manure, and sewage deposited in the court yards (Aleksandrovskii et al., 2015; Alexandrovskaya & Alexandrovskiy, 2000). The subsoil SIC stocks in urban soils were 7.8 ± 1.0 kg C/m^2, twice as high as in the upper 100 cm. All these findings clearly show that urban subsoils and cultural layers contain very large C and N stocks in various forms and especially in the depth, and therefore deep layers (subsoil and cultural layers) should be considered for C stocks. We conclude that because C stocks in deep layers are not considered, most studies underestimate the importance of urban soils for C sequestration. Future analyses of deeper layers will greatly increase estimations of the total C stocks of urban soils.

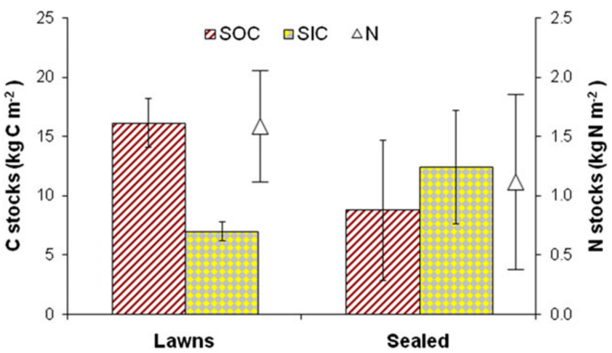

FIGURE 7 Soil organic C (SOC), soil inorganic C (SIC), and N stocks (<100 cm) in urban sealed soils and lawns [Colour figure can be viewed at wileyonlinelibrary.com]

3.5 | Mechanisms and processes of C accumulation in urban soils: synthesis and principal outcomes

3.5.1 | Mechanisms of C accumulation in urban soils

Urban ecosystems consume resources from far beyond the city boundaries to sustain growing economies and populations (Grimm et al., 2008; Pickett et al., 2011). Large C stocks in urban soils and specifics of their spatial and depth distribution result from various processes and mechanisms, influencing urban soil formation and

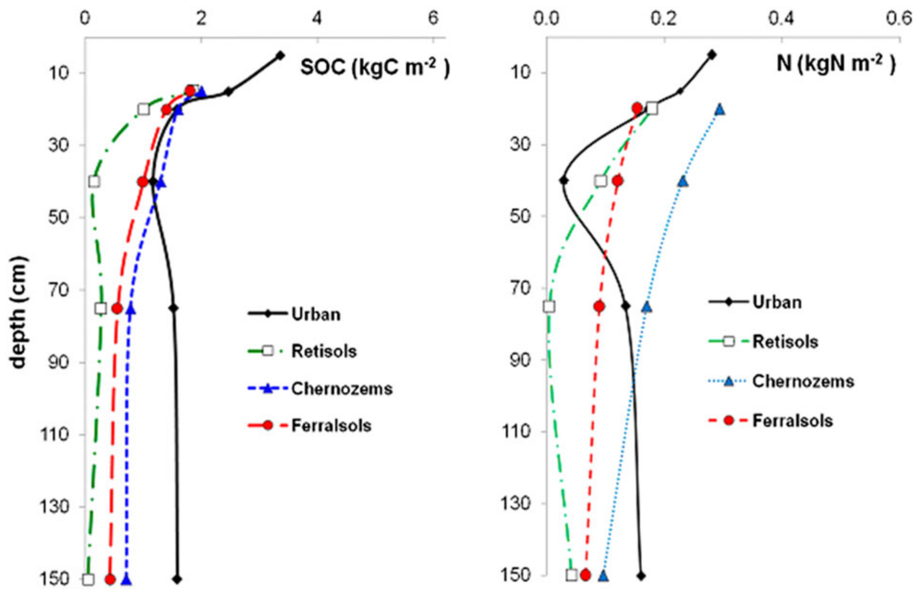

FIGURE 8 Profile distribution of soil organic C (SOC) stocks (left) and N stocks (right), standardized per for 10 cm, in urban soils (based on this review) in comparison with natural soils (derived from Batjes, 1996) [Colour figure can be viewed at wileyonlinelibrary.com]

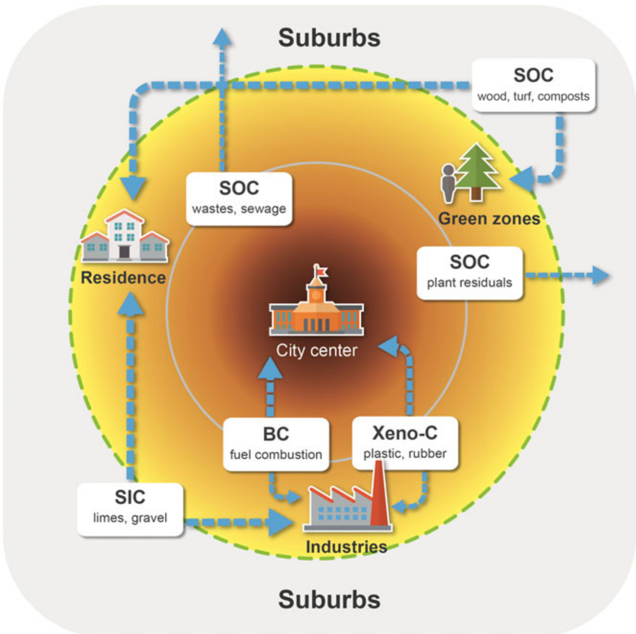

FIGURE 9 A scheme of mechanisms, contributing to C accumulation in urban soils (boxes: soil organic carbon [SOC], soil inorganic carbon [SIC], black carbon [BC], and xenobiotic carbon [xeno-C] stocks; arrows: C inputs and outputs; the solid line depicts a road, and the dashed line depicts the city boundary) [Colour figure can be viewed at wileyonlinelibrary.com]

functions over long time periods. These mechanisms include (a) C inputs from natural sources outside the city; (b) C inputs from artificial sources inside the city with further redistribution within city boundaries; and (c) in situ transformation of C stocks, mainly resulting in retarded decomposition of soil organic matter (Figure 9). The first group of mechanisms includes the flows of energy, food, goods, and other materials from the suburbs to the city, ultimately contributing to C inputs into urban soils. Turf, peat, and organic composts, used for landscaping, contribute to SOC stocks. Gravel and lime, delivered from quarries and mining areas for civil engineering and cement industries, are important inputs of SIC. Food delivery and consumption involve a variety of processes including the generation of domestic waste, which is partly removed from the city to landfills and partly recycled and redistributed within the city, contributing to SOC and N stocks in urban soils (Bernstad & la Cour Jansen, 2011; Otterpohl, Grottker, & Lange, 1997).

The second group of mechanisms involves artificial C inputs, including mainly xeno-C and BC, produced by chemical industries, construction, and transportation systems. This is redistributed within the city boundaries with the maximal accumulation in industrial areas, roadsides, and public and residential zones (J. Yang et al., 2016; J.-L. Yang & Zhang, 2015). Long degradation times of xeno-C and BC stocks (Kuzyakov, Bogomolova, & Glaser, 2014) highlight their importance, but their contribution to C accumulation in urban soils remains unknown.

Finally, the third group of mechanisms—in situ transformations of C stocks—does not affect C inputs directly but contributes to C accumulation. These mechanisms include soil sealing, overcompaction, and waterlogging. They isolate C pools from the atmosphere and hamper decomposition by creating unfavourable conditions for microorganisms (Raciti, Hutyra, & Finzi, 2012; Piotrowska-Długosz & Charzyński, 2014), thereby retarding SOC decomposition and so contributing to C accumulation.

3.5.2 | Growth rate of urban soils and C accumulation

Over a long period, the mechanisms described above lead to gradual C accumulation in cities, resulting in unique soil-forming processes and morphological properties that are completely different from those in natural soils. All natural soil-forming factors lead to soil development directed down the profile (except Fluvisols and Andosols; Dobrovolsky

& Urussevskaya, 2004). In contrast, urban soils tend to grow upward (so-called synlithogenic; Prokof'eva et al., 2017). Consequently, ancient cultural layers are covered by much younger sediments. Urban soil profiles usually contain more layers and with more abrupt boundaries than horizons in natural soils. The composition of C stocks in urban soils is also very diverse, including SOC, SIC, BC, and xeno-C stocks, whereas natural soils mainly contain SOC in temperate and boreal climates and additionally SIC stocks in semiarid and arid areas, with some BC background everywhere. In contrast to natural soils with the largest C stocks in the topsoil, urban soils accumulate substantial C stocks in deep cultural layers. The long-term upward growth of urban soils results in well-developed cultural layers, with a maximal depth of 10 m described for the oldest parts of cities (usually, historical centres; Figure 10).

Estimates of urban soil growth rates are very rare and imprecise because of data limitations and methodological constraints. For example, the urban cultural layers in Veliky Novgorod (Russia) at a depth of 250–450 cm were archeologically dated to the 10th–15th centuries AD and at a depth of 100–150 cm to the 18th–20th centuries AD (Aleksandrovskii et al., 2015; Dolgikh & Aleksandrovskii, 2010). A rough estimation gives an average upward soil growth rate of 40–60 cm per century. Similar rates of approximately 50 cm per century were estimated for the cultural layer in Krakow (Poland), where more than 200 cm was accumulated between the 12th and 16th centuries AD (Mazurek et al., 2016). A young, 10-cm-deep Technosol was formed on an abandoned asphalt surface in Moscow by deposition of solid airborne particles (dust) over 20 years, which gives the same average soil growth rate of 50 cm per century (Prokof'eva et al., 2017). We conclude that the rate of 50 cm per century can be considered as a relevant approximation of urban soils' upward growth. Obviously, approximation based on just a few studies may result in a rather rough and uncertain conclusion; however, this is the best guess we can make based on the literature review. In the future, a radiocarbon dating approach can be suggested for a more realistic elucidation of this mechanism.

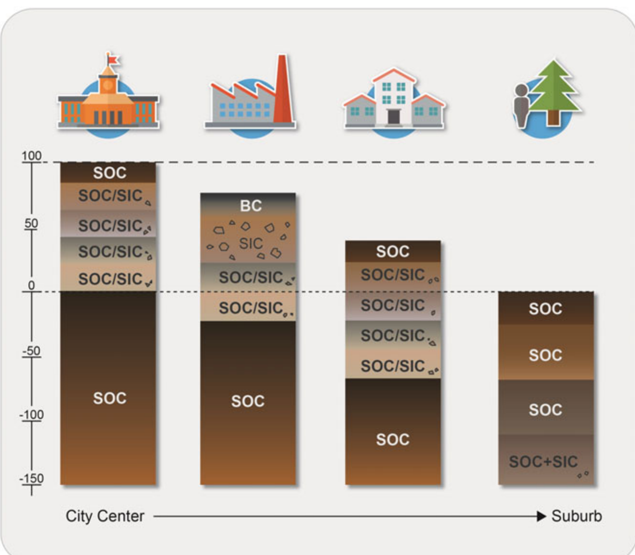

FIGURE 10 Schematic profiles of urban soils located in different functional and historical zones in comparison with a natural soil (the colour darkness represents the amount of C stocks, with the maximal stocks depicted with black; white circles represent the gravel; the picture refer to the same functional zones as described in Figure 9). BC = black carbon; SIC = soil inorganic carbon; SOC = soil organic carbon [Colour figure can be viewed at wileyonlinelibrary.com]

Considering an average SOC content of 3–5% reported for cultural layers (Alexandrovskaya & Alexandrovskiy, 2000) and a bulk density of 1.3 g/cm^3, 20–30 kg C/m^2 is accumulated per century. This is 2–3 times higher than the 8–10 kg C/m^2 per century reported for urban lawns (Qian & Follett, 2002) and similar to the 24–35 kg C/m^2 per century reported for golf courses (Selhorst & Lal, 2011). This means that urban soils gain as much SOC in a single century as they accumulate over the entire development of Chernozems and Phaeozems, the natural mineral soils with the highest C stocks. This estimate and comparison clearly show a huge potential for C sequestration in urban soils and cultural layers, which is at least one order of magnitude higher and faster than that in natural soils.

3.5.3 | Perspectives on C accumulation in urban soils for sustainable urban development

Carbon accumulation in urban soils is an important ecosystem service that mitigates climate change (Morel et al., 2014). The role of urban soils in C sequestration depends heavily on the stability of their C stocks. Sustainable urban development tends to enhance C stock resilience by various C-friendly management strategies (Lorenz & Lal, 2015). Considering the proposed mechanisms of C accumulation in urban soils (Figure 9), sustainable urban development needs to minimize C inputs from outside the city and maximize C circulation inside the city, in situ C transformation, stabilization, and storage.

Importing organic substrates from outside the city is less important for C sequestration than recycling plant residues and organic wastes and returning these to soils as organic fertilizers and compost. Fertilization stimulates biomass production and may limit soil respiration, both contributing to C sequestration (Janssens et al., 2010; Zang, Wang, & Kuzyakov, 2016). This practice will be most beneficial in cold and temperate climates, where SOC decomposition is limited. In arid regions, enhancing SIC stocks by adding lime and chalk and protecting SIC stocks from leaching are more essential for sustainable management of soil C stocks (Lorenz & Lal, 2015), but SIC, compared with SOC, has fewer ecosystem functions. The positive role of BC-containing materials, including charcoal, biochar, and soot, in enhancing the resilience of urban soil C stocks was recently reported (Basta et al., 2016; Ghosh, Yeo, Wilson, & Ow, 2012; Scharenbroch, Meza, Catania, & Fite, 2013). Much less is known about the contribution of xeno-C stocks to C sequestration in urban soils. Potentially, xenobiotics constitute substantial C stocks, which are not considered in C management. Accounting for these stocks in urban soil C balances would be very beneficial for sustainable urban development.

4 | CONCLUSIONS

Traditional views of ecology and environmental protection relate urbanization to severe land and soil degradation. However, urban soils have a huge potential to provide important functions and ecosystem services. In this review, we have clearly shown one of the ecosystem services of urban soils: C sequestration. The estimated C stocks in urban soils were 3–5 times higher than in natural soils and were based on long-term accumulation of four C forms: SOC, SIC, BC, and xeno-C. Considering the urban area of 2.5% globally and the 3–5 times higher C stocks than that of natural soils, the contribution of urban soils to global C stocks is about 7–13%.

Urban soils are 'human made,' and therefore the anthropogenic factor overshadowed the other five classical factors of soil formation. Local specifics of city management and historical development explained the much higher variability of C accumulation and stocks in urban soils compared with those in their natural counterparts. The analysis of 116 cities around the globe showed a clear positive correlation between SOC stocks and latitude and, therefore, the climate effect. City size and age were the main factors explaining intercity variability of C stocks, with higher stocks in small cities compared with megapolises, and in medieval compared with younger cities. Intracity variability of C stocks was dominated by functional zoning: The largest SOC stocks were commonly in residential and public zones, but the highest SIC and BC stocks were in industrial areas and roadsides. Because very large stocks of SOC and SIC are located in subsoils (below 30 cm) and cultural layers (below 100 cm) of sealed soils, most studies measuring C only in the topsoil strongly underestimate the C amounts sequestered in urban soils. Consideration of these hidden stocks is important for C assessments of urban soils and comparisons with their natural counterparts.

The much higher C stocks in urban soils than in natural soils are explained by fast C accumulation in urban areas. We suggested a conceptual model for C accumulation in urban soils that contains the following mechanisms: (a) C inputs from suburban areas (e.g., transfer of food, wood, and raw materials); (b) C circulation and redistribution inside the city (e.g., xenobiotics, soot, and charcoal); and (c) in situ transformations (e.g., sealing, overcompaction, and waterlogging). Upward growth of urban soils over a long period results in very deep cultural layers with very high C accumulation. Urban soils grow upward by about 50 cm per century, corresponding to a C accumulation rate of 20–30 kg C/m^2 per century. This results in SOC stocks in 0–200-cm depths in soils of medieval cities, which are higher than the maximal SOC stocks in Chernozems and Phaeozems, the natural mineral soils with the highest C stocks. Such high rates of C accumulation in urban soils highlight their potential to mitigate climate change despite their comparatively small area.

Urbanization is one of the most important aspects of global change and is ongoing very fast. Consequently, the importance of urban soils as ubiquitous components of cities will increase in the future. Urban soils should be considered not only as repositories of wastes and pollutants (as in most studies to date) but also as the basis for a broad range of ecosystem functions, at least one of which—long-term C sequestration—is much more effective than in natural soils.

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SUPPORTING INFORMATION

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