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Natural *versus* urban global soil organic carbon stocks: A meta-analysis

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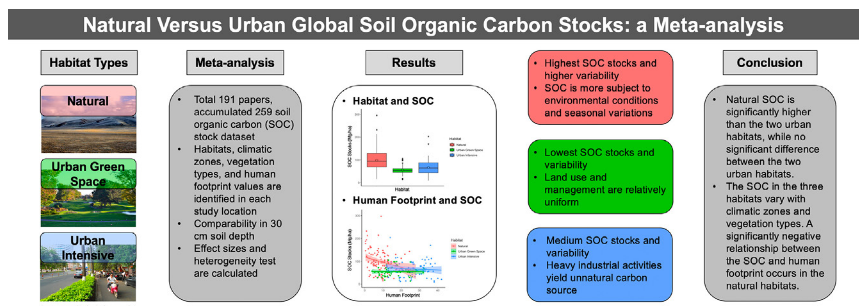
HIGHLIGHTS

- Soil organic carbon (SOC) stocks are greater in natural than in urban habitats.
- SOC stocks vary with climate and vegetation under natural and urban habitats.
- A negative relationship between SOC and human footprint is found in natural habitats.
- Urban SOC stocks are less variable, due to uniform anthropogenic effects.

GRAPHICAL ABSTRACT



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ABSTRACT

Increasingly, the human existence in urban environments is growing. In addition, anthropogenic activity has altered the global carbon (C) cycle and triggered climate change. Soil is the largest pool of organic C in terrestrial ecosystems, but its ability to retain and store C varies. As humans move forward to mitigate climate change, there is a growing need to understand the C storing capacity of soils and their interactions with factors like climate, vegetation or a footprint of human activity. Here, we constructed a meta-analysis which focused on 30 cm soil depth by collecting data from over 191 studies measuring soil organic carbon (SOC) stocks across natural, urban green space, and urban intensive habitats. We then compared the SOC data between different climatic zones, vegetation types, and anthropogenic influences with the human footprint index. The results indicate that SOC stocks in natural habitats (98.22 ± 49.10 Mg ha^{-1}) are significantly higher than those of urban green spaces (54.61 ± 22.02 Mg ha^{-1}) and urban intensive habitats (65.88 ± 35.27 Mg ha^{-1}). We find a significant and negative relationship between the human footprint and SOC stocks of natural habitats but not between the human footprint and either of the urban habitats. Urban intensive and urban green space habitat soils store less C than natural ones. However, when compared across climatic zones or vegetation types, the capacity of natural soils to store C is variable and vulnerable to human activity. Carbon storage in urban soils is likely limited by persistent and stable anthropogenic influences keeping variability low. This is most pronounced in urban green spaces where human management is high (*i.e.* a golf course) and SOC is low. A comprehensive understanding of C storage in soils is essential to land management and climate mitigation measures.

1. Introduction

Anthropogenic exploitation of natural resources, landscape alterations and the excessive emission of carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases has resulted in climate change and global warming (Change, 2018; Chaysaz et al., 2019). As the global

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human population grows exponentially, the rate of urban expansion is likely to rise in the following decades (Nowak et al., 2005; Nowak and Walton, 2005).

It is estimated that urban land cover will increase from 602,864 km^2 in 2000 to 3,114,330 km^2 in 2050, approximately from 0.4% to 2.1% of total land area on Earth (Angel et al., 2011). Material production and infrastructure development, accompanied with increased urbanization, will likely lead to even higher carbon (C) emissions (Miller et al., 2018). The growth both in global population and urban expansion makes net zero CO_2 emission by 2050 a significant challenge (Deutch, 2020). Therefore, global climate mitigation efforts are required to sustain a stable human existence (Macreadie et al., 2017). There are several opportunities to mitigate climate change, even in urban areas (Dhakal, 2010), but a deeper understanding of urban soil C is needed.

In terrestrial habitats, soils support the largest C pools and the greatest opportunity to mitigate atmospheric C imbalances while also providing diverse ecosystem functions (Palosuo et al., 2016), including support for plant growth, habitat for soil organisms, and nutrient cycling (Lavelle et al., 1997; Wander, 2004). During photosynthesis, plants absorb atmospheric C and transform it into biomass and organic compounds (Ehleringer et al., 1997), and simultaneously, some of the fixed C is leaked from the plant root as a flux to rhizosphere soil (Grayston et al., 1997; Haase et al., 2007). Although some atmospheric CO_2 can dissolve directly into soils (Kindler et al., 2011), this mechanism is relatively less important than that of autotrophic or plant-based C fixation. This fact verifies the importance of planted ecosystem (Paul et al., 2002; Zhiyanski et al., 2016), urban green space (Strohbach et al., 2012), and urban parks (Bae and Ryu, 2015) to store C and mitigate the impacts of global climate change.

Extensive research has been focused on the value of soils to store C, and many factors that are biotic, abiotic, and anthropogenic, can influence terrestrial soil organic C (SOC) concentration and stocks (Percival et al., 2000; Guo et al., 2006; Hirano et al., 2007). Huge variability in C storage can be explained by climatic patterns and the background vegetation of that ecosystem (Jiang et al., 2017). Likewise, favorable climatic conditions, like higher temperature and precipitation, are positively linked to higher SOC (Chen et al., 2018), but this can be moderated by increased decomposition rates in for example, tropical biomes (Luyssaert et al., 2007). This is because climate largely determines plant productivity and vegetation cover, and the amount of SOC is controlled by the aboveground biomass and plant composition (Fornara and Tilman, 2008; Steinbeiss et al., 2008). Several studies indicate that higher plant biomass aboveground, like forests, possess higher SOC than the areas with lower plant biomass, like shrubland or grassland (Zimmermann et al., 2010; Fialho and Zinn, 2014) because higher aboveground and belowground biomass are mutually associated. In this case, the root system can contribute to important soil C storage *via* root exudates (Eisenhauer et al., 2017; Shen et al., 2020). However, these processes will depend upon local climate and ecosystem variables. For example, tropical forest soils generally have relatively low SOC due to leaching (Major et al., 2009) and elevated decomposition (Luyssaert et al., 2007), and the nutrients and C are retained within the large trees (Phillips and Lewis, 2014). When ecologists begin to incorporate anthropogenic factors and even urbanization, geographic and climate driven patterns of SOC become far more complicated.

In urban environments, industrial activities and high population density considerably shape habitats with respect to land use and management. Very often, urban soils are highly disturbed, compacted, and contaminated by human activity, and these changing soil properties can affect SOC and ecosystem functioning (Hagmann et al., 2019; Navarrete et al., 2017). When compared to natural habitats, urban soils typically store less C, like the comparison of soil C stocks between natural (Lv and Liang, 2012) and urban forests (Abril and Bucher, 2001). This phenomenon may be tied to anthropogenically driven increases in bulk density, which is usually negatively correlated with the SOC pool (Heuscher et al., 2005; Perie and Ouimet, 2008; Blanco-Canqui et al., 2009; Ruehlmann and Körschens, 2009; Sakin, 2012). However, some studies mention that urban soils can possess uncommonly high SOC, that is of both anthropogenic or natural origins (Hagmann et al., 2019; Huygens et al., 2005; Edmondson et al., 2015), but the mechanisms to explain this are context dependent and subject to the history of the site.

Anthropogenic influences on SOC are complex, and much research has attempted to tease apart the drivers of SOC across diverse habitats and influences. Nonetheless, most of these studies define their research scope at a relatively small scale, either within a single location or a city (Chen et al., 2016; Iimura et al., 2019; Canedoli et al., 2020), within a country (VandenBygaart et al., 2003; Olsson et al., 2009; Ausseil et al., 2015), or across several locations regionally (Bernal and Mitsch, 2008; Rawlins et al., 2008). Moreover, other studies may restrict the scope of their study to SOC under a single vegetation type (Genxu et al., 2002; Mitra et al., 2005; De Silva et al., 2016) or only one habitat type (Pouyat et al., 2002). It is challenging to gain a broad perspective on the influence of contextual factors like climate, vegetation or the anthropogenic influence on SOC even when independent studies provide clear and significant patterns. Furthermore, in contrast to the soils of highly urban areas or even completely natural areas, C stocks of soils in the margin, in areas with less human activity and disturbance that we refer to as urban green space (golf courses, urban greenspace or large urban parks), are largely unknown.

In an effort to capture environmental differences and the naturally occurring gradients in anthropogenic effects, we conducted a meta-analysis of SOC stocks. That is, we calculated the total amount of C stored as Mg ha^{-1}, from a global sampling of natural, urban green space and urban intensive soils. We conducted this analysis on calculated C stocks in an effort to capture the relative role of these habitats in soil C storage. This effort generated a substantial database of C stocks that we further resolved with respect to the surrounding climate (*i.e.* tropical, subtropical, temperate, and Arctic), vegetation community (*i.e.* bareland, grassland, shrubland, forests, wetland, tundra, and mixed) and anthropogenic influence (human footprint). The objectives of this paper are (1) to examine how SOC stocks vary under different habitat types, climatic zones, and vegetation types and (2) investigate the relationship between SOC storage and human footprint. We hypothesized that SOC stocks in natural habitats would be the highest, followed by urban green space habitats across all climatic zones and vegetation types. We also hypothesized that SOC stocks are negatively related to human footprint value in all habitat types. Through investigating C stocks in urban environments and comparing them to the ones in natural ecosystems, we aim to illuminate how urbanization moderates SOC storage and inform future land use and management for climate change mitigation.

2. Materials and methods

2.1. Data collection

We searched the literature and collected data by utilizing Google Scholar and Web of Science. Our keywords included in various combinations: soil, organic carbon, organic carbon stocks, habitat, natural, urban, greenspace, roadside, urban parks, climate, tropical, subtropical, temperate, Arctic, vegetation, desert, bareland, grassland, shrubland, forests, tundra, and human intervention. We included previous meta-analysis papers, and the publication year of the collected papers ranged from 2000 to 2020 in order to avoid outdated datasets. We recorded general information in each paper in detail, including study location, sample size, the climate data of the study location, climate type, habitat, vegetation, dominant plant species (if existed and mentioned), human intervention, bulk density, SOC concentration, and SOC stocks. When needed, we contacted authors to acquire missing information, though this was rare. As large sample size generally has small variation in meta-analysis research (Coory, 2010; Hedges and Olkin, 2014), we continued to accumulate data from the literature until variance stabilized and the addition of new datasets no longer changed the outcome of analysis. Some of the papers measured soil C stocks in more than two locations or were meta-analysis papers that analyzed many data sets allowing us to collect more than one data set from that publication. Therefore, we utilized a total of 191 papers and from those, accumulated a total of 259 SOC datasets. All data will be available in an open access format within the Knowledge Network for Complexity database (https://knb.ecoinformatics.org/) upon publication.

2.2. Criteria for defining the habitat

To study how SOC stocks are influenced by the habitat type and urbanization, we analyzed data with respect to three designated habitat types: natural, urban green space, and urban intensive. Urban soils are located in a city center and are generally compacted (Jim, 1998; Gregory et al., 2006) and often subject to contamination, occasionally by heavy metals (El Baghdadi et al., 2012; Liu et al., 2016). Given that different land management might have varied effects on SOC storage in the urban habitats, we further divided urban habitats into two subsets: urban green space and urban intensive. In this study, we defined urban green space as the locations having less human activity or disturbance but still geographically situated in urban areas or a city center. Example keywords were: urban garden, urban greenspace, golf course and large urban park. The soils in these areas were less perturbed or modified by humans though still closely associated with urban development. Urban intensive habitats were also always located inside a city but subject to higher or more severe human disturbance and impact. Example keywords were: urban, civic, busy, industrialized or commercial. For instance, Central Park in Manhattan, New York was defined as urban green space, while the roadside soils in the commercial areas of lower Manhattan were classified as urban intensive. Natural habitats were all non-urban and not tied closely to a city center. Example keywords were: natural, intact, pristine, and undisturbed. Nevertheless, if there was no keyword for the habitat identification, we used the satellite function of Google Maps to define one habitat type that was the most suitable for the study location, and more information of the study site was collected if necessary. We avoided agricultural studies when possible. If included, their study locations were either defined as natural or urban green space (like a small urban garden or urban farm) habitat according to their geographical locations. Agricultural soil data approximately accounted for 10.42% of the total datasets. Given each habitat type, we then compared how SOC stocks varied across different global climatic zones and then separately across different background vegetation types.

2.3. Criteria for defining the climate zone

We assigned a climatic zone for each study location. Most papers indicated the climatic zone of their study locations. However, if the papers did not provide the climate information, we utilized the climate map of related literature (Olson and Dinerstein, 2002; Zhang et al., 2017; Gardner et al., 2020) to identify the zone. The climate types we included in this study were: tropical rainforest, tropical savanna, tropical monsoon, subtropical monsoon, temperate oceanic, temperate monsoon, temperate continental, Mediterranean, mountain plateau, desert (including tropical and temperate desert climate), and Arctic. If a study location overlapped between two (or more) different climate zones, we would choose the zone that covered the largest proportion of the research area.

2.4. Criteria for defining the vegetation

We defined the vegetation type for each data set, and the classifications consisted of: bareland (including desert), grassland (including savanna), shrubland, forests, wetland, tundra, and mixed. The group 'forests' included all types of forests, ranging from tropical rainforests, evergreen forests, to deciduous forests and coniferous forests. Most papers clearly defined the vegetation cover of their study locations; if papers provide dominant plant species rather than vegetation type, we would define the vegetation type based upon geography and the dominant plant species mentioned by these papers. If a study location (such as an urban park) included several types of vegetation, we chose the most dominant type. However, if we could not identify dominant vegetation, the site would be defined as "mixed". The documentation of the mixed vegetation cover was more common in the urban intensive habitats than in natural or urban green space habitats. If the vegetation information was lacking in a paper, we would refer to the map of terrestrial biomes from Olson and Dinerstein (2002) to determine vegetation type.

2.5. Criteria for defining the human disturbance

To quantify the impact of human use on the study sites, we used the 'human footprint' index defined by Williams et al. (2020). Their human footprint index follows the methodologies of earlier works (Sanderson et al., 2002; Venter et al., 2016) and has been updated to account for shifts in human activity from 2000 to 2013. The human footprint index is based on the data and information of built environments, population density, electric infrastructure, crop and pasture lands, roadways, railways, and navigable waterways. It is a unitless index, and the scores in each subgroup of human impact ranged from 0 to 10 and the total human footprint index occurs on a scale from 0 to 50 with a higher footprint index indicating the area is more disturbed, polluted, or urbanized by humans. This index has been widely utilized in many ecological and environmental studies (*sensu* Ellis and Ramankutty, 2008; Halpern et al., 2008). As in the mapping data of Williams et al. (2020), we adjusted the value of the human footprint to account for the anthropogenic impact in each study location. When required and to reflect different land use and management more specifically, the value was subject to change and became slightly higher or lower (our adjustment was within ± 5). The modification chiefly depended on the site descriptions in each collected paper, and the extent of change was based on the context of the discussion. That is, keywords making the footprint value higher were: busy, commercial, disturbed, perturbed, polluted, contaminated, degraded, deteriorated, overexploited, over-populated, and heavily-industrialized, while the keywords making the footprint value lower were: natural, intact, pristine, undisturbed, unperturbed, isolated, tree-planting, *etc.* If the manuscript lacked specific site details for study location, the human footprint value would remain unchanged.

2.6. Data processing in soil organic carbon

When papers only present SOC concentration rather than stock, we used that value together with soil bulk density to calculate C stocks by using the following formula (Ellert et al., 2001; Gelaw et al., 2015; Ghosh et al., 2016):

$$SOC_{stocks}\left(\mathrm{kg\ m^{-2}}\right) = SOC_{concentration}(\%) \times BD\left(\mathrm{kg\ m^{-3}}\right) \times Soil\ depth\ (\mathrm{m}) \quad (1)$$

where SOC_{stocks} is soil organic carbon stocks, $SOC_{concentration}$ means soil organic carbon concentration, and BD denotes soil bulk density. For those papers which had the data of soil carbon concentration but did not provide soil bulk density, we utilized the following equation to estimate bulk density with the data of soil organic carbon concentration or soil organic matter (Post and Kwon, 2000; Guo and Gifford, 2002):

$$BD = \frac{100}{\frac{OM\%}{0.244} - \frac{100 - OM\%}{MBD}} \quad (2)$$

where BD is soil bulk density, OM% means the percentage of soil organic matter, and MBD is mineral bulk density. Here we followed previous research and assumed that soil organic matter is calculated by dividing SOC concentration with 0.58 (Mann, 1986; Shi et al., 2018) and that the typical value of MBD was 1.64 (Mann, 1986; Shi et al., 2018).

To improve comparability of the SOC stocks among different habitats, climate zones and vegetation types, we adopted an average value of SOC stocks (or calculated the C stocks by the SOC concentration and bulk density) to 30 cm and 1 m (presented in the supplementary information) soil depth for each study. For those papers whose database did not reach to 30 cm/1 meter soil depth, we calculated one average value from all available data lower than 30 cm/1 meter soil depth that each paper provided. Moreover, we converted each mean value of the soil C stock from a certain soil depth (lower than 30 cm/1 meter) to 30 cm/1 meter soil C stock by the following two asymptotic equations (Jobbágy and Jackson, 2000; Jobbágy and Jackson, 2001):

$$Y = 1 - \beta^{d} \tag{3}$$

$$X_{100} = \frac{1-\beta^{100}}{1-\beta^{d0}} \times X_{d0} \tag{4}$$

where Y is the cumulative proportion of soil carbon stock from the soil surface to its depth (cm); β is the relative decrease of soil carbon stock with soil depth; X_{100} denotes the soil carbon stock in upper 100 cm; d_0 is the original soil depth (cm) in the individual soil research, and X_{d0} indicates the soil carbon stock from surface soil to d_0 soil depth.

In this meta-analysis study, we adopted the value of β as 0.9786 (Li et al., 2012) uniformly across all habitat types, climatic zones, and vegetation types given that the depth distribution of soil C did not significantly vary among diverse ecosystems or between individual ecotones and the global average (Jobbágy and Jackson, 2000). Then, we calculated the value of the SOC stock in the upper 100 cm (X_{100}) and 30 cm (change X_{100} into X_{30}) in each study, and ultimately, we converted all units into Mg ha^{-1}. We found the results were not different between the two soil depth scenarios, and we presented the results to 30 cm depth. All the results in 100 cm soil depth are presented in Supplementary Figs. 3–8. Several studies demonstrated that different soil depths do not alter the values of soil C in their meta-analyses (Yang et al., 2011; Li et al., 2012). Moreover, previous research concluded that there would be no difference between measured and estimated values of soil C stocks by using the above asymptotic equations (Li et al., 2012). In fact, not adjusting for soil depth, in some cases, may give rise to small misestimations of different factors on SOC stocks per unit land area (Post and Kwon, 2000; Guo and Gifford, 2002).

2.7. Calculating effect sizes and heterogeneity

Again, data were organized into three habitat types: natural, urban green space, and urban intensive. For each of these habitat types we generated effect size with respect to C stocks for multiple global climatic zones and multiple different background vegetation types. To estimate the effect sizes, we averaged the data within that entire habitat type; this served as the 'control'. Then, we compared the value for each different climatic zone and vegetation type back to that habitat mean value to determine the effect size with respect to the C stocks. For each of these effect sizes, a standardized mean per parameter in all data for the climatic zones and vegetation types was calculated by presenting Hedges' g, which would be the values modified from Cohen's d (Rosenberg et al., 1999; Cohen, 2013). The standardized mean difference between the control and treatment was measured by the pooled variance and multiplied by factor J to amend the bias of the sample size in a meta-analysis following the methods of Gurevitch and Hedges, 2001. After the calculation of the effect sizes, we used the package "metafor" in R (version 3.6.3) to generate forest plots (see Blanck et al., 2018; Viechtbauer, 2010; software package: https://www.metafor-project.org/doku.php) for both soil depths by using a random effects model with a conservative estimation (r = 0.7) (Rosenthal, 1986) (Supplemental Figs. 1 to 4). Because a single heterogeneity measure might not be sufficient and appropriate to all situations, we utilized the total observed variation (I^2) and a test of heterogeneity (Q) to verify the heterogeneity of the collected data. A Higgins' I^2 value higher than 75% indicates substantial heterogeneity (Higgins et al., 2003). The null hypothesis of the Q statistics assumes that all the papers or groups share the summary effect size (Borenstein et al., 2011). A significant Q_{total} demonstrates that effect sizes are not evenly distributed across the studies or that the direction of the effect sizes quite differs between the studies, showing higher heterogeneity (Meisner et al., 2014). The effect sizes and heterogeneity test in the SOC stocks with respect to climatic zone and vegetation type were calculated (Supplemental Table 1).

2.8. Statistical analysis

We calculated SOC stocks under the three different habitat types with two influencing factors: climate and vegetation. To determine the global effect of the habitat on SOC, we pooled all data and conducted Shapiro-Wilk test to determine normality. We found the SOC data were not normally distributed in each habitat type (p-value < 0.05), so we used Kruskal–Wallis test to determine significant difference among the three habitat types. If yes (p-value < 0.05), we utilized Wilcoxon rank-sum test with Bonferroni correction (Verhoeven et al., 2005) to verify which pairs of groups were different. Following this, we performed Kruskal–Wallis and Wilcoxon rank-sum test to examine if habitat type determined C storage in the different climatic zones and again across different background vegetation types. In order to resolve potential influences of human use on the C stocks, we regressed our calculated human footprint against the C stocks in each of the three habitat types. All statistical analyses, including the effect sizes and heterogeneity test (I^2 value and Q statistics), were performed in R (Version 3.6.3).

3. Results

3.1. Data distribution, effect sizes and heterogeneity test

Our dataset represents a wide global sampling (Fig. 1). In the effect sizes and forest plots, the different climatic zones vary greatly in their capacity to store C (Supplemental Fig. 1), but this depends upon the habitat type. We find the least variability in C stocks depending on climatic zone in the urban green space habitats where there is little effect of climate on C storage at all (Supplemental Fig. 1b). With respect to vegetation type, we find relatively less variability in capacity to store C across the three habitats. Only the natural habitats vary much with bareland storing the least C and tundra storing the most (Supplemental Fig. 2a). However, in the urban green space or urban intensive habitats, background vegetation does not greatly affect the amount of C stored (Supplemental Fig. 2b and c). When we compare the climate and vegetation factors with respect to C stocks, it seems that variability is explained more by climate than surrounding vegetation. Our analysis does not test whether or not this is an ecological response to climatic drivers or a statistical artifact of the fact that each effect size is distributed across more categories of climate than of vegetation.

Because the database and sample sizes are large but are not evenly distributed, not all confidence intervals of the Hedges' d are narrow. For the heterogeneity test, half of the I^2 and Q value all shows high heterogeneity (either I^2 value $> 75\%$ or p-value < 0.05 in Q statistics) across all the C stocks parameters (Supplemental Table 1). The data of the natural habitats show high heterogeneity when divided by climate and vegetation variables, while not all urban soil data have that same outcome. However, we still feel confident that both climate and vegetation can help resolve and explain heterogeneity in our database as we simultaneously use I^2 value and Q statistics to measure heterogeneity (Shim and Kim, 2019); especially in the natural habitats, given that the

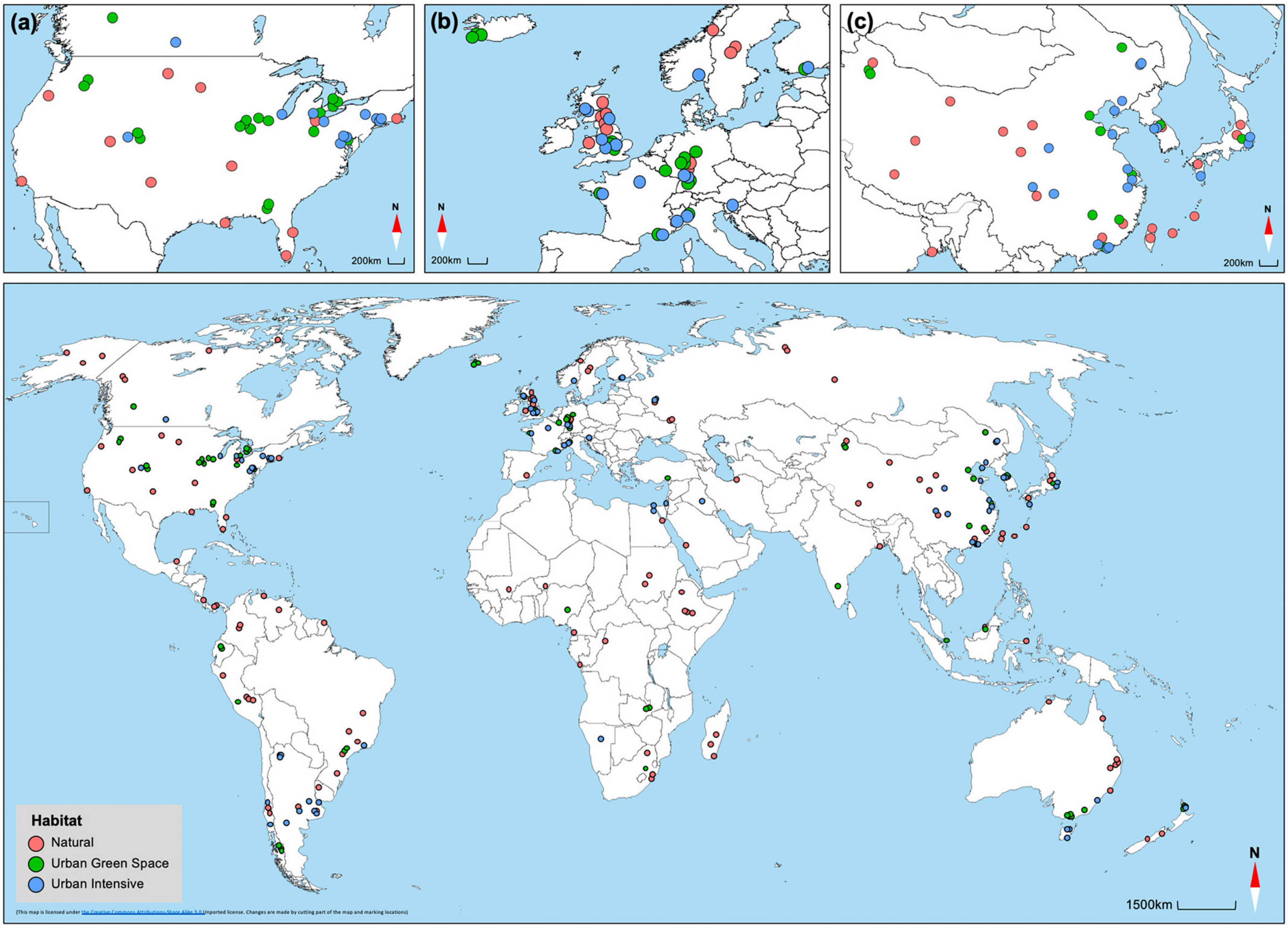

Fig. 1. Global distribution of all study locations and acquired datasets for natural, urban green space and urban intensive habitats. Locations with higher density of study locations in (a) North America, (b) Europe, and (c) East Asia are zoomed. (The World Map is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license.)

urban soil profiles may not simply differentiate among climatic zones or vegetation types when urban soils are under the influence of anthropogenic disturbance. Moreover, natural habitats are shown to be highly heterogeneous, validating the diversity of our database.

3.2. Habitat and SOC stocks

The natural habitats hold significantly higher SOC stocks than either the urban green space or urban intensive habitats (98.22 ± 49.10 Mg ha^{-1}, chi-square = 51.94 and p-value < 0.0001), and it is also the most variable (Fig. 2). Though non-significant, the urban intensive habitats have higher SOC stocks (65.88 ± 35.27 Mg ha^{-1}) than the SOC in the urban green space habitats (54.61 ± 22.02 Mg ha^{-1}).

3.3. Climate and SOC stocks

When we consider the different climate factors in the comparison across different habitat types (Fig. 3), the lowest C stocks are in the urban intensive tropical monsoon area (18.09 ± 6.46 Mg ha^{-1}) (Fig. 3c) and are significantly lower than the SOC stocks in natural and urban green space tropical monsoon regions (p-value < 0.05). The Arctic climate has the highest SOC stocks (157.25 ± 59.02 Mg ha^{-1}) (Fig. 3i). The differences in SOC stocks between the urban green space and urban intensive habitats vary among the climate zones. Whereas only in the desert do we find a setting in which the natural habitats do not store the most C (Fig. 3k). Indeed, the urban green space habitats store the most C in the desert, and this may be the consequence of human management like a park or golf course in an otherwise dry and nutrient poor environment.

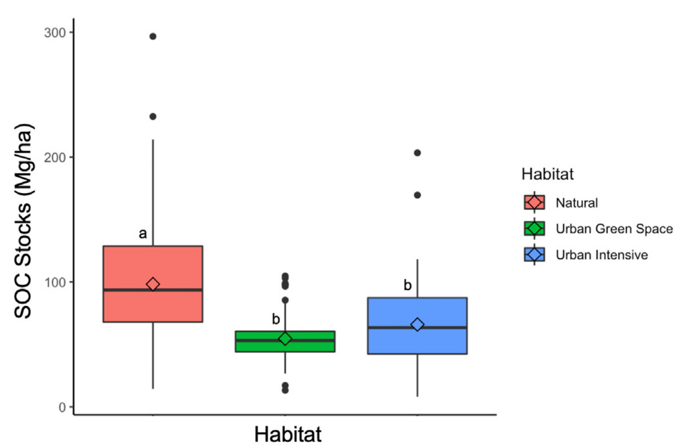

Fig. 2. Total SOC stocks of the three different habitat types in 30 cm soil depth. The mean and median are represented as the diamond and mid line respectively for each box. The first and third quartiles are framed in the box, and solid dots indicate outliers. Each letter represents a significant difference (p-value < 0.0001). The SOC stocks in the natural habitat (n = 112) are significantly higher than urban green space (n = 72) or the urban intensive (n = 75). For the analysis of the 1 meter soil depth, please see Supplemental Fig. 5.

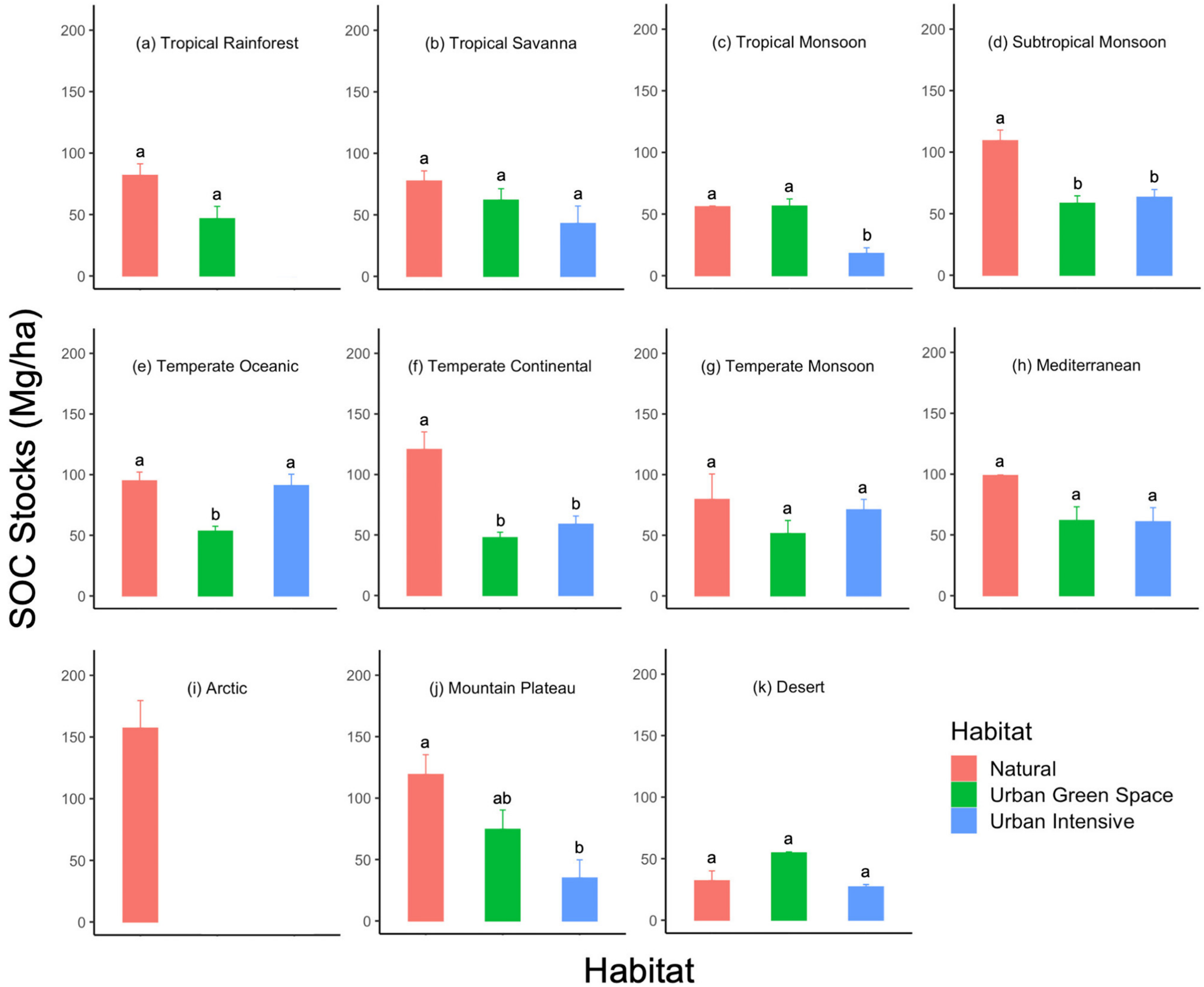

Fig. 3. SOC stocks under different climate zones separated by the three habitat types in 30 cm soil depth with (a) tropical rainforest, (b) tropical savanna, (c) tropical monsoon, (d) subtropical monsoon, (e) temperate oceanic, (f) temperate continental, (g) temperate monsoon, (h) Mediterranean, (i) Arctic, (j) mountain plateau, and (k) desert. Significant differences within each climate zone are indicated by different letters (p-value < 0.05), and error bars represent standard error. Note, our literature search finds no urban intensive data under the tropical rainforest climatic zone and no urban green space and urban intensive data under the Arctic climatic zone. For the analysis of the 1 meter soil depth, please see Supplemental Fig. 6.

3.4. Vegetation and SOC stocks

Of all vegetation types (Fig. 4), the lowest C stocks are found in the natural bareland (27.13 ± 4.82 Mg ha^{-1}), and though they are lower, its difference with the two urbanized areas is not significant (Fig. 4a). The tundra in the natural habitats supports the highest SOC stocks (188.95 ± 28.57 Mg ha^{-1}) (Fig. 4e). However, a comparison with habitat type cannot fully be made because we do not find studies that measured C in urban green space or urban intensive habitats of tundra regions. Broadly, and sometimes significantly so, the natural habitats support higher C stocks than the urban green space and urban intensive habitats across all vegetation types. Significant differences (p-value < 0.05) between natural and urban habitats are found in grassland, shrubland, forests, and mixed vegetation types. In addition to bareland, the exception includes wetland where edaphic factors likely dominate the benefits of reduced human influence (Fig. 4f).

3.5. Human footprint and SOC stocks

We regressed an index of the human footprint against C stocks for each of the three habitat types (Fig. 5). As expected, data points for the urban habitats are skewed toward a higher human footprint, and those in the natural habitats are toward a lower human footprint. In the natural and urban intensive habitats, we find a negative relationship between the C stocks and human footprint, but only in the natural habitats is the relationship significant (p-value < 0.01, $R^2 = 0.00652$, SOC Stock $= 118.59 - 2.31 *$ Human Footprint, for natural habitats; p-value $= 0.51$, $R^2 = 0.0059$, SOC Stock $= 75.23 - 0.35 *$ Human Footprint, for urban intensive habitats). The relationship between SOC and the human footprint shows a slightly positive, but non significant trend in urban green space habitats (p-value $= 0.94$, $R^2 = 0.0001$, SOC Stock $= 54.13 + 0.029 *$ Human Footprint). We also note that variability increases with the human footprint in all the habitats, but also, the natural habitats seem to be more sensitive to the increase in human activity than the urban green space and urban intensive habitats. That is, the range of variability at the high end of the human footprint index for the natural habitats is much higher than at the low end of human activity for that habitat.

4. Discussion

Soil organic carbon stocks in natural habitats are significantly higher than those of the urban green space and urban intensive habitats, and

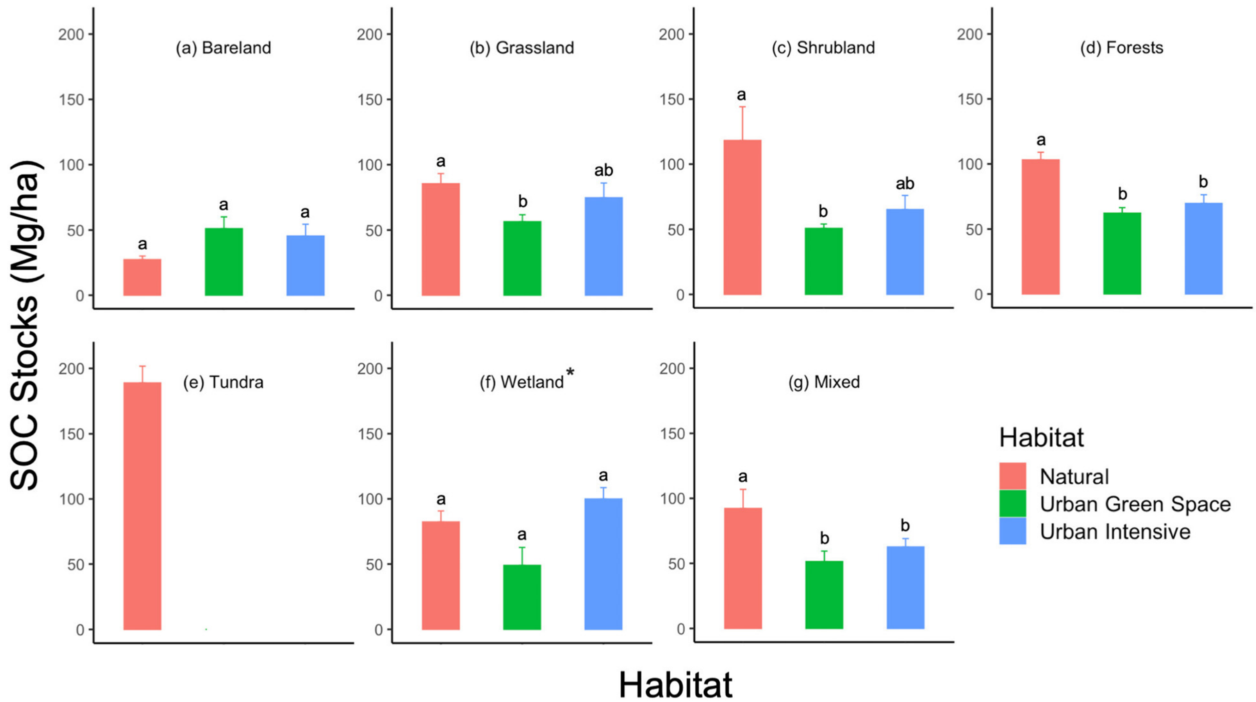

Fig. 4. Bar plot of the SOC stocks under different vegetation types separated by the three habitat types in 30 cm soil depth with (a) bareland, (b) grassland, (c) shrubland, (d) forests, (e) tundra, (f) wetland, and (g) mixed. Significant differences within each vegetation type are indicated by different letters (p-value < 0.05), and error bars represent standard error. Note, our literature search finds no urban green space or urban intensive data in the tundra vegetation zone. Note for wetlands data (*), in this study, we mostly incorporate terrestrial wetlands. Therefore, marine associated wetlands, like salt marshes and mangroves, are not well represented. Wetland SOC data here may not be representative of all global wetlands. For the analysis of the 1 meter soil depth, please see Supplemental Fig. 7.

they are also the most variable. This finding partially supports our first hypothesis and reflects the sensitivity and environmental heterogeneity of natural habitats relative to urban. The soils in natural ecosystems have a high potential to store organic C, but they appear to be more influenced by factors like climate and vegetation than urban green space or urban intensive habitats where anthropogenic effects may dominate.

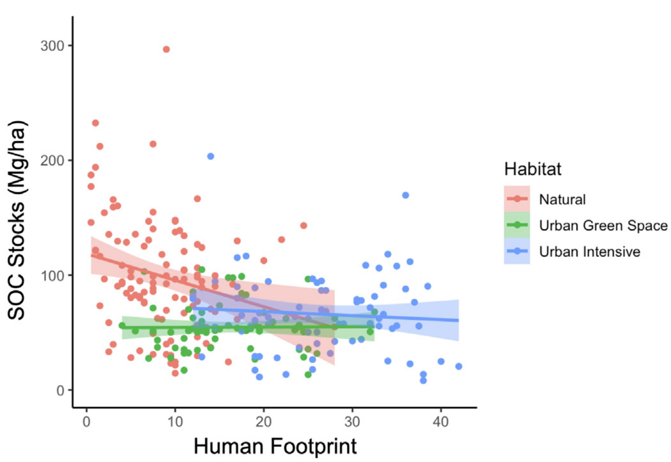

Fig. 5. Scatter plot of SOC stocks with respect to the human footprint under each of the three habitat types in 30 cm soil depth. A higher human footprint value indicates higher human disturbance and modification of the land. The line represents the line of best fit for each habitat, and the shaded area under color indicates 95% confidence interval from the line of best fit. In the natural habitat, n = 112, in the urban green space habitat, n = 72 and in the urban intensive, n = 75. Because natural habitats are less likely to be impacted by human activity, their human footprint value is relatively low. Likewise, the value for both urban green space and urban intensive are relatively higher. The relationships between the human footprint and SOC stocks are negative in natural and urban intensive habitats, but only that found in natural habitats is significant (p-value < 0.01). For the analysis of the 1 meter soil depth, please see Supplemental Fig. 8.

For instance, the lowest SOC stocks are consistently found in natural habitats of desert climates (Wang et al., 2014) or in bareland that lacks vegetation as one may find in an urban center (Li et al., 2010), the environments that are vulnerable to extreme variability in temperature and moisture. In contrast, the soils in the natural habitats of the Arctic climate and associated tundra vegetation have very high soil C that may be linked with a cold and stable natural ecosystem (Rodionov et al., 2007; Liang et al., 2018). The nature of the diverse environmental conditions across most natural habitats drives the large variance of the SOC stocks even when the mean value is still considerably higher. This is likely due to lower human disturbance and the fact that climate and vegetation play a more pressing role on C storage in natural areas than the stable and persistent effects of human activity.

Our meta-analysis supports the notion that anthropogenic influences can significantly influence SOC stocks. Urban land use and management can lead to variability in SOC stocks across different urban soil studies (Aragón et al., 2000; Pouyat et al., 2006; Cotching, 2012). Some unnatural C sources, like coal and ash, contribute to higher SOC stocks in some urban intensive habitats (Edmondson et al., 2015). However, the variability is still lower in urban intensive and even urban green space soils than it is in the natural habitat soils. We suspect that this is because most urban ecosystems may be more stable, reflecting human patterns to live in stable environments and our living requirements that are fairly uniform across different cities. This is demonstrated by the lower standard deviation of average C stocks in the urban green space habitats, and suggests that its land use and influences upon it may be more homogeneous. For instance, urban greenspaces (Lindén et al., 2020), golf courses (Livesley et al., 2016) or agroecosystems (Chuai et al., 2012) are all subject to consistent and broadly accepted management practices. Practitioners supervise these lands regularly including use of irrigation and fertilizer. However, the fact that urban green space habitats were urbanized and developed by humans in the past still triggers its lower average SOC stocks when comparing to comparable natural habitats. This is illustrated by the fact that the state of being located in an urban center with a higher human footprint like in the United Kingdom (Edmondson et al., 2012), the Northeastern United States (Pouyat et al., 2009) or Southeastern China (Zhang et al., 2007) is still less important to soil C storage than the drivers of urban green space habitats. We suspect this is tied to intensive land management of the urban associated green spaces (Fig. 6).

Soil C stocks vary with climate, and in fact they are different among the three habitat types with respect to different climatic zones. In the tropical savanna and monsoon region, SOC stocks in the urban green space habitats are higher than the urban intensive habitats. However, the urban intensive environment has higher soil C stocks in the temperate oceanic, monsoon, and continental climate region. The pattern and extent of urban land use and management between developed and developing countries across these climatic zones may account for the two opposite results. It is noteworthy that we could not find representative data from urban habitats in tropical ecosystems. The developing countries in tropical savannas, like in Brazil and Namibia, may be inclined to over-degrade natural resource and soil environment for urgent crop harvest and economic growth (Pinheiro et al., 2004; Nijbroek et al., 2018). Intensive yet small scale agriculture is likely to deteriorate soil health and nutrient cycling, resulting in lower C stocks. Moreover, heavy urban industrialization and metal contamination in developing countries of the tropical monsoon region jeopardize soil stability and its ability to retain C (Bhagure and Mirgane, 2011; Wang et al., 2013). On the other hand, developed countries in the temperate climate zones, like Europe, Australia and Northeast Asia, have the resources to manage their cities in a more sustainable way, and a proper urban management strategy can benefit SOC stocks (Cotching, 2012; Bae and Ryu, 2015; Weissert et al., 2016).

We consider climate zone and vegetation type in two separate analyses. However, those two factors obviously interact with each other. We see this in the fact that the Arctic climate and the tundra vegetation logically both support very high C stocks. However, this analysis reveals that C stocks also interact with human use of global landscapes. For instance, natural shrubland has a large capacity to store C, but also very high variation. This outcome may reveal that the different shrublands in natural, urban intensive or urban green space habitats are a diverse category, and they are widely influenced by anthropogenic disturbances (Bationo and Bürkert, 2001; Mekuria et al., 2014; Montes-Pulido et al., 2017). On the other hand, we found urban wetland data to be limited, and therefore this analysis may not perfectly reflect the current state of wetland soils (see Fig. 4f). Nevertheless, this does support the importance and urgency of urban wetland soil research.

The human footprint data distribution of the three habitats types (Fig. 5) reflects our definitions of these habitats and what one would expect given a coarse gradient of urban intensive, urban green space and natural habitats. Generally, we find a negative relationship between the human footprint and SOC stocks in the natural and urban intensive habitats, and the human footprint may be an indicator that can predict SOC stocks for an environment, especially in a natural habitat where the relationship between human use and C stocks is significant. We argue that our second hypothesis, therefore, may only be relevant in natural ecosystems. It is understandable that soil C stocks decline in natural habitats as the human footprint increases. However, in the urban intensive habitats, the negative relationship is less obvious and not significant; the relationship is even slightly positive in the urban green space habitats, though non-significant. This suggests that at the high end of human influence, SOC stocks are less affected by variability or nuances in anthropogenic effects. The urban green space habitats are either less influenced by people and or located in the less-populated area within a city. This reflects that the distribution and variance of the SOC stocks are not only influenced by the habitat types but also controlled by varied land use and management.

It is not surprising that more natural soils with less anthropogenic influence store more C than more urban and human influenced soils do. However, the nuances of when and how all habitats may store C is a question that needs addressing in a comprehensive way. Our analysis helps support this understanding of global soil C storage with respect to human land use. For example, in an agroforestry system, the mean of soil C stocks in 1 meter depth is estimated to be 126 Mg ha^{-1} (Shi et al., 2018). This value falls within a standard deviation of our average value for urban green space habitats in 1 meter soil depth (101.26 ± 36.47 Mg ha^{-1}) (see Supplemental Fig. 5). Likewise, with respect to prior values of SOC stocks in urban ecosystems to 1 meter depth, our values in 1 meter soil depth are comparable (123.08 ± 64.95 Mg ha^{-1} *versus* 85.13 Mg ha^{-1}) (Pouyat et al., 2006) (see Supplemental Fig. 5). The gap between the mean value of Pouyat et al. (2006) and our analysis of urban soil C also falls within a standard deviation of the average value of the urban intensive habitats in our research. The way that climatic conditions influence soil C stocks is pertinent to biotic mechanisms, such as the productivity of vegetation and decomposition of soil organic matter (Post et al., 1985; Li et al., 2012). When taking a global perspective, both total litter fall input and soil decomposition rate as soil C sources decline with increasing latitude (Zhang et al., 2008). As a result, soil C accumulation rates are lower in the ecotones of both tropical and

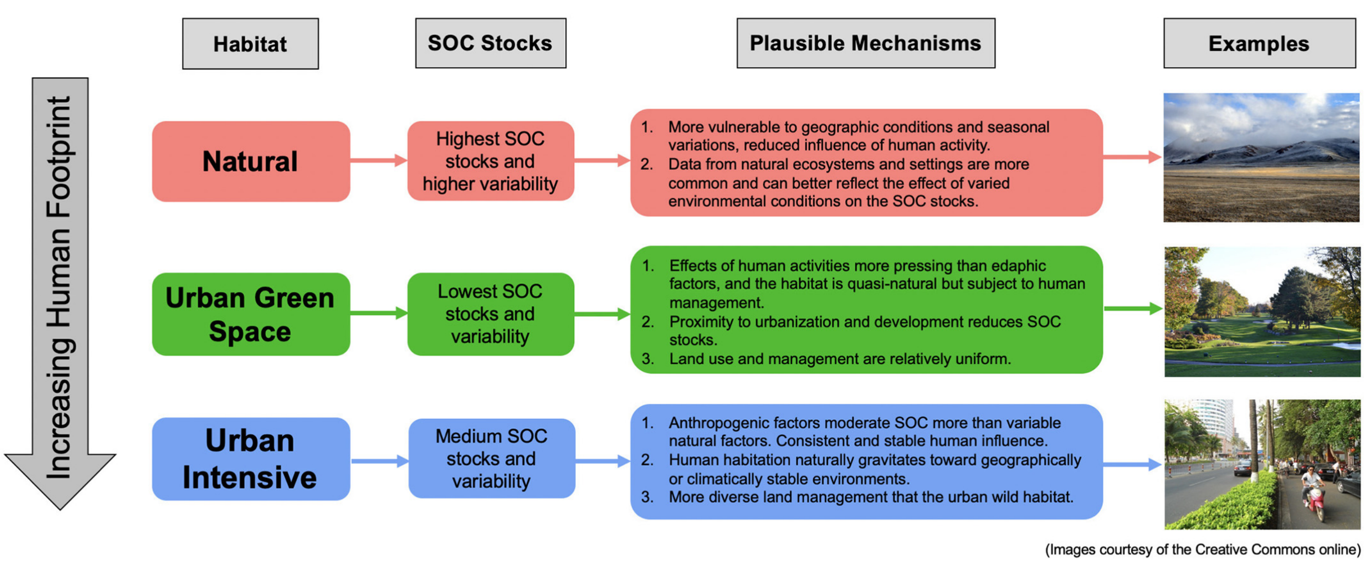

Fig. 6. Summary of effects and plausible mechanisms for the variation in SOC stocks.

temperate regions given that the effect of litter fall on the SOC stocks is compensated by the influence of microbial decomposition. This ecological process is reflected in our finding in the climatic effects on the soil C.

The effect of vegetation on SOC stocks is somewhat complicated, especially when we incorporate human impacts on land. At a global scale, soil C stocks generally increase after afforestation on bareland, grassland, and cropland across varied climatic zones (Li et al., 2012), and this finding corresponds to our research outcome in the effect of vegetation on the SOC stocks. Even though growing SOC stocks with increased vegetation cover are not observed in the urban green space and urban intensive habitats (Fig. 4a to d, see the green and blue bars), the SOC stocks do increase from bareland and grassland, to shrubland and forests in the natural habitats (Fig. 4a to d, see the red bars). Likewise, the extent of increase in soil C often will depend on the primary species planted (Paul et al., 2002; Berthrong et al., 2009), the arrangement of plant composition (Chen et al., 2020), and the preference of management strategy. These influencing factors accordingly reflect the human footprint in different habitat types (across natural to more urban).

In additional to habitat, climate, vegetation and human disturbance, other key factors, like soil texture, may influence soil C storage as well. For example, previous research found that sandy-loam and clay have a positive association with SOC (Schillaci et al., 2017); a meta-analysis also reveals that soil clay content is a crucial factor in controlling soil C storage and its response to plant residue retention (Wan et al., 2018). However, in our literature search, very few papers acknowledge soil texture as a variable in C storage, especially in human influenced soils (approximately 10%–15% of papers). Furthermore, given that soil texture and composition can vary with climate gradients (Ito and Wagai, 2017), and they are associated with aboveground vegetation (Dodd et al., 2002; English et al., 2005), we believe the effect of soil texture on SOC stocks is an important avenue for future research in urban soils.

5. Conclusion

In this study, SOC stocks among natural, urban green space, and urban intensive habitats under different climatic zones and vegetation types were compared. Our database shows high heterogeneity, and our analysis reveals that natural ecosystems have significantly higher SOC stocks than the urban green space and urban intensive habitats. The difference in C stocks between the urban green space and urban intensive habitats is not significant, and we find a significant negative relationship between the human footprint and SOC stocks in natural habitats. Broadly, we find that although natural ecosystems store the most C, they are the most variable. We suspect this is due to a lack of human influence and management and a greater vulnerability to climatic drivers, and that will also interact with vegetation.

In this meta-analysis, we help create a more comprehensive picture of the difference in SOC stocks among diverse habitats. Our research findings can be a useful reference for natural resource management and urban design to manage C budgets and mitigate climate change impacts at a global scale. As industrialization and urbanization have been happening dynamically over time, future studies can follow these patterns and further investigate the difference of soil C under varied climatic zones, vegetation types, and human impacts. Future work can further explore the ecological processes and mechanisms behind our findings and develop mathematic models to link the factors that moderate SOC stocks.

Comparing the capacity of urban and natural habitats to store C in their soils in one comprehensive analysis has a distinct value. So often, urban ecosystems are considered in isolation and without reference to locations lacking human influence. The large database generated by this work informs under what circumstances soils store the most C across a global sampling. The degree to which urban intensive or even urban green space soils store C can inform urban and natural human use and management strategies. Our research further supports the notion that omitting urban soils from investigations of C storage and budgets will never fully capture the global C cycle and balance.

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CRediT authorship contribution statement

Shih-Chieh Chien: Conceptualization, Methodology, Analysis, Writing. **Jennifer Adams Krumins:** Conceptualization, Writing, Supervision, Revising and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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