The impact of urbanization on soil organic carbon stocks and particle size and density fractions

Aurélie Cambou, Tiphaine Chevallier, Bernard Barthès, Delphine Derrien, Patrice Cannavo, Adeline Bouchard, Victor Allory, C. Schwartz, Laure Vidal Beaudet

► To cite this version:

Aurélie Cambou, Tiphaine Chevallier, Bernard Barthès, Delphine Derrien, Patrice Cannavo, et al.. The impact of urbanization on soil organic carbon stocks and particle size and density fractions. Journal of Soils and Sediments, 2023, 23 (2), pp.792-803. 10.1007/s11368-022-03352-3 . hal-03980388

The impact of urbanization on soil organic carbon stocks and particle size and density fractions

Aurélie CAMBOU[1,2,3,4*], Tiphaine CHEVALLIER[1], Bernard G. BARTHÈS[1], Delphine DERRIEN[5], Patrice CANNAVO[2], Adeline BOUCHARD[3], Victor ALLORY[3], Christophe SCHWARTZ[3], Laure VIDAL-BEAUDET[2]

[1]present address: Eco&Sols, Univ Montpellier, CIRAD, INRAE, Institut Agro, IRD, 34060 Montpellier, France
[2]Institut Agro, EPHOR, 49000 Angers, France
[3]Université de Lorraine, INRAE, LSE, F-54000 Nancy
[4]Agence de la transition écologique (ADEME), 49004 Angers, France
[5]INRAE, BEF, F-54000 Nancy, France

Authors' email information:

Aurélie CAMBOU: aurelie.cambou@ird.fr
Tiphaine CHEVALLIER: tiphaine.chevallier@ird.fr
Bernard G. BARTHÈS: bernard.barthes@ird.fr
Delphine DERRIEN: delphine.derrien@inrae.fr
Patrice CANNAVO: patrice.cannavo@agrocampus-ouest.fr
Adeline BOUCHARD: adeline.bouchard@univ-lorraine.fr
Victor ALLORY: victor.allory@univ-lorraine.fr
Christophe SCHWARTZ: christophe.schwartz@univ-lorraine.fr
Laure VIDAL-BEAUDET: laure.beaudet@agrocampus-ouest.fr

* **Corresponding author:** Aurélie CAMBOU (aurelie.cambou@ird.fr)

Postal address: UMR Eco&Sols, Institut Agro, Bâtiment 12,
2 Place Viala
34060 Montpellier Cedex 2
France

Phone number: +33 6.20.20.59.73
ORCID: https://orcid.org/0000-0002-4661-7466

Type of paper: Full research paper

Abstract

Purpose. Urbanization is a major driver of land use change and can affect the soil organic carbon (SOC) pools. This study aimed to understand the urbanization impact on SOC stocks and pools at profile scale (0-100 cm).

Methods. The SOC was studied at 0-30 and 0-100 cm depths in park and sealed soils of three French cities (Marseille, Nancy and Nantes). Physical fractionation was performed to gain insight on the size of different SOC pools (particulate and organo-mineral soil fractions).

Results. The SOC stocks were seven to ten times higher in parks than in sealed soils, but lower than in natural soils according to literature data. The contribution of the first 30 cm to profile SOC stock was around 40%, with strong heterogeneity, especially in sealed soils. Considering the whole 0-100 cm profile, SOC stocks in particulate organic matter fractions (light fraction > 50 µm) were 25-48 times higher in parks than in sealed soils, while SOC stocks in mineral-associated fractions (< 50 µm) were only 4-6 times higher in parks than in sealed soils. An unexpectedly high proportion of SOC was found in the heavy fraction > 50 µm, particularly in sealed soils (11% in average at 0-100 cm depth). This fraction associated to sand is usually poor in SOC in natural or agricultural soils. In these urban soils, it might be bitumen, a dense organic artifact.

Conclusion. The SOC stocks up to 100 cm depth and their heterogeneity pleaded to strengthen and expand SOC studies in all urban soils.

Keywords

soil organic carbon pools; park soils; sealed soils; Technosol; organic artifacts; soil organic matter

1. Introduction

Soil organic matter (SOM) plays an essential role in soil functioning. It contributes to the maintenance of soil physical (e.g., soil aeration, aggregation), chemical (e.g., pH regulation and nutrient reserve) and biological fertility (e.g., through soil organism activity; Lal 2014). Moreover, the current increase in atmospheric carbon dioxide (CO_2) concentration could be mitigated by increasing soil organic carbon (SOC) stocks ("4 per 1000" Initiative 2018; Dignac et al. 2017; Minasny et al. 2017). Thus, maintaining or enhancing the SOM stocks, made up of at least 50% of SOC, is an important issue considering their key role in soil ability to provide ecosystem services (e.g., climate change mitigation, biomass supply).

Yet, SOM is characterized by a very large diversity of compounds with specific dynamics and responses to disturbance. Several SOM physical fractionation methods have thus been developed to separate SOM pools according to their dynamics and resilience in soils (Balesdent 1996; Moni et al. 2012; Poeplau et al. 2018; Cotrufo et al. 2019). Two fractions of SOM have mainly been distinguished: (i) the light and coarse particulate SOM (POM; > 50 µm), whose origin is mainly vegetal and assumed to be largely young, easily decomposable and vulnerable to disturbance (labile fraction); and (ii) the finer mineral-associated SOM (< 50 µm), supposed to be older and more stable due to chemical bonding to minerals and physical protection in small aggregates (stable fraction; Lehmann and Kleber 2015; Cotrufo et al. 2019). Then, within these two fractions, the finer the SOM, the more decomposed and stable it is assumed to be (Balesdent 1996).

Many studies have focused on SOM fractions in soils of natural (e.g., grassland, forest) or agricultural ecosystems (both referred to as non-urban soils; Feller and Beare 1997; Balesdent et al. 1998, 2000; d'Annunzio et al. 2008; Cardinael et al. 2015). They showed a strong effect of land use and management practices on the size and dynamics of SOM fractions.

Urbanization has been accelerating since the industrial revolution and is nowadays one of the major drivers of land use change, converting non-urban into urban soils (Liu et al. 2014; Nuissl and Siedentop 2021). The latter are specific to urban areas, which can be defined as the total areas within the administrative boundaries of cities, including all the sealed and vegetated areas, barren land and water bodies (Liu et al. 2014). Thus, urban areas are expected to extend quickly in the coming decades: between 1970 and 2000, urban areas increased by nearly 58,000 km², and are expected to increase by around 1.5 million km² between 2000 and 2030 (Seto et al. 2011). Urbanization, and particularly soil sealing, is often associated with soil degradation. Indeed, urban soils are often considered as surface areas to be built instead of resources to preserve (Blanchart et al. 2018a; Vasenev and Kuzyakov 2018). The levels of soil disturbance vary widely in the urban environment. Some urban soils are particularly marked by human activities and are referred to as Technosols when they contain at least 20% of artifacts (materials that have been created, modified or brought to the surface by humans) to a depth of 100 cm (IUSS Working Group WRB 2015; Allory et al. 2021): this is the case for sealed soils, which are referred to as Ekranic Technosols (IUSS Working Group WRB 2015). A high variability in urban soil properties exists and needs to be known for urban planning (Blanchart et al. 2018b). Concerning SOM status, high stocks have been found in urban green space soils (e.g., parks; Cambou et al. 2021); they could even be higher than in non-urban soils up to 30 or 100 cm depth (Pouyat et al. 2009; Lorenz and Lal 2015; Cambou et al. 2018; Allory et al. 2021). Much lower SOC stocks have been observed in sealed topsoils (0-30 cm), but this is not necessarily the case if considering 100 cm depth (Edmondson et al. 2012; Raciti et al. 2012; Wei et al. 2014a; Cambou et al. 2018). Although sealed areas predominate in cities, very few studies have focused on their underlying layers to date. Urban SOC stocks have rarely been estimated overall, and the study of SOC fractions in these soils has even been less so. Only one study focused on SOC fractions in urban soils, based on two cities in the USA (Moscow, ID and Pullman, WA; Scharenbroch et al. 2005). The study only focused on the 15 first cm of green space soils and showed an effect of green space age and type on the size of the different SOC fractions.

Thus, further studies on the impact of urbanization on the different SOC fractions in various urban soil profiles, including topsoils and subsoils, are needed. To address this lack of knowledge, the present study aimed at characterizing the particle size and density fractions of SOM at 0-30 and 0-100 cm depths in three parks and two sealed soils of three urban areas of France (Marseille, Nancy and Nantes).

2. Materials and methods

2.1. Studied urban areas

Three urban areas, contrasting in their pedoclimatic context, size and history, were selected in France for this study: Marseille, Nancy and Nantes.

Marseille, first founded in 600 B.C., is located in the south of France, along the Mediterranean Sea. With a surface of 241 km², it was in 2017 the second most populated city in France, with 863,310 inhabitants (INSEE, n.d.). The city is settled in a calcareous Oligocene basin surrounded by reliefs and opened onto the sea, with altitudes ranging from 0 to 632 m a.s.l. According to Köppen-Geiger classification, the climate is Csa (Mediterranean), with mean annual temperature and rainfall of 15.5°C and 505 mm, respectively (data from 1980-2017; Infoclimat, n.d.).

The metropolis of Nancy is located in the east of France and includes the city of Nancy (founded in the 11th century) and its agglomeration. In 2017, this metropolis had 256,769 inhabitants over an area of 142 km² (INSEE, n.d.). The area is divided into three geological units, each with different topographical characteristics, and with altitudes ranging from 190 to 420 m a.s.l.: (i) the city of Nancy, made up of alluvium (e.g., sand, gravel and stones), (ii) the hillside, characterized by clays covered with a ferruginous layer, itself under a calcareous layer, and (iii) the plateau, covered with a calcareous layer > 100 m thick. According to Köppen-Geiger classification, the climate is Cfb (semi-continental), with mean annual temperature and rainfall of 10.6°C and 822 mm, respectively (data from 1980-2017; Infoclimat, n.d.). The metropolis of Nancy, for the sake of simplification, will be called "Nancy" in the rest of the study.

Nantes (conquered by the Romans in 56 B.C.) is located in the west of France, about 50 km from the Atlantic Ocean, with altitudes ranging from 0 to 55 m a.s.l. In 2017, Nantes was the sixth most populated city of France, with 309,346 inhabitants, over a surface area of 65 km² (INSEE, n.d.). Nantes is located at the intersection of three rivers: the Erdre, the Sèvre Nantaise and the Loire, where the granite bedrock outcrops. The city is therefore based on crystalline bedrock, with the Loire corridor however characterized by recent and ancient alluvial deposits. Moreover, backfills are present in many parts of the city, with thickness up to 10 m. According to Köppen-Geiger classification, the climate is Cfb (temperate oceanic), with mean annual temperature and rainfall of 12.4°C and 854 mm, respectively (data from 1980-2017; Infoclimat, n.d.).

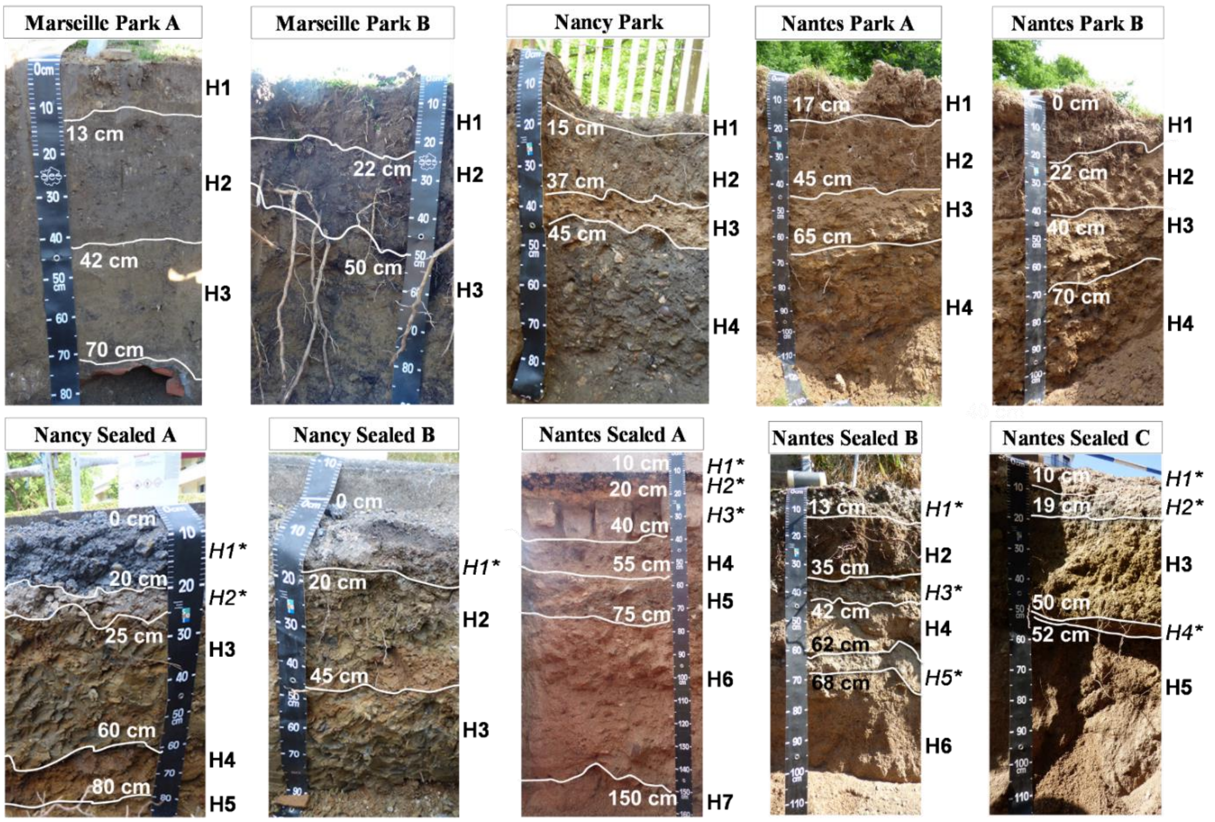
2.2. Studied sites and soil sampling

Five sites were sampled in 2017: (i) three parks under lawn, one in each studied city, and (ii) two sealed areas, one in Nancy and one in Nantes, which are described in Table 1. When possible, two to three replicate pits were dug several meters apart in the parks and the sealed soils; but for logistic reasons, this was not possible in each study site. In total, five pits nearly 1 m deep were dug in parks specifically for the study, using an excavator (Marseille Park A, Marseille Park B, Nancy Park A, Nantes Park A, Nantes Park B). In the same way, five pits of 0.9 to 1.6 m depth, already dug as part of pavement maintenance work, were selected in sealed soils (Nancy Sealed A, Nancy Sealed B, Nantes Sealed A, Nantes Sealed B, Nantes Sealed C). In a same site, the pits (A, B or C) were considered as sampling repetitions. Each soil profile was divided into horizons according to macromorphology (color, structure, texture and stoniness), and these horizons, successively named from H1 to H7, were then sampled (in total, 32 horizons were studied; Fig. 1). The sampled sealed and park soils indistinctly covered a large range of soil texture (Appendix). A notable variability in soil texture between horizons was observable in both sealed soils. The sampling was carried out on the entire width of each horizon, resulting in the collection of 32 disturbed samples. An undisturbed sample was also taken, using a 0.25 L cylinder, in the middle of each horizon (32 cylinder samples). Some horizons could not be sampled because they did not contain any soil particles (i.e. impervious layers) or were too thin or too rich in coarse elements (Fig. 1).

Table 1. Description of the studied sites and pits.

Site name	Location	Soil description**	Year of creation / renovation	Vegetation maintenance (parks) / establishment way (sealed soils)	Profile, cover	Pit depth (cm)	Number of horizons
Marseille Park	Marseille, Borély Park (17 ha) 43°15'39.62"N 5°22'55.83"E	Calcareous Fluvisol on recent fluvial alluvium (sand, silt, gravel, stones)	Creation: 1860-1880	Lawn clipping returned + daily watering	A Lawn	70	3
					B Lawn (place of a former tree)	85	3
Nancy Park	Nancy, Pépinière Park (22 ha) 48°41'47.40" N 6°11'0.23" E	Calcareous Technosol on alluvium from valley bottoms (clay, silt, sand) and calcareous backfill (16th-18th century; Nancy city)	Creation: 1765; renovation: 1840	Lawn clipping returned (mowing 2-3 times a year). No organic input or watering	A Lawn (one tree 3 m away)	90	4
Nantes Park	Nantes, cemetery with park (50 ha) 47°16'14.77" N 1°34'58.16" O	Cambisol on mica-schist and altered clay	Creation: 1976-1979	Mowing every 15 days: in winter, clippings are removed; from spring: mulching. No organic input or watering	A Lawn	125	4
					B Lawn	110	4
Nancy Sealed	Villers-lès-Nancy, pavement (40 m²) 48°40'6.25" N 6° 8'52.08" E	Ekranic Technosol on Brunisol developed from sandy marls, septaria marls, black shale (Nancy hillside)	Creation: 2000 or before*	Topsoil removal and soil sealing	A Pavement	90	3
					B Pavement	90	2
Nantes Sealed	Nantes, railway station (0.3 ha) 47°13'2.02"N 1°32'37.40"O	Ekranic Technosol on anthropic sandy backfill	Creation: 1960*	Topsoil and subsoil removal, then sandy backfill addition and soil sealing	A Car park	160	4
					B Pavement	115	3
					C Pavement	110	2

* according to historical satellite images (Google Earth)
** according to IUSS Working Group WRB (2015)


Marseille Park A

Marseille Park B

Nancy Park

Nantes Park A

Nantes Park B

Nancy Sealed A

Nancy Sealed B

Nantes Sealed A

Nantes Sealed B

Nantes Sealed C

Fig. 1 Description of the profiles studied in urban park soils under lawn and in sealed soils of three French cities. The lines represent the limits between soil horizons. The horizons with names in italics and "*" were not sampled because they did not contain soil particles (e.g., sealed layers) or were too thin or too rich in coarse elements

2.3. Particle size and density fractionation and SOC analyses

The 32 disturbed samples were air-dried then gently broken up and sieved to 2 mm to separate fine earth from coarse particles (> 2 mm). Particle size and density fractionation of SOM was performed on the fine earth (< 2 mm), using a moderate mechanical dispersion of the soil. The method was adapted from Balesdent (1996). Aliquots of 15 g of air-dried soil were shaken with six glass beads for 16 h in 54 mL of demineralized water. Two wet sieving sequences were carried out on these samples, at 200 then 50 µm, respectively. After each wet sieving, the fraction retained on the sieve was collected and the light POM (supposed to be labile) was separated from the heavier minerals by flotation-sedimentation in water. Unlike the method described in Balesdent (1996), no ultrasonic treatment was applied on the 0-50 µm fractions. This choice was made according to Moni et al. (2012), who hypothesized that ultrasonic dispersion could redistribute SOM from the 20-63 µm fraction to the 0-20 µm fraction. The 20-50 and 0-20 µm fractions (F 20-50 µm and F 0-20 µm, respectively; both supposed to be stable) were separated in water by successive sedimentation until depletion, followed by a centrifugation of each fraction to separate the soil particles from water. When the soil particles were hardly separated from water, a flocculating agent was added ($SrCl_2$; between 300 and 800 µl depending on the samples) and centrifugation was performed again. At the end of each fractionation, an aliquot of the water used during all the steps was then recovered in order to analyze its dissolved organic carbon (DOC) content: it corresponded to actual DOC present in soil initially, but also included, probably, SOM that was solubilized during the fractionation process.

Thus, seven fractions were obtained: (i) the light SOM (i.e. POM) with a size ranging 200-2000 µm (L 200-2000 µm); (ii) the 200-2000 µm heavy fraction (H 200-2000 µm); (iii) the 50-200 µm POM (L 50-200 µm); (iv) the 50-200 µm heavy fraction (H 50-200 µm); (v) F 20-50 µm; (vi) F 0-20 µm; (vii) DOC. Each solid fraction was dried for 48 h at 60°C and its mass was determined (g kg^{-1}). Each fraction was then ground to 0.2 mm (ball mill, MM 400, Retsch, Haan, Germany) and its SOC concentration (SOC_{fr} concentration; gC kg^{-1} fraction) was analyzed by dry combustion (ISO 1995) using a CHN elemental analyzer (Flash EA 1112, CE Instruments, Rhodano, Italy), after decarbonatation by chlorhydric acid (HCl) for samples originating from Marseille and Nancy. Decarbonatation was achieved using the procedure described by Allory et al. (2019): 10 µL HCl 4 M was slowly added to 25 mg of soil contained in a silver capsule (resistant to HCl), which was then dried for 4 h at 40°C. This procedure was repeated until the end of gaseous emission. SOC content (gC kg^{-1} soil) of each fraction could then be calculated. The DOC concentration in the solution (gC L^{-1}) was obtained using a COT-meter (TOC-VCSH, OCT-1, ASI-V, Shimadzu, Kyoto, Japan). As the total amount of water used during each sample fractionation was known, DOC content in soil (gC kg^{-1} soil) was also calculated.

2.4. Determination of the bulk density

The bulk density of fine earth (D_b; g cm^{-3}) was determined using the 32 cylinder samples. The same methodology as in Allory et al. (2019) was carried out: the samples were air-dried then sieved to 2 mm to separate fine earth from coarse particles. The dry mass of fine earth (M_f; g) was measured after 48 h oven-drying at 105°C. The volume of coarse particles (V_c; cm^3) was measured in a graduated cylinder partly filled with water, by difference between water levels before and after the addition of coarse particles.

Thus, D_b could be determined as following (Poeplau et al. 2017):

$$D_b = \frac{M_f}{V_t - V_c} \qquad (1)$$

where V_t is the volume (cm^3) of the cylinder.

2.5. Calculation of SOC stock in each particle size and density fraction and contribution to total SOC stock

To allow a standardized comparison of SOC amount between the studied soil profiles and the literature, SOC stock (kgC m^{-2}) was calculated for each profile at 0-30 and 0-100 cm depths, respectively (the impervious layers of sealed soils were not considered).

First, the following equation was used to calculate SOC stock (kgC m^{-2}) of the non-fractionated soil (< 2 mm) in each profile horizon:

$$\text{SOC stock} = \text{SOC content} \times D_b \times \left(1 - \frac{V_c}{V_t}\right) \times \text{thickness} \qquad (2)$$

with thickness, the thickness of the considered horizon (m).

The SOC stocks of horizons in each profile were summed up to 30 cm depth and to 100 cm depth, respectively. For the profiles thinner than 100 cm due to logistical issues in the field (the pits were dug beforehand without measuring the exact depth, in Marseille Park, Nancy Park and Nancy Sealed; Fig. 1), the last horizon observed in each profile was assumed to be homogeneous up to 100 cm depth.

The same work was then carried out to calculate SOC stock in each studied particle size and density fraction (section 2.3), separately. Finally, for each soil profile, the contribution of each particle size and density fraction to the total SOC stock (%) was calculated by the ratio of the fraction SOC stock to the sum of SOC stocks of the seven different fractions, at 0-30 and 0-100 cm depths, respectively.

3. Results

3.1. Distribution of particle size and density fractions

Table 2 shows the results of the particle size and density fractionation for each site. The same fraction predominated: the mass of F 0-20 µm was the highest in all sites, except for Nancy Park and Nantes Sealed, where sands and particularly coarse sands (H 200-2000 µm) predominated. In parks, the coefficient of variation (CV; ratio of standard deviation, SD, to mean; in %) was low for all fractions (7-52%), except for both fractions L > 50 µm (58-177%). However, when considered per soil horizon rather than per city, CV was low for L 50-200 µm in each horizon and for L > 200 µm in deeper horizons (CV = 5-49% for L 50-200 µm and 62-86% in H3-H4 for L > 200 µm; data not shown). In sealed soils, the CVs were higher than in parks whatever the considered fraction (32-182%), without common trend between both sites.

In all cases, the mean recovery allowed by the fractionation method was comprised between 985 g kg^{-1} and 997 g kg^{-1} indicating its overall accuracy.

Table 2. Distribution of particle size and density fractions after moderate dispersion (without SOM destruction) averaged per studied site. The results are presented as mean (standard deviation). n is the number of samples; D_b is the bulk density of the fine earth (< 2 mm). F refers to Fraction and H and L are heavy and light fractions, respectively.

Landscape	**Park**			**Sealed**	
City	**Marseille**	**Nancy**	**Nantes**	**Nancy**	**Nantes**
n	6	4	8	5	9
D_b (g cm^{-3})	1.3 (0.3)	1.2 (0.1)	1.2 (0.2)	1.4 (0.1)	1.5 (0.1)
Distribution of particle size and density fractions after moderate dispersion (g fraction kg^{-1} soil)					
H 200-2000 µm	99 (51)	522 (80)	177 (32)	140 (248)	766 (310)
L 200-2000 µm	17 (18)	57 (102)	7 (7)	0 (0)	1 (3)
H 50-200 µm	261 (18)	101 (16)	190 (15)	215 (145)	94 (115)
L 50-200 µm	48 (28)	30 (30)	40 (28)	23 (14)	8 (13)
F 20-50 µm	223 (33)	82 (30)	269 (23)	160 (52)	42 (58)
F 0-20 µm	336 (47)	192 (64)	310 (34)	456 (207)	86 (125)
Recovery	985 (0.9)	985 (1.9)	993 (4.7)	994 (4)	997 (2)

3.2. Soil organic carbon stock in particle size and density fractions per urban landscape

Fraction SOC stock was calculated and averaged for each urban landscape (park or sealed soil) at 0-30 and 0-100 cm depths (Table 3). The average ratio of the sum of fraction SOC stocks to SOC stock of non-fractionated soil was 98 ± 11% in parks and 111 ± 10% in sealed soils up to 100 cm depth (the fraction SOC recovery > 100% in sealed soils is considered in the next paragraph).

Considering non-fractionated soil, parks had 10 and 7 times higher SOC stock than sealed soils at 30 and 100 cm depths, respectively. These differences were also observed in the seven fractions, with variations according to the fraction. The highest difference concerned L 200-2000 µm and L 50-200 µm: SOC stocks were respectively 25 and 39 times higher at 0-30 cm depth and 48 and 25 times higher at 0-100 cm depth in parks than sealed soils. Then, F 20-50 µm was 6 and 8 times higher in parks than in sealed soils at 0-30 and 0-100 cm depths, respectively. The other fractions (H 200-2000 µm, H 50-200 µm, F 0-20 µm and DOC) were 4-6 times higher in parks than in sealed soils for both depths. Finally, fraction SOC stocks were particularly low at 0-30 cm in sealed soils (mean fraction SOC stocks were 0.02-0.08 kgC m^{-2}), except for F 0-20 µm (0.50 kgC m^{-2}). Fraction SOC was very low in sealed soils, so difficult to quantify and probably overestimated, hence fraction SOC recovery > 100% of the SOC of non-fractionated soil (which was not so low and thus more easily quantifiable).

Table 3. Soil organic carbon (SOC) stock (kgC m^{-2}) in each particle size and density fraction calculated at 0-30 and 0-100 cm depths in parks and sealed soils, separately. The results are presented as mean (standard deviation). n is the number of samples. F refers to Fraction and H and L are heavy and light fractions, respectively; DOC for Dissolved Organic Carbon, is SOC in the water solution at the end of the fractionation.

Urban landscape	**Park**		**Sealed**	
Layer	**0-30 cm (n = 5)**	**0-100 cm (n = 5)**	**0-30 cm (n = 5)**	**0-100 cm (n = 5)**
H 200-2000 µm	0.14 (0.06)	0.53 (0.57)	0.03 (0.03)	0.09 (0.06)
L 200-2000 µm	1.01 (0.57)	1.92 (1.43)	0.04 (0.08)	0.04 (0.08)
H 50-200 µm	0.09 (0.05)	0.32 (0.23)	0.02 (0.02)	0.06 (0.04)
L 50-200 µm	1.56 (0.69)	2.80 (1.35)	0.04 (0.05)	0.11 (0.10)
F 20-50 µm	0.60 (0.26)	1.34 (0.58)	0.08 (0.08)	0.22 (0.19)
F 0-20 µm	3.19 (0.58)	7.39 (0.86)	0.50 (0.46)	1.70 (1.71)
DOC	0.29 (0.06)	0.78 (0.28)	0.06 (0.04)	0.17 (0.14)
Sum of fraction SOC stocks	6.9 (1.8)	15.1 (4.2)	0.8 (0.6)	2.4 (2.1)
Non-fractionated soil	7.1 (2.3)	15.9 (6.4)	0.7 (0.7)	2.2 (2.0)

In terms of fraction contributions to total SOC stocks, at least half of SOC stock was systematically included in F 0-20 µm. This proportion was higher in sealed soils than in parks: it averaged 61% in sealed soils and 48% in park soils at 0-30 cm depth, and respectively 65% and 51% at 0-100 cm depth. In park soils, high proportion of SOC stock was also found in

L > 50 µm (it averaged 36% and 30% at 0-30 and 0-100 cm depth, respectively). In average, the proportion of SOC stock was 1.5 times higher in L 50-200 µm than in L 200-2000 µm for both depths. In sealed soils, contributions of light coarse fraction SOC were 3-4 times lower: the mean proportion of SOC stock in L > 50 µm was 10% and 7% at 0-30 and 0-100 cm depths, respectively. The contributions of other fractions to SOC stock were low for both urban landscapes (averages ≤ 11%). Though SOC stock in H > 50 µm was much lower in sealed soils than in parks, its contribution to total SOC stock was 2-3 times higher in sealed soils than in parks (9% and 11% vs. 3% and 5% at 0-30 and 0-100 cm, respectively). The contribution of F 20-50 µm to total SOC stock was ca. 9% in parks and sealed soils for both depths. The DOC was also lower in sealed soils but its contribution was 2 times higher in sealed soils than in parks (8-11% vs. 4-5%, respectively).

The contribution of the first 30 cm of soil to the SOC stock at 0-100 cm varied according to the urban soils and to the soil fractions. In parks, in average (± SD) 46 ± 7% of SOC stock of non-fractionated soil at 0-100 cm depth was included in the first 30 cm. Similar ratio was found for F 0-20 µm and F 20-50 µm (43 ± 4% and 45 ± 6%, respectively). This proportion was higher for L 50-200 µm and L 200-2000 µm (57 ± 12% and 56 ± 14%, respectively), and lower for H 50-200 µm, H 200-2000 µm and DOC (35 ± 11%, 38 ± 15% and 39 ± 7%, respectively). In sealed soils, the contribution of 0-30 cm depth to 0-100 cm SOC stock varied strongly between soil profiles for the non-fractionated soil (39 ± 39%) and for all studied fractions (from 29 ± 20% to 44 ± 34%, without considering SOC stock of L 200-2000 µm, which was non-existent for most soil profiles, except for one, where it was only in the first 30 cm).

It is worth noting that average horizon D_b was higher in sealed soils than in parks (1.4-1.5 vs. 1.2-1.3 g cm^{-3}, respectively; Table 2). Thus, the soil mass used to calculate SOC stock was not exactly the same between both landscapes, particularly at 0-100 cm depth. However, calculating SOC stocks at equivalent soil mass, as proposed by Ellert and Bettany (1995), would reduce SOC stocks in sealed soils, compared to park soils, so it would accentuate the strong differences already evidenced between both urban landscapes. It was not considered useful, as SOC stocks are less directly understandable when presented at equivalent soil mass than at equivalent depth.

3.3. Soil organic carbon stocks in particle size and density fractions per studied site

The Fig. 2 shows the SOC stock in each fraction for 0-30 and 0-100 cm depths, averaged per studied site (several pits per site, except for Nancy Park). As observed with averages presented in Table 3, on the one hand, parks had much higher SOC stocks than sealed soils for both profile depths, whatever the fraction considered. On the other hand, in all studied sites, F 0-20 µm had the highest contribution to SOC stock: this was more remarkable in sealed soils than in parks, where SOC stock in L > 50 µm was also quite high.

When considering parks only, SOC stock of non-fractionated soil was higher in Marseille than in Nancy and Nantes: at 0-30 cm depth, SOC stock (mean ± SD) was 9.6 ± 0.5 kgC m^{-2} in Marseille, 5.8 kgC m^{-2} in Nancy and 5.3 ± 0.4 kgC m^{-2} in Nantes; at 0-100 cm depth, it was 22.4 ± 4.6, 12.7 and 10.9 ± 0.6 kgC m^{-2}, respectively. This result was firstly due to differences in fractions > 50 µm between the three parks: at 0-100 cm depth, where the discrepancies were accentuated, average SOC stocks of fractions > 50 µm (pooled) were 8.6 ± 3.7, 4.4 and 3.0 ± 0.7 kgC m^{-2} in Marseille, Nancy and Nantes, respectively. The same trend was observed for each fraction > 50 µm considered separately: Marseille Park had the highest SOC stock in each of these fractions, two (for L 50-200 µm) to five times (for H 200-2000 µm) higher than in Nantes Park, where SOC stock was the lowest in all fractions > 50 µm. In contrast, SOC stock in F 0-20 µm in parks was rather homogeneous between sites: it was comprised between 2.7 kgC m^{-2} in Nancy and 3.6 ± 0.6 kgC m^{-2} in Marseille at 0-30 cm depth, and between 6.9 ± 0.3 kgC m^{-2} in Nantes and 8.0 ± 1.2 kgC m^{-2} in Marseille at 0-100 cm depth. And indeed, the contribution of 0-30 cm depth to SOC stock of 0-100 cm depth was quite homogeneous between parks for F 0-20 µm and F 20-50 µm (respectively 38-45% and 43-50%). The contribution of the top 30 cm was less homogeneous between park sites for DOC, L 50-200 µm and L 200-2000 µm (31-48% for DOC, 47-62% for L 50-200 µm and 49-66% for L 200-2000 µm); and even less homogeneous for H 50-200 µm and H 200-2000 µm (respectively 25-42% and 21-42%).

In sealed soils, SOC stock in non-fractionated soil was similar at 0-30 cm depth between both studied sites (0.8 ± 0.7 kgC m^{-2} in Nancy and 0.7 ± 0.8 kgC m^{-2} in Nantes), but 4.6 times higher in Nancy than in Nantes at 0-100 cm depth (4.2 ± 1.7 and 0.9 ± 0.6 kgC m^{-2}, respectively). Similarly, SOC stock in F 0-20 µm was quite homogeneous between studied sealed sites up to 30 cm depth (0.6 ± 0.5 kgC m^{-2} in Nancy and 0.5 ± 0.5 kgC m^{-2} in Nantes), but not at 0-100 cm depth (3.3 ± 1.5 kgC m^{-2} in Nancy and 0.6 ± 0.4 kgC m^{-2} in Nantes). The other fractions in sealed soils were very poor in SOC and at the same level of magnitude. The contribution of 0-30 cm depth to SOC stock of 0-100 cm depth was very different between the sealed sites: in Nantes, it ranged from 40% (for H 200-2000 µm) to 100% (for L 200-2000 µm), and in Nancy, from 16% (for H 200-2000 µm) to 34% (for H 50-200 µm), while L 200-2000 µm was SOC-free in Nancy profiles.

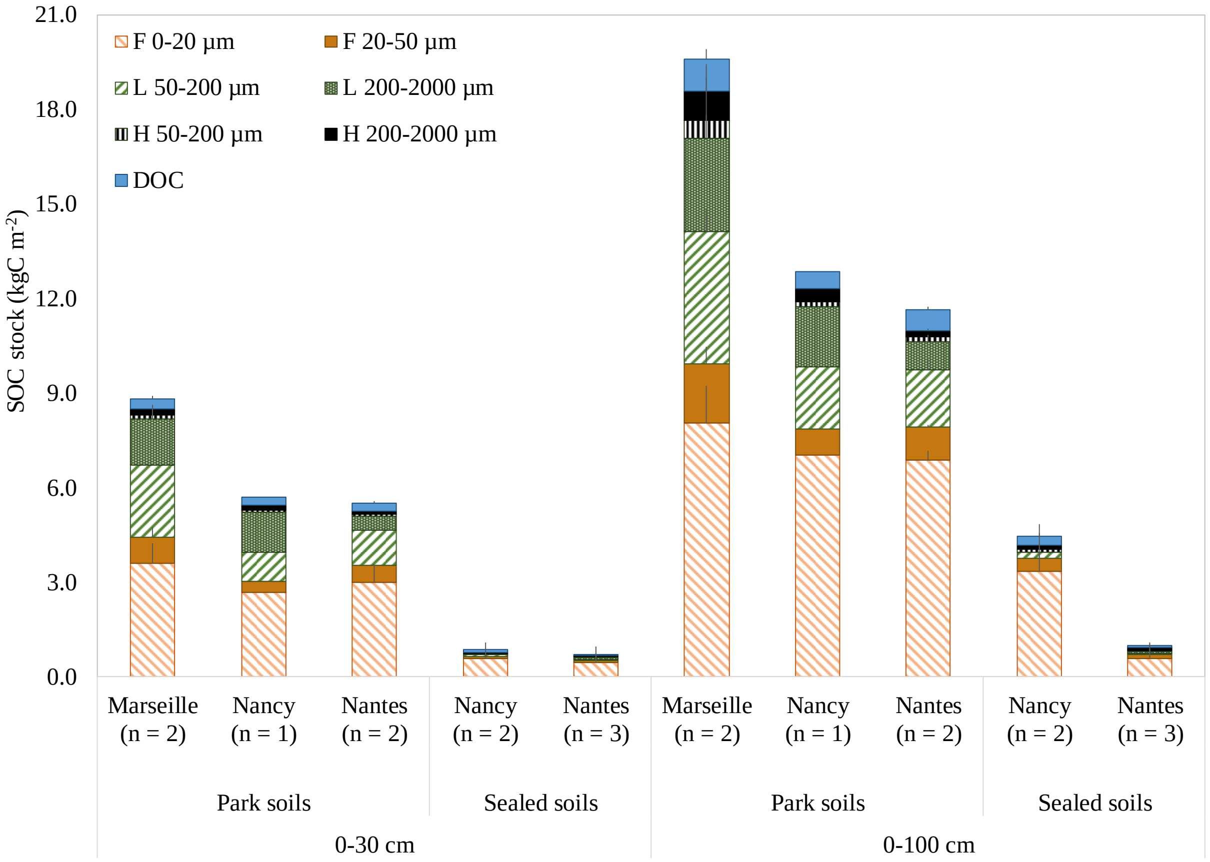


Fig. 2 Soil organic carbon (SOC) stock (kgC m^{-2}) in each particle size and density fraction at 0-30 and 0-100 cm depths in each studied site separately. The graph bars correspond to means and the error bars to standard deviations. n is the number of pits. F refers to Fraction and H and L are heavy and light fractions, respectively; DOC for Dissolved Organic Carbon is SOC in water solution at the end of the fractionation

4. Discussion

4.1. Mass and SOC distribution in the soil fractions

The fractionation procedure used for studying particle size and density fractions allowed an accurate recovery of total soil sample mass and SOC, as the sums of fraction masses and SOC were close to total sample mass and SOC, respectively. However, the fraction mass distribution did not systematically match with that achieved after destruction of SOM and $CaCO_3$ (i.e. complete dispersion, performed as part of the textural analysis; AFNOR 2003), which tended to yield more fine particles (in average, the mass of the fraction 0-20 µm was 25% larger with than without SOM and carbonate destruction; data not shown). According to Poeplau et al. (2018), who compared 20 fractionation methods, the method of the present study is accurate for the fraction > 50 µm; but these authors did not fractionate the fractions < 50 µm and they only worked with $CaCO_3$-free samples.

For the fractions < 50µm, the fractionation method used in this study was similar to that of Watteau et al. (2006) and different from Balesdent (1996) since ultrasonication was not used.

As mentioned in the section 2.3, this choice was made to avoid breaking the SOM < 63 µm (Moni et al. 2012), but it could also explain the incomplete dispersion of some mineral-associated SOM. However, and importantly, even if dispersion might be incomplete using the fractionation procedure adopted here for studying particle size and density fractions of SOC, this could not affect the trends observed between parks and sealed soils or between fractions within a given urban landscape, since the differences in SOC were very marked.

4.2. Impact of urbanization on soil organic carbon pools

4.2.1. Effect of urban landscape

The SOC stock of non-fractionated soil was highly impacted by soil sealing. Indeed, the SOC stock in sealed soils represented about 10% and 14% of the SOC stock in parks, at 0-30 and 0-100 cm, respectively. This result was in accordance with the literature, but even more contrasting: at 0-20 cm depth, Wei et al. (2014a) and Wei et al. (2014b) observed that SOC stock in sealed soils was 32-52% of that in open soils (Yixing City and Nanjing City, China, respectively). At 0-100 cm depth, Cambou et al. (2018) reported that SOC stock in sealed soils was 50% of that in open soils in New York City (using SOC stock medians).

In the present study, for each soil depth, SOC stock in each fraction was also higher in park soils than in sealed soils. The difference was large for labile SOC (L > 50 µm) but less marked for stable SOC (0-50 µm fractions). This is consistent with published results on the effects of soil disturbance (such as soil sealing) on POM. For instance, d'Annunzio et al. (2008) showed that the only significant differences between the studied treatments (savanna, young or old eucalyptus plantations possibly burnt) in sandy soils of Congo were observed on the fractions > 50 µm. In the same way, Feller and Beare (1997) reported in the conclusion of their review paper that the POM pool was particularly affected by soil disturbance. This result is also in accordance with regular inputs of fresh organic matter into the park soils. The SOC stocks of sealed soils were low and mainly located in the stable pool. The impervious layers both inhibit fresh organic matter inputs into the soil and allow long-term stabilization of SOM already present (Vasenev and Kuzyakov 2018).

To date, there has been no publication on SOM particle size and/or density fractionation in sealed soils. However, in parks, Scharenbroch et al. (2005) performed particle size fractionation of SOM (by wet sieving) at 0-15 cm depth, with a two-year monitoring (in 2002-2003) in Moscow (ID, USA) and Pullman (WA, USA). Concerning the non-fractionated fine earth (< 2 mm), they reported as much SOC in the first 15 cm (7.8 kgC m^{-2} in 2003) as was reported up to 30 cm in the parks of the present study (mean of 7.1 kgC m^{-2}), suggesting higher SOC stocks in their study up to 30 cm. In their study, 83% of SOC was in the 0-53 µm fraction (vs. 17% in L > 53 µm), which was higher than in the parks of the present study (56% in F 0-50 µm vs. 36% in L > 50 µm in average). Although these results are hardly comparable because of the different depths considered, the observed differences could be due to the systematic proximity of trees in the sampling design chosen by these authors, but also to the intensive management occurring in these parks (N fertilization, frequent irrigation, weekly mowing with mulching) compared to the parks of the present study (no fertilization, irrigation in Marseille Park only, less frequent mowing with or without mulching; Table 1). Thus, in the parks of Moscow and Pullman, the input of tree and lawn litter into the soil, as well as microbial dynamics, were stimulated, which could lead to higher total SOC stocks and quick decomposition of POM that supplies the organo-mineral pool (i.e. mineral-associated SOC).

Comparison could also be made with non-urban soils. Park SOC stocks of the present study were lower than those reported by Balesdent et al. (1998) in a humic acid loamy soil of a temperate forest (French Pyrenean piedmont) at 0-30 cm depth, for (i) non-fractionated soil (7.1 vs. ca. 20 kgC m^{-2} in average, respectively), (ii) F 0-50 µm (3.8 vs. ca. 15 kgC m^{-2} in average, respectively) and (iii) to a lesser extent L > 50 µm (2.6 vs. 6-7 kgC m^{-2}, respectively). The differences between forest and park soils probably reflected the lower historical disturbance in forests, allowing sustainable ecosystem functioning and long-term preservation of SOM, compared to parks. It may also be due to the low pH in this forest soil (pH = 4.8 vs. 8.2 in both Marseille and Nancy parks and 4.9 in Nantes; data not shown) since low pH inhibits soil respiration and thus SOM degradation (Rousk et al. 2009). However, the park soils had nearly as much SOC in non-fractionated soil as a 35-year-old conventionally cultivated soil (also a humic acid loamy soil in the French Pyrenean piedmont) at 0-30 cm depth (Balesdent et al. 1998): 7.1 kgC m^{-2} in average in the present study vs. nearly 8 kgC m^{-2}. However, parks had much lower SOC stock in F 0-50 µm than the cultivated soil up to 30 cm depth: 3.8 kgC m^{-2} in the present study vs. mean of ca. 6 kgC m^{-2} in the conventionally cultivated soil. By contrast, in L > 50 µm, higher SOC stock was observed in parks than in the cultivated soil (2.6 vs. 1.4 kgC m^{-2}). The distribution of SOC stocks in the different pools of an urban park is specific: it is neither equivalent to that of a forest nor a cultivated soil.

In addition in the present study, a high proportion of SOC stock was found in H > 50 µm in park and sealed soils, when compared to data from forest and cultivated soils reported by Balesdent et al. (1998). This SOC could be (i) SOM that could not be separated from the mineral fraction (e.g., because of strong bindings between POM and the mineral fraction or some insufficiently dispersed aggregates that still contained smaller SOM), or (ii) dense organic artifacts (*e.g.*, bitumen or coked coal; Allory et al. 2021). The latter assumption could also explain why the proportion of SOC in this fraction was higher in Marseille Park and sealed soils, as some bitumen elements were observed in these soils (fraction > 2 mm; Fig. 3). Thus, the strongly anthropized soils could be characterized by very stable SOC from artifacts, hardly separable from the mineral heavy fraction due to its similar density: the nature and dynamics of this SOC fraction should be further studied.

The comparison between parks in the present study showed similar SOC stocks in F 0-20 µm but different SOC stocks in L > 50 µm and H > 50 µm, particularly between Marseille and both other parks at 0-100 cm depth. As mentioned before, some bitumen elements were found in the deepest horizon of Marseille Park (Fig. 3), explaining the differences in SOC stock in H > 50 µm. Moreover, dead roots of a former tree were observable in Marseille Park B (Fig. 1), which could explain higher SOC stock in L > 50 µm. By contrast, Nantes Park was a young park (1976-1979) built on a former cultivated soil, and was characterized by clipping residue removal during a part of the year, hence lower SOC stock (Qian et al. 2003). In Nancy Park, all soil layers seemed to have been imported, possibly resulting in a disturbance of soil profile, and there was in particular a 9-cm thick calcareous backfill horizon poor in SOC (cf. H3 in Fig. 1; 0.3 kgC m^{-2} in the non-fractionated soil; data not shown), which impacted SOC stock to 100 cm depth. Thus, the trends observed in non-urban soils to 100 cm depth could hardly be applied to parks, whose history should be considered in the study of SOC pools. In sealed soils, for both sites, soils under pavement (Nancy Sealed A & B and Nantes Sealed B & C) were characterized by the presence of living roots (Fig. 1; Fig. 3) from lawn strips or vegetation bed next to the profile. These roots were probably at the origin of some fresh organic matter input into the soils (through root exudation or turnover) but in too low amount to allow significant SOC stock increase. Moreover, a high difference was observable between both studied sites at 0-100 cm depth, with higher fraction SOC stocks in Nancy than in Nantes. This difference could be explained by the higher level of anthropic disturbance in Nantes (all soil profile removal and use of sandy backfill) than in Nancy (removal of the first soil horizons only; Table 1).


Marseille Park A H3 – bitumen

Nantes Sealed B H2 – roots


Nantes Sealed B H4 – bitumen

Nancy Sealed B H2 – roots

Fig. 3 Examples of coarse (> 2 mm) bitumen particles and living roots found in some studied horizons

4.2.2. Effect of depth

The contribution of 0-30 cm layer to SOC stock of 0-100 cm depth was not systematically the same between the studied fractions, and depended on urban landscape. However, there was a non-negligible part of SOC stock in deep horizons: for the non-fractionated soil in parks and sealed soils, the contribution of the 30 first cm to SOC stock of 0-100 cm depth observed here (46 ± 7% and 39 ± 39%, respectively) was lower than some literature results. Indeed, Simo et al. (2019) studied agricultural soils in Ireland at national scale and reported a contribution of

63% of the first 30 cm depth to SOC stock of 0-100 cm depth. In the same way, Jobbágy and Jackson (2000) reported that 75% of SOC stock to 100 cm depth was included in the first 30 cm of soil under forest at global scale. By contrast, this proportion was estimated around 40% in alluvial soils at global scale (Batjes 1996). For urban soils, Edmondson et al. (2012) found a proportion (42%) similar to that of the present study, but considering only the contribution of the 20 first cm of soil to the SOC stock at 0-100 cm in Leicester (UK); this suggested that the contribution of the 30 first cm would be higher in their study. Cambou et al. (2018) also reported a higher proportion than in the present study when considering median SOC stocks at 0-30 and 0-100 cm depths in green spaces of New York City (68%), but similar proportion considering average SOC stocks (44%). Moreover, in the present study, the contribution of the first 30 cm could be much lower for some SOC fractions (the lowest contributions of the 30 first cm were for H 200-2000 µm and F 0-20 µm in Nancy Sealed; they averaged 16% and 17%, respectively). By contrast, 0-30 cm depth highly contributed to SOC stock of L > 50 µm (> 45% in average, and up to 100% in some sealed soils), except in Nancy Sealed. This is consistent with the fact that fresh SOM is mostly added in the first soil horizons (as mentioned above, living roots could also be observed under pavement). The high and variable potential contribution of deep soils to the total SOC stocks of urban soils, even more than in non-urban soils, confirmed the necessity to study SOC pools below 30 cm depth in urban soils.

5. Conclusion

Soils in parks had 10 times more SOC than sealed soils over the first 30 cm and 7 times more over the first meter, which showed the strong negative impact of soil sealing on SOC stocks. Differences were observed for all the particle size and density fractions, but especially for the light coarse fractions > 50 µm, i.e. the particulate organic matter. A specific type of SOC in H > 50 µm (or even probably in smaller fractions), possibly bitumen, could be observed in urban soils, suggesting the necessity to deepen the study on such organic artifact pools in urban soils, parks as well as sealed soils. Moreover, the distribution of SOC stocks in the different pools in urban soils seems to differ from the distribution observed in forest or cultivated soils. Our study highlighted similarities between parks and sealed soils and pleaded for further studies on the variable and determining history of the SOC pools in such soils. Indeed, the differences between sites showed the strong effect of site history and biomass management on SOC pools. For example, the presence of trees or lawn strips close to sealed soils could be beneficial in terms of SOC storage. The contribution of the 30 first cm to the SOC of the whole soil profile also seems to be specific in the urban soils, i.e. lower and highly variable, especially in the sealed soils. Thus, the SOC pool quantification in urban soils should be conducted at the soil profile level to estimate the size of these pools more accurately and better evaluate the contribution of urban soils to global SOC stocks. The results shown in the present study should be now confirmed through various case studies in order to better understand the effect of anthropic factors on SOC pools and thus, to be able to provide generalized conclusions for urban soils.

Acknowledgements

This study was supported by the SUPRA project (grant number 1772C0021), founded by ADEME (French Environmental Agency), which also founded the PhD grant of the first author, with the Région Pays de la Loire. Aurélie Cambou's PhD manuscript ("Evaluation du stock et de la stabilité du carbone organique dans les sols urbains"; https://tel.archives-ouvertes.fr/tel-02088714), already published in December 2018, was used as a support to write this article. We would like to thank the INRAE laboratory of soil analyses of Arras (France), Claudie Mazzega, Yvette Roussel and Lucas Charrois for the soil physicochemical analyses, Aude Aguzou for the coarse element photography and Dominique Renard for his help in sampling work. We also would like to thank INSEE (France) and Infoclimat (France) for providing data. Finally, we thank Lydie Lardy-Chapuis (French National Research Institute for Sustainable Development; IRD) for her support. We would also like to thank the municipalities of Marseille, Nancy and Nantes for the access given to the investigation sites. Finally, helpful comments by the anonymous referee are gratefully acknowledged.

References

"4 per 1000" Initiative (2018). http://4p1000.org. Accessed 8 Jul 2020

AFNOR (Association Française de Normalisation) (2003) NF X 31-107 – Qualité du sol – Détermination de la distribution granulométrique des particules du sol - Méthode à la pipette. AFNOR, Paris

Allory V, Cambou A, Moulin P, et al (2019) Quantification of soil organic carbon stock in urban soils using visible and near infrared reflectance spectroscopy (VNIRS) in situ or in laboratory conditions. Sci Total Environ 686:764–773. https://doi.org/10.1016/j.scitotenv.2019.05.192

Allory V, Séré G, Ouvrard S (2021) A meta-analysis of carbon content and stocks in Technosols and identification of the main governing factors. Eur J Soil Sci 73:1–17. https://doi.org/10.1111/EJSS.13141

Balesdent J (1996) The significance of organic separates to carbon dynamics and its modelling in some cultivated soils. Eur J Soil Sci 47:485–493. https://doi.org/10.1111/j.1365-2389.1996.tb01848.x

Balesdent J, Besnard E, Arrouays D, Chenu C (1998) The dynamics of carbon in particle-size fractions of soil in a forest-cultivation sequence. Plant Soil 201:49–57. https://doi.org/10.1023/A:1004337314970

Balesdent J, Chenu C, Balabane M (2000) Relationship of soil organic matter dynamics to physical protection and tillage. Soil Tillage Res 53:215–230. https://doi.org/10.1016/S0167-1987(99)00107-5

Batjes NH (1996) Total carbon and nitrogen in the soils of the world. Eur J Soil Sci 47:151–163. https://doi.org/10.1111/j.1365-2389.1996.tb01386.x

Blanchart A, Consalès JN, Séré G, Schwartz C (2018a) Consideration of soil in urban planning documents — a French case study. J Soils Sediments 19:3235–3244. https://doi.org/10.1007/s11368-018-2028-x

Blanchart A, Séré G, Cherel J, et al (2018b) Towards an operational methodology to optimize ecosystem services provided by urban soils. Landsc Urban Plan 176:1–9. https://doi.org/10.1016/j.landurbplan.2018.03.019

Cambou A, Saby NPA, Hunault G, et al (2021) Impact of city historical management on soil organic carbon stocks in Paris (France). J Soils Sediments 21:1038–1052. https://doi.org/10.1007/s11368-020-02869-9

Cambou A, Shaw RK, Huot H, et al (2018) Estimation of soil organic carbon stocks of two cities, New York City and Paris. Sci Total Environ 644:452–464. https://doi.org/10.1016/j.scitotenv.2018.06.322

Cardinael R, Chevallier T, Barthès BG, et al (2015) Impact of alley cropping agroforestry on stocks, forms and spatial distribution of soil organic carbon — A case study in a Mediterranean context. Geoderma 259–260:288–299. https://doi.org/10.1016/j.geoderma.2015.06.015

Cotrufo MF, Ranalli MG, Haddix ML, et al (2019) Soil carbon storage informed by particulate and mineral-associated organic matter. Nat Geosci 12:989–994. https://doi.org/10.1038/s41561-019-0484-6

D'Annunzio R, Conche S, Landais D, et al (2008) Pairwise comparison of soil organic particle-size distributions in native savannas and Eucalyptus plantations in Congo. For Ecol Manag 255:1050–1056. https://doi.org/10.1016/j.foreco.2007.10.027

Dignac M-F, Derrien D, Barré P, et al (2017) Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. Agron Sustain Dev 37:1–27. https://doi.org/10.1007/s13593-017-0421-2

Edmondson JL, Davies ZG, McHugh N, et al (2012) Organic carbon hidden in urban ecosystems. Sci Rep 2:963. https://doi.org/10.1038/srep00963

Ellert BH, Bettany JR (1995) Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can J Soil Sci 75:529–538. https://doi.org/10.4141/cjss95-075

Feller C, Beare MH (1997) Physical control of soil organic matter dynamics in the tropics. Geoderma 79:69–116. https://doi.org/10.1016/S0016-7061(97)00039-6

Infoclimat Base climatologique/pluviologique. In: Infoclimat, la météo en France en temps réel. https://www.infoclimat.fr/climato/. Accessed 12 Jan 2021

INSEE (Institut National de la Statistique et des Etudes Economiques) Statistiques et études. https://www.insee.fr/fr/statistiques?debut=0&theme=0. Accessed 12 Jan 2021

ISO (International Organization for Standardization) (1995) ISO 10694:1995 — Soil Quality — Determination of Organic and Total Carbon after Dry Combustion (Elementary Analysis). ISO, Geneva

IUSS (International Union of Soil Science) Working Group WRB (World Reference Base) (2015) World Reference Base for Soil Resources 2014, Update 2015: International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports, 106, FAO, Rome

Jobbágy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol Appl 10:423–436. https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2

Lal R (2014) Soil conservation and ecosystem services. Int Soil Water Conserv Res 2:36–47. https://doi.org/10.1016/S2095-6339(15)30021-6

Lehmann J, Kleber M (2015) The contentious nature of soil organic matter. Nature 528:60–68. https://doi.org/10.1038/nature16069

Liu Z, He C, Zhou Y, Wu J (2014) How much of the world's land has been urbanized, really? A hierarchical framework for avoiding confusion. Landsc Ecol 29:763–771. https://doi.org/10.1007/s10980-014-0034-y

Lorenz K, Lal R (2015) Managing soil carbon stocks to enhance the resilience of urban ecosystems. Carbon Manag 6:35–50. https://doi.org/10.1080/17583004.2015.1071182

Minasny B, Malone BP, McBratney AB, et al (2017) Soil carbon 4 per mille. Geoderma 292:59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

Moni C, Derrien D, Hatton P-J, et al (2012) Density fractions versus size separates: does physical fractionation isolate functional soil compartments? Biogeosciences 9:5181–5197. https://doi.org/10.5194/bg-9-5181-2012

Nuissl H, Siedentop S (2021) Urbanisation and Land Use Change. In: Weith T, Barkmann T, Gaasch N, et al. (eds) Sustainable Land Management in a European Context, Human-Environment Interactions, vol 8. Springer International Publishing, Cham, pp 75–99

Poeplau C, Don A, Six J, et al (2018) Isolating organic carbon fractions with varying turnover rates in temperate agricultural soils – A comprehensive method comparison. Soil Biol Biochem 125:10–26. https://doi.org/10.1016/j.soilbio.2018.06.025

Poeplau C, Vos C, Don A (2017) Soil organic carbon stocks are systematically overestimated by misuse of the parameters bulk density and rock fragment content. Soil 3:61–66. https://doi.org/10.5194/soil-3-61-2017

Pouyat RV, Yesilonis ID, Golubiewski NE (2009) A comparison of soil organic carbon stocks between residential turf grass and native soil. Urban Ecosyst 12:45–62. https://doi.org/10.1007/s11252-008-0059-6

Qian Y, Bandaranayake W, Parton WJ, et al (2003) Long-term effects of clipping and nitrogen management in turfgrass on soil organic carbon and nitrogen dynamics: the CENTURY model simulation. J Environ Qual 32:1694–1700. https://doi.org/10.2134/jeq2003.1694

Raciti SM, Hutyra LR, Finzi AC (2012) Depleted soil carbon and nitrogen pools beneath impervious surfaces. Environ Pollut 164:248–251. https://doi.org/10.1016/j.envpol.2012.01.046

Rousk J, Brookes PC, Bååth E (2009) Contrasting soil pH effects on fungal and bacterial growth suggest functional redundancy in carbon mineralization. Appl Environ Microbiol 75:1589–1596. https://doi.org/10.1128/AEM.02775-08

Scharenbroch BC, Lloyd JE, Johnson-Maynard JL (2005) Distinguishing urban soils with physical, chemical, and biological properties. Pedobiologia 49:283–296. https://doi.org/10.1016/j.pedobi.2004.12.002

Seto KC, Fragkias M, Güneralp B, Reilly MK (2011) A meta-analysis of global urban land expansion. PloS One 6:e23777. https://doi.org/10.1371/journal.pone.0023777

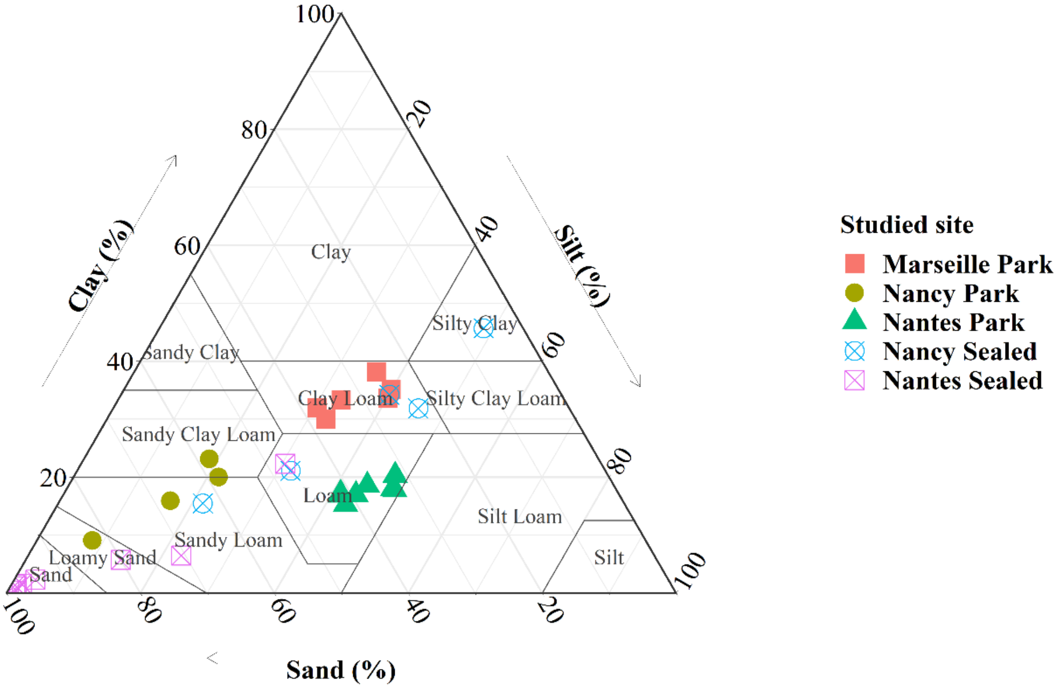
Simo I, Schulte R, O'Sullivan L, Creamer R (2019) Digging deeper: Understanding the contribution of subsoil carbon for climate mitigation, a case study of Ireland. Environ Sci Policy 98:61–69. https://doi.org/10.1016/j.envsci.2019.05.004

Vasenev VI, Kuzyakov Y (2018) Urban soils as hot spots of anthropogenic carbon accumulation: Review of stocks, mechanisms and driving factors. Land Degrad Dev 29:1607–1622. https://doi.org/10.1002/ldr.2944

Watteau F, Villemin G, Burtin G, Jocteur-Monrozier L (2006) Root impact on the stability and types of micro-aggregates in silty soil under maize. Eur J Soil Sci 57:247–257. https://doi.org/10.1111/j.1365-2389.2005.00734.x

Wei Z-Q, Wu S-H, Yan X, Zhou S-L (2014a) Density and stability of soil organic carbon beneath impervious surfaces in urban areas. PloS One 9:e109380. https://doi.org/doi.org/10.1371/journal.pone.0109380

Wei Z-Q, Wu S-H, Zhou S-L, et al (2014b) Soil organic carbon transformation and related properties in urban soil under impervious surfaces. Pedosphere 24:56–64. https://doi.org/10.1016/S1002-0160(13)60080-6



Appendix Distribution of the 32 studied samples on the United States Department of Agriculture (USDA) soil texture triangle