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Surface Soil Carbon Storage in Urban Green Spaces in Three Major South Korean Cities

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Abstract: Quantifying and managing carbon (C) storage in urban green space (UGS) soils is associated with the ecosystem services necessary for human well-being and the national C inventory report of the Intergovernmental Panel on Climate Change (IPCC). Here, the soil C stocks at 30-cm depths in different types of UGS's (roadside, park, school forest, and riverside) were studied in three major South Korean cities that have experienced recent, rapid development. The total C of 666 soil samples was analyzed, and these results were combined with the available UGS inventory data. Overall, the mean soil bulk density, C concentration, and C density at 30-cm depths were 1.22 $g \cdot cm^{-3}$, 7.31 $g \cdot C \cdot kg^{-1}$, and 2.13 $kg \cdot C \cdot m^{-2}$, respectively. The UGS soil C stock ($Gg \cdot C$) at 30-cm depths was 105.6 for Seoul, 43.6 for Daegu, and 26.4 for Daejeon. The lower C storage of Korean UGS soils than those of other countries is due to the low soil C concentration and the smaller land area under UGS. Strategic management practices that augment the organic matter supply in soil are expected to enhance C storage in South Korean UGS soils.

Keywords: park; riverside; roadside; settlement; soil carbon sequestration

1. Introduction

Enhancing ecosystem services and human well-being is especially vital for urbanized lands (see the definition in the footnotes of Table 1) [1,2] where half of the global population and 90% of the South Korean population lives. Designing, establishing, and managing urban green spaces (UGS's), as well as preserving remnant ecosystems in a city, could be one way to secure or restore ecosystem services in urbanized lands [3]. Soils support various ecosystem services such as nutrient cycling, habitat provision, food production, storm water management, and carbon (C) storage [3–6]. Here, the emphasis on the conservation or sequestration of soil C, with a C stock greater than that of atmosphere and biomass combined [7–11], is extended to urban soil C, both organic and inorganic C [12–14]. The significance of UGS's for terrestrial C inventories and the need to treat them distinctly from other major land types (e.g., forest, agricultural land, grassland, and wetland) is underscored by its special treatment as a separate land category, *settlements*, which encompasses all developed land according to the Good Practice Guidance (GPG) and Guidelines (GL) of the

Intergovernmental Panel on Climate Change (IPCC) [15,16]. Moreover, organic and inorganic C in soils increases their quality, indirectly supporting other ecosystem services such as nutrient cycling and pollution mitigation [3]. Not surprisingly, there is an increasing concern to manage UGS soil C among various interested stakeholders, including scientists, local governments and NGOs, and international institutions [3,4,15,16]. To date, most studies on UGS soil C have focused on *old cities*, that is, cities with a relatively long history of urbanization and hence more potential to store abundant C in UGS soils [3,17,18]. Given the changing global trends of urbanization in the last 100 years, UGS soil C of *young cities* with a relatively recent history of urbanization has not been adequately studied. In South Korea, a few studies have reported on UGS soil C [19,20]; however, these studies investigated UGS soil C at a single site or in a single city.

Here, we sought to quantify the soil C stocks of the UGS's at 30-cm depths in three South Korean cities and thereby provide a current estimate of the soil C status. Because land use, land cover change, and/or urbanization history can all affect UGS soil C [17,20–22], soil C densities in different types of UGS's such as roadside, park, school forest, and riverside were quantified and then compared to vegetation C density and site history. In addition, we reviewed the management of soil C in UGS's to enhance the ecosystem services of C storage. South Korea is a populous urbanized country with 505 people· km^{-2} and has experienced rapid urbanization since the 1960s; for instance, since then, its urban population has increased from 10 million to 45 million (Korean Statistical Information Service; http://www.kosis.kr). By studying UGS soils in multiple South Korean cities, we can provide needed information on baselines of UGS soil C in recently developed cities.

2. Materials and Methods

The study was conducted in three major South Korean cities: Seoul, Daegu, and Daejeon (Table 1). Seoul, the capital city since the late 14th century, has the highest population, and its population density and urbanized land cover are also high compared to the other cities [23,24]. Daegu, a principal city in Southeastern Korea since the 15th century, has the fourth highest population in South Korea, while Daejeon, which was established early in the 20th century, now has the fifth highest population [25]. The population density and relative urbanized land cover is now similar between Daegu and Daejeon. In tandem with human population growth, the expansion of road networks and residential developments was mostly completed by the early 1990s in Seoul and Daegu [23–25]. Since then, their infrastructure has been renovated for the well-being of citizens in various ways, for example, by restoring streams and establishing UGS's [24]. Being the youngest city in this study, the population growth and infrastructure development in Daejeon has remained steady until 2014 [25]. The three cities have a climate best described as *Dfa* (hot summer continental climate) under the Köppen climate classification; however, Daegu is moderately warmer with less precipitation than the other two cities.

Table 1. Environmental, demographic, and land use characteristics of the three studied cities.

	Seoul	**Daegu**	**Daejeon**
Environment *			
Location	37°34′ N, 126°58′ E	35°52′ N, 128°36′ E	36°21′ N, 127°23′ E
Mean annual temperature	12.5 °C	14.1 °C	13.0 °C
Mean annual precipitation	1451 mm	1064 mm	1459 mm
Demography †			
Area	605.18 km^2	883.63 km^2	540.1 km^2
Population	10.02 million	2.52 million	1.54 million
Population density	16,659 people· km^{-2}	2857 people· km^{-2}	2873 people· km^{-2}
World urban areas rank by population density ‡	#238	#272	#181

Table 1. *Cont.*

	Seoul	**Daegu**	**Daejeon**
Land uses [§]			
Urbanized land area (% of total city area)	316.5 km^2 (52.1%)	154.1 km^2 (17.5%)	89.0 km^2 (16.5%)
Impervious area (% of total city area)	347.3 km^2 (57.2%)	172.2 km^2 (19.5%)	102.4 km^2 (19.0%)
Forest (% of total city area)	127.8 km^2 (21.1%)	274.1 km^2 (31.0%)	249.9 km^2 (46.3%)
Green space area (% of total city area)	44.1 km^2 (7.3%)	19.4 km^2 (2.2%)	18.5 km^2 (3.4%)
Roadside area	4.06 km^2	1.30 km^2	1.01 km^2
Park area	30.31 km^2	12.69 km^2	14.10 km^2
School forest area	0.98 km^2	0.85 km^2	0.36 km^2
Riverside area	6.19 km^2	0.15 km^2	0.54 km^2

[*] Korea Meteorological Administration (http://www.kma.go.kr). [†] Korean Resident Registration Demographics (http://rcps.egov.go.kr:8081). [‡] Demographia World Urban Areas [26]. Note that the population density rank of Seoul is downgraded because it includes other cities near Seoul (e.g., Incheon, Ansan, and Suwon) in the database. [§] The categories of land uses are based on the National Urban Forest Inventory [27] and the Environmental Geographic Information Service (http://egis.me.go.kr) and defined as follows: Urbanized land is the city district area excluding forest, agriculture land, grassland, wetland, bare land, and water cover. Forest is the forested land excluding green space. Green space is the aggregate of vegetated area close to the living space of inhabitants. Roadside is the vegetated area of sidewalk, roadway, and traffic island. Park is the artificially vegetated area, as defined by the Urban Park Act. School forest is the vegetated area on school grounds. Riverside is the vegetated area adjacent to flowing water, as defined by the River Act.

We investigated total soil C in the roadside, park, school forest, and riverside, following the legal classification of UGS's as defined by the National Urban Forest Inventory [27] and the Environmental Geographic Information Service (http://egis.me.go.kr) (full details in the footnotes of Table 1). Because the inorganic C produced by carbonation reactions in calcareous materials (e.g., concrete, cement, parent material) can form a fraction of soil C, in the present study, in addition to organic C [12–14,28], we focused on total C, covering both organic and inorganic C. The UGS's exclude remnant, non-urbanized, and mountainous forest areas, such as green belt and conservation areas in the city districts (as defined by the administrative system of Korea). The four UGS types represent approximately 90% of all the UGS areas in South Korea. Since mountainous forests dominate the land cover of Korea, urban areas are developed in the lowland basins of the city districts; together, the remnant, non-urbanized, and mountainous forests account for an appreciable or considerable portion of city land cover (27.5% for Seoul, 63.8% for Daegu, and 70.4% for Daejeon) and of ecosystem C sequestration [29], even in highly inhabited cities [26]. However, this study excluded measurement of soil C in these non-UGS types, which are accounted for in the *forest* category of IPCC [15,16] and the National Forest Inventory of Korea [30]. It should be noted that soils beneath impervious surfaces (e.g., paved roads), which may have a significant potential C storage capacity with C density equivalent to that of UGS's soils [31], were not investigated in this study.

In each city, we selected 3 to 10 replicate sites per each UGS type—except at riverside due to its lack of suitable sites for replication or limited accessibility—considering their distribution, history, area, location, vegetation cover, and accessibility after discussion with experts (see Table 2). Unfortunately, detailed records of soil management practices undertaken at each UGS site were unavailable to us; however, it is commonly agreed upon that this management had been poor and lacked specific guidelines, regulations, or acts. In general, UGS soils have an insufficient supply of organic matter from aboveground. For the park and school forest UGS's, the grass was regularly mowed, and grass clippings and leaf litter were removed to maintain surface cleanliness and prevent inconvenience for users. Park, school forest, and riverside soils were irrigated but generally not fertilized, whereas roadside soils were hardly managed. These aspects of UGS soil management have been listed in local government ordinances or guidelines since 2010. Site history (year of construction) was available for 34 of the 64 sites. Tree C density at each site (unpublished data)—a corollary of vegetation cover—was estimated by a biometric approach that used measurements of tree stem diameters at breast height and urban-specific allometric equations [32].

Table 2. Soil bulk density, C concentration, and area-based C density in urban green spaces (UGS) soils for 0–30 cm depth. Values in parentheses represent one standard deviation.

	N		**Bulk Density**	**Soil C Concentration**	**Soil C Density**
	Site	**Soil**	**(g· cm^{-3}) ***	**(g· C· kg^{-1})**	**(kg· C· m^{-2}) †**
Roadside					
Seoul	12	120	1.24 (0.22)	9.97 (7.31)	3.03 (2.15)
Daegu	9	60	1.04 (0.34)	9.08 (6.97)	2.10 (1.33)
Daejeon	10	72	1.07 (0.23)	6.62 (5.62)	1.56 (1.23)
Total	31	252	1.14 (0.27)	8.92 (6.95)	2.41 (1.85)
Park					
Seoul	3	117	1.34 (0.19)	6.66 (3.94)	2.24 (1.34)
Daegu	3	36	1.07 (0.31)	8.37 (6.26)	2.34 (1.94)
Daejeon	3	18	1.11 (0.13)	4.96 (3.99)	1.28 (0.97)
Total	9	171	1.27 (0.23)	6.48 (4.32)	2.05 (1.40)
School forest					
Seoul	13	150	1.27 (0.22)	6.13 (4.38)	1.88 (1.39)
Daegu	3	30	1.18 (0.31)	5.38 (3.48)	1.49 (0.89)
Daejeon	4	24	1.28 (0.15)	4.62 (3.69)	1.36 (0.97)
Total	20	204	1.26 (0.23)	5.82 (4.21)	1.76 (1.30)
Riverside					
Seoul	1	18	1.27 (0.25)	9.61 (6.31)	2.96 (1.73)
Daegu	2	12	1.23 (0.34)	8.58 (3.34)	2.90 (1.24)
Daejeon	1	9	1.32 (0.14)	6.09 (2.57)	1.92 (0.83)
Total	4	39	1.28 (0.24)	8.29 (4.94)	2.63 (1.45)
All					
Total	64	666	1.22 (0.25)	7.31 (5.63)	2.13 (1.59)

* Bulk density was corrected by gravel content (see Equation (1)). † Soil C concentration was multiplied by a ratio of soil dry weight to total volume of soil and gravel (see Equation (2)).

Soil cores 30 cm deep were taken in random triplicate using a soil sampler (Ø 5.5 cm, 50-cm length; Shinill Science Inc., Seoul, Korea) at each UGS site in August 2009 for Seoul, August 2010 for Daejeon, and August 2011 for Daegu. The soil sampler using a manually driving hammer probe may result in a potential error in determining bulk density due to compaction or stretching of the soil core [33]; nonetheless, this method is considered best practice for sampling urban soils and has been documented to present minimal site disturbance, soil excavation, and error [33]. A total of 666 soil samples were taken: 252 from roadside, 171 from park, 204 from school, and 39 from riverside UGS's (see Table 2).

The soil cores were separated into 10-cm sections in the field. In laboratory, the samples were air-dried and filtered through 2-mm sieves to exclude roots and gravel (*i.e.*, >2 mm). The oven-dried (105 °C) weight of soils (<2 mm) and gravel were determined separately. The bulk density was determined by the ratio of the oven-dried weight to the volume of the sieved soils, which was calculated by extracting the volume of the gravel from the volume of the original soil core (Equation (1)). The volume of the gravel was determined from its weight, assuming a gravel density of 2.65 g· cm^{-3} [34,35]. This correction procedure is required to accurately report bulk density, which can be affected by the gravel content. The subsamples of air-dried soils were ball-milled before their C concentrations were determined by an elemental analyzer (Vario Macro CN analyzer, Elementar Analysensysteme GmbH, Hanau, Germany).

The soil C concentration ($g\cdot C\cdot kg^{-1}$) was converted to soil C density ($mg\cdot C\cdot cm^{-3}$ or $kg\cdot C\cdot m^{-2}$) by multiplying the density of fine soil in the soil core (see Equations (2) and (3)) instead of multiplying the bulk density, to avoid the miscalculation of C density due to gravel content in the soil core. The total UGS's C stock (Gg· C) of each city was estimated as the product of the land area covered by each UGS type and their corresponding soil C density (Equation (4)).

$$\text{Bulk density } (\text{g}\cdot\text{cm}^{-3}) = DW_s/(V_t - V_g), \tag{1}$$

$$\text{Soil C density } (\text{mg}\cdot\text{C}\cdot\text{cm}^{-3}) = C_s \times DW_s/V_t, \tag{2}$$

$$\begin{aligned}\text{Area} - \text{based soil C density } (\text{kg}\cdot\text{C}\cdot\text{m}^{-2}\text{; 30 cm deep}) &= \text{mean soil C density} \\ &(\text{mg}\cdot\text{C}\cdot\text{cm}^{-3}) \text{ in each soil profile} \times 0.3\ (\text{m}), \text{ and}\end{aligned} \tag{3}$$

$$\begin{aligned}\text{Soil C stock } (\text{Gg}\cdot\text{C; 30 cm deep}) &= \text{area} - \text{based soil C density } (\text{kg}\cdot\text{C}\cdot\text{m}^{-2}\text{; 30 cm deep}) \\ &\times \text{land cover } (\text{km}^2),\end{aligned} \tag{4}$$

where DW_s is the dry weight of soil (g), V_t is the total volume of soil and gravel (cm^3), V_g is the volume of gravel (cm^3), and C_s is the soil C concentration ($g\cdot C\cdot kg^{-1}$).

All response variables satisfied data normality, according to the Shapiro–Wilk test. The effects of city, UGS type, and soil depth on the variables of soil bulk density, C concentration, and C density were tested using a factorial three-way ANOVA. When the ANOVA model was significant ($p < 0.05$), Duncan's multiple range test was performed to determine the differences between the means for each city, UGS type, and/or soil depth. Regression analysis was performed among soil bulk density, C concentration, and C density. In addition, the effects of site history and tree C density on soil C density were determined using regression analysis. All statistical analyses were conducted using *R* (version 3.2.3) [36].

3. Results

The main effects of city, UGS type, and soil depth all significantly affected soil bulk density, C concentration, and C density at 30-cm depths (Tables 2 and 3). The soil C density was greatest in Seoul (2.37 $kg\cdot C\cdot m^{-2}$), followed by Daegu (2.07 $kg\cdot C\cdot m^{-2}$), and then Daejeon (1.39 $kg\cdot C\cdot m^{-2}$); this order seemed largely due to the higher bulk density of Seoul (1.28 $g\cdot cm^{-3}$) and higher soil C concentrations of Seoul (7.58 $g\cdot C\cdot kg^{-1}$) and Daegu (8.22 $g\cdot C\cdot kg^{-1}$) (Table 3, Figure 1). Considering the four UGS types, the soil C density values were significantly higher in soils at riverside (2.62 $kg\cdot C\cdot m^{-2}$) and roadside (2.41 $kg\cdot C\cdot m^{-2}$) than at park (2.05 $kg\cdot C\cdot m^{-2}$) and school (1.76 $kg\cdot C\cdot m^{-2}$), which corresponded to the order of their soil C concentrations (Table 3). Bulk density increased, while both soil C concentration and C density decreased significantly with soil depth, from surface (0–10 cm) to deeper soil depths (10–30 cm) (Table 3). The descriptive summary for mean values of soil bulk density, C concentration, and C density in each city and UGS type are presented in Table 2.

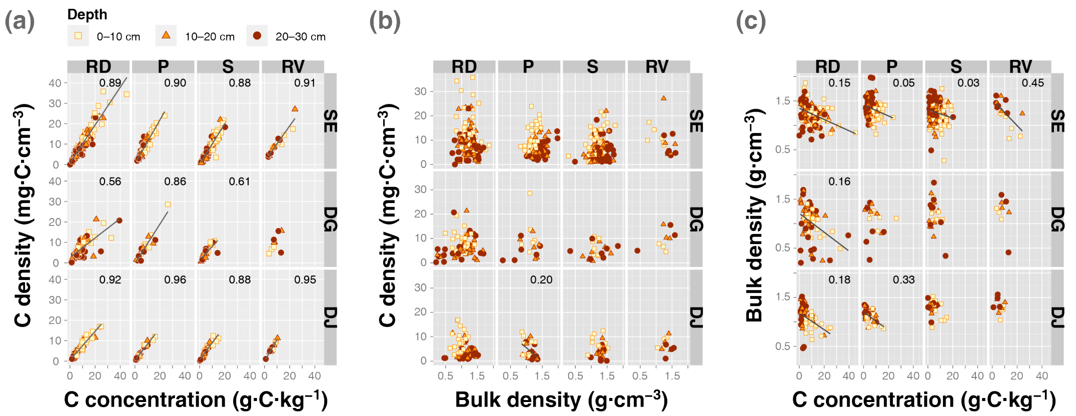

Figure 1. Pairwise relationships among soil bulk density, C concentration, and volume-based C density of soils in different urban green space types for three cities in South Korea (**a**): soil C concentration-C density, (**b**): soil bulk density-C density, (**c**): soil C concentration-bulk density). Where the linear regression was significant ($p < 0.05$), a solid line and an R^2 value number are drawn (numbers in the upper right corner of each sub-panel). Abbreviations are explained in Table 1.

Table 3. A three-way factorial ANOVA that tested for significant differences in soil bulk density, C concentration, and C density by city, UGS type, and soil depth. The table gives the *p*-values; those highlighted in bold are statistically significant ($p < 0.05$).

	df	Bulk Density	Soil C Concentration	Soil C Density
City (C)	2	**<0.001** SE > DJ > DG †	**<0.001** DG = SE > DJ	**<0.001** SE > DG > DJ
Type (T)	3	**<0.001** RV = P = S > RD ‡	**<0.001** RD = RV > P = S	**<0.001** RV ⩾ RD ⩾ P > S
Depth (D)	2	**<0.001** 20–30 = 10–20 > 0–10	**<0.001** 0–10 > 10–20 = 20–30	**<0.001** 0–10 > 10–20 > 20–30
C × T *	6	**<0.001**	0.46	**<0.05**
C × D	4	**<0.001**	**<0.05**	0.33
T × D	6	0.09	0.44	0.07
C × T × D	12	0.18	0.80	0.81

* ×: interaction effect; † SE: Seoul, DG: Daegu, DJ: Daejeon; ‡ RD: roadside, P: park, S: school forest, RV: riverside.

Pairwise correlations among soil bulk density, C concentration, and C density suggested that soil C density was largely regulated by soil C concentration, rather than bulk density (Figure 1). In most cases, the soil C concentration showed a strong relationship with soil C density; while the bulk density did not. However, the soil C concentration and bulk density variables were independent of, or weakly dependent on, each other. The mean soil C density was not significant correlated with either tree C density ($p = 0.20$; data not shown) or year since construction ($p = 0.85$; data not shown) for all UGS types.

The total soil C stocks of each city at 30-cm depths were estimated by combining our empirical data with known UGS inventory data (Table 1). The total UGS soil C stocks in Seoul, Daegu, and Daejeon were estimated to be 105.6, 43.6, and 26.4 Gg· C, respectively (Figure 2). Parks contributed the most to the soil C stocks, accounting for more than two thirds of the total UGS soil C stock. Soil C stocks in other UGS types were consistent with their relative ranking in land cover in each city. For example, riverside had a more abundant soil C stock in Seoul than the other cities due to its relatively large coverage there. Similarly, the school contributed negligible soil C stocks (<2%) due to its limited cover in all cities. Nationwide, UGS soils (385.1 km^2) stored 812.8 Gg· C, as estimated by applying mean soil C densities for each UGS type to nationwide UGS areas.

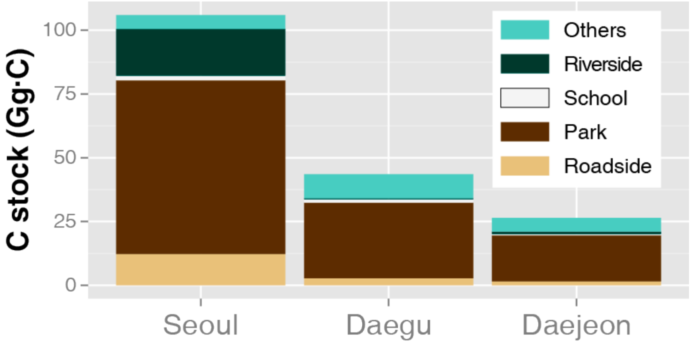

Figure 2. Soil C stock at 30-cm depths of urban green spaces in Seoul, Daegu, and Daejeon (South Korea).

4. Discussion

The soil C density of UGS's in Korea was lower than those in other countries. For instance, area-based total C densities of urban soils at 30-cm depths are reported to be 8.2 kg· C· m^{-2} for turf and 7.9 kg· C· m^{-2} for tree-planted areas in urban parks of Tokyo, Japan [21], 7.3 kg· C· m^{-2} for urban lawns in Fort Collins, USA [37], 5.0–17.2 kg· C· m^{-2} for golf courses in Melbourne, Australia [38], and 4.9–17.5 kg· C· m^{-2} for UGS's and urban forests in Auckland, New Zealand [22,39]. These values are much higher than the range of C densities, also at 30-cm depths, found in this study (1.55–3.02 kg· C· m^{-2}; Table 2). However, the bulk density in the present study (1.22 g· cm^{-3}) was comparable to that in other studies [31,40], apart from a few extraordinary cases of high bulk densities in compacted soils (>1.6 g· cm^{-3}) [41,42]. In contrast, the soil C concentrations found in this study (5.38–9.97 g· C· kg^{-1}) were much lower than not only other UGS soils, such as 20.9–32.0 g· C· kg^{-1} for golf courses in Melbourne, Australia [38], 39.2 g· C· kg^{-1} for UGS's in Auckland, New Zealand [39], and 12.3 g· C· kg^{-1} for lawns in Phoenix, USA [43], but also the 19.2 C· kg^{-1} for remnant urban forests in South Korea [44].

The factors driving the exceptionally low soil C concentration and density of UGS's in South Korea relative to other cities worldwide are not understood. Conceivably, the relatively short history of UGS (<~30 years) and the inappropriate management of UGS soils (e.g., loss of organic matter supply [3,45]) might explain the low soil C storage. That Daejeon had the lowest soil C density among the three cities (Tables 2 and 3) might reflect its relatively short history of urbanization and limited UGS development. Different management practices might also affect the C densities in UGS types. For instance, the riverside soils, which were less disturbed (*i.e.*, not subject to leaf litter and clipping removal) than other UGS soils, also stored the highest C content (Tables 2 and 3). On the other hand, human interference could reduce the input of organic matter and consequently the soil C concentration of park and school soils. In one of the park sites used in our study, Bae and Ryu [20] reported a noticeable increase in total soil C concentration (256%) over a decade as a result of sound management practices, such as proper irrigation and the application of a compost amendment made from removed site litter. It has been further suggested that management practices to enhance organic matter supply and soil environment should also be considered for enhancing C storage in UGS soils [46].

To better manage UGS soil C including organic and inorganic C, sufficient organic matter supply from litter, most of all, must first be designed [3]. The litter cycling of natural ecosystems may not be applicable to urban settings where social demands and services predominate, namely for maintaining surface cleanliness and users' convenience. Nonetheless, leaving a minimum amount of litter and grass clippings or alternative practices which offset the loss of organic matter supply to UGS soils, could be adopted. Compost amendment application and mulching, or both, can increase urban soil C storage [46,47]. Recently, in South Korea, collected litter has been reutilized as compost amendments for agriculture. Thus, these composts can be applied to UGS soils. Black C or biochar applications to urban soils may be effective not only for increasing soil organic C storage but also for enhancing soil fertility for vegetation growth [3,4]. On the other hand, inorganic C from carbonate reactions may be difficult to control through management practices, given the current dearth of knowledge in this field [3].

Bulk density estimates in the present study were within the normal range. Hence, soil compaction, which represents soil physical structures, might not be a critical concern for soil C density in this study. Nevertheless, we note that soil physical structures could be improved by having sufficient pore spaces, silt, and clay to support rhizosphere activity and soil organic matter accumulation [45,48]. Compost practices are also effective at reducing soil compaction and improving soil physical structure [49–51]. The resulting enhanced physical and chemical soil characteristics could support more vigorous vegetation growth, which in turn leads to more organic matter supply from aboveground and belowground [45,48], and consequently more soil organic C too. For instance, compost amendment practices during soil rehabilitation activities have successfully reduced bulk density and enhanced tree growth in highly urbanized soils [52]. Here, constructing physically fine soils at the beginning of the establishment phase is essential because, unlike agricultural soils, the practices that improve the physical properties of UGS soils are not easily undertaken later. In South Korea, specific guidelines on the construction and management of UGS soils, which were unavailable in the past, have been developed recently [53], and applying them can promote conditions for C sequestration. The citywide assessments in this study described the current status of UGS soil C; however, we could not analyze the full effects of management practices on UGS soil C. For this reason, further experimental studies and long-term monitoring on UGS soil C stocks are warranted.

A comparison of C storage across land uses would suggest that the C storage in UGS's is negligible in South Korea, due to its small land cover and low soil C density when compared to major land uses such as forests and agricultural lands. Soil C stock in South Korean forests covering approximately 60,000 km^2 is estimated to be 341.7 Tg· C at 30-cm depths, according to the Korean Forest Soil Carbon model [30]. The UGS's of South Korea have neither noteworthy land cover (0.4%) nor high soil C density, resulting in their low C storage (0.8 Tg· C; 30 cm deep) being an order of magnitude different from the nationwide values.

In summary, we report the current status of total C storage in UGS soils in three South Korean cities. These results may provide a baseline to help construct the inventory of settlements on the IPCC-GPG and GL, develop sound management guidelines for improving UGS soil C, and safeguard the ecosystem services of UGS soils in terms of C storage.

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