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Ludovic Foti, Sébastien Barot, Jacques Gignoux, Michel Grimaldi, Jean-christophe Lata, Thomas Lerch, François Nold, Naoise Nunan, Xavier Raynaud, Luc Abbadie, et al.

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## Topsoil characteristics of forests and lawns along an urban-rural gradient in the Paris region (France)

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Dear Editor

We thank you for considering our manuscript and thank the reviewers for their valuable comments. Below you will find our responses to the reviewers' comments and descriptions of the changes made to the manuscript. All changes were mentioned in red color in the manuscript. However, I do not understand the return of referee 1 because I sent a point-by-point list during the first review, and I think I answered all his suggestions for correction. I think there was an error in the transmission of our list point-by-point to referee 1, especially since referee 2 is satisfied with our feedback, even suggesting the final acceptance of our manuscript.

***Reviewer #1:** In this manuscript, authors investigated the chemical, physical and hydro structural characteristics of topsoil from forests and lawns and how the urbanization affects topsoil. This paper is well organized and concise, but the literature review is insufficient and some references are outdated. The novelty and importance of this paper also need to emphasize.*

Thank you for this relevant comment. As suggested, we have looked for more recent studies. As a result, we have replaced the outdated references (Lines 47, 51, 54, 60, 66, 74, 77, 80, 82, 83 and line 86).

We have also rewritten a part of the introduction to better introduce the novelty of the study (Lines 72 to 87).

*The specific comments are as follows:*

*1/ The titles of the tables and figures are too long, some information can be listed below the tables or figures in the form of notes.*

Thank you for this comment. Titles of the tables and figures have been shortened accordingly. As suggested, some information has been listed below the tables or figures in the form of notes (See Table 1, Figures 1 to 5, and Tables and figures A.1 and A.2 of the supplementary materials).

*2/ Line 239: "Total phosphorus" and "Total P". The expression should be unified.*

Thank you for this relevant remark. We unified the expression using Total Phosphorus (lines 168, 239 and 240, 358 and 359).

*3/ Some editorial errors should be corrected, such as line 241, line 432, etc.*

We apologize for the “editorial errors”. We have therefore made changes to the part “3.2- *Effects of land-use types and urban-rural gradient on chemical, physical, and hydrostructural soil characteristics*”. All data already present in the tables, figures and supplementary material have been deleted.

We have also made changes in the parts “4.1- *Impact of urban-rural gradient on forest topsoil characteristics*”, “4.2- *Impact of the urban-rural gradient on lawn topsoil characteristics*”, and in *the conclusion*. In these parts, some sentences have been restructured in order to remove “editorial errors” (lines 275 to 278, 291, 310 to 316, 321 to 322, 342 to 343, 356 to 357, 363 to 364 and lines 419 to 422).

**Reviewer #2:** *In this study, the authors described the chemical, physical and hydrostructural characteristics of 180 forest and lawn surface soil samples, taken along an urban-rural gradient in the Paris region. This manuscript presents interesting information to the scientific community. However, writing style and structure of the manuscript are to be polished. Revision is needed before publication. Specific comments are provided as follows:*

*1/ Line 32: “Forests and lawns are the main vegetation types found in this region, and represent 3.5% and 22.2% of the territory’s surface area, respectively.” One of the main type only represent 3.5%? Please double-check.*

Thank you for your comment: it was a mistake. Forests represent 21% of the territory surface area, for a national average of 30%. Correction was done in the corresponding section (line 32 and 134).

*2/Line 47: some of cited references were outdated. Recent findings should be critically reviewed in order to illustrate the novelty of this study.*

Thank you for this relevant comment. As suggested, we have reviewed more recent studies. As a result, we have replaced the outdated references (Lines 47, 51, 54, 60, 66, 74, 77, 80, 82, 83 and line 86).

We have also rewritten a part of the introduction to better introduce the novelty of the study (Lines 72 to 87).

*3/Line 71: current limitations and information gap are now very clear.*

Thank you very much for this remark.

*4/Line 165: The description of the experimental procedures can be made more concise without loss of key information.*

Thank you for this suggestion. Some parts of the description of the experimental procedures have been deleted to make it more concise, trying not to lose too much information:

*“The water retention of the soils was measured following classical methods (Pansu and Gautheyrou, 2006). Samples were saturated from the bottom using a sandbox suction table until equilibrium at 0 kPa matric potential at the bottom of the samples and -0.5 kPa at the top was reached. A pressure plate apparatus was used to equilibrate each soil sample at -33 kPa (field capacity). The remainder of the samples was immediately enclosed in brass rings of 5.35 cm diameter and 3.0 cm height and placed on a pressure membrane apparatus to determine the water retained at -1500 kPa matric potential (permanent wilting point). The volumetric water content at each matric potential was determined from the gravimetric water contents and the bulk density (Table A.1). The pore-neck diameters of the maximum water-filled pores radius corresponding to the three-selected matric potentials were 600  $\mu\text{m}$  (-0.5 kPa), 9  $\mu\text{m}$  (-33 kPa), and 0.2  $\mu\text{m}$  (-1500 kPa), which were determined in accordance with Jurin’s law. They delimited the macropores (600-9  $\mu\text{m}$ ), mesopores (9-0.2  $\mu\text{m}$ ), and micropores ( $r < 0.2 \mu\text{m}$ ). The megapores ( $r > 600 \mu\text{m}$ ) represent the quasi-permanent air filled soil porosity (See Table A.1). The soil water retention measurements were performed at 20°C. The pressure vessels, plates, and sandbox suction table used were manufactured by Soil Moisture Equipment Corp. The sandbox suction table was by Eijkerkamp”.*

*Figure 1: it is better to explain “RL, SL, etc.” in the figure caption.*

Thank you for this comment. Some information has been listed below the tables or figures in the form of notes (See Table 1, Figures 1 to 5, and Tables and figures A.1 and A.2 of the supplementary materials).

*Figure 3: What are the meanings of x-axis and y-axis?*

For more clarity, information has been listed below the figures. The two figures are dependent on each other and must be read together. As explained lines 212 to 221, axis 1 (x-axis) discriminated urban forest soils from all the other soils. The bulk density and megaporosity were the main explanatory variables in the discrimination of the Land-use type along Axis 2 (y-axis).

*5/Line 412: In conclusion, the authors should summary the major findings and contributions to the scientific community. I think the conclusion should be rewritten.*

Thank you for this remark. We have rewritten the conclusion following your suggestions (See lines 409 to 428).

*6/ Line 444: Recent findings should be critically reviewed in order to illustrate the novelty of this study.*

Think you for this comment. As suggested above we are now quoting more recent references.

For Peer Review

1 **Topsoil characteristics of forests and lawns along an urban-rural gradient in the Paris**  
2 **region (France)**

3 **Running title : TCFLURGPR**

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20 **Keywords:** Anthrosols, Forests, lawns, urban-rural gradient, chemical urban soil  
21 characteristics, physical urban soil characteristics, hydrostructural urban soil characteristics

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24

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## 25 **Abstract**

26           Urban soils are a crucial component of urban ecosystems, especially in public green  
27 spaces, because of the ecosystem services they provide (*e.g.* public recreation, urban cooling  
28 or water infiltration). In this study we describe the chemical, physical and hydrostructural  
29 characteristics of 180 forest and lawn surface soil samples, taken along an urban-rural  
30 gradient in the Paris region. This was done in order to identify how these soils have been  
31 affected by urbanization. Forests and lawns are the main vegetation types found in this region,  
32 and represent 3.5% and 22.2% of the territory's surface area, respectively. Many of the  
33 properties of urban forest soils differed from those of other sites (*e.g.* texture, organic carbon  
34 content, total nitrogen and carbonate contents), possibly because the urban forests are much  
35 older than the lawns and because of the legacy of the historical management of soils in this  
36 region (Haussmann period). Urban lawn soils were more compacted than urban forests,  
37 probably due to higher foot traffic. The effects of urbanization were, at times, confounded  
38 with other processes (*e.g.* sandier texture of urban forests), which suggests that surface soil  
39 characteristics were influenced by past urban planning. Finally, this study constitutes a  
40 baseline analysis for the monitoring of soil quality in the region.

41

## 42 **1- Introduction**

43           Cities and towns exert significant pressures on both urban and surrounding  
44 environments (Kaushal et al., 2014; Chambers et al., 2016). Urban soils are particularly  
45 impacted, in that they are heavily managed, with whole soil profiles often being  
46 anthropogenic. For example, fertile agricultural soils from rural areas are often imported for  
47 use in constructing urban green spaces (Bullock and Gregory, 1991). Furthermore, they are  
48 subjected to the addition of waste materials, pollutants from numerous point and diffuse  
49 sources, atmospheric deposition of carbon and nitrogen, or heat island effects. Town planning  
50 and landscaping decisions can also result in rapid changes in land-use, which modify soil



51 properties in a complex manner, *e.g.* capacity to store carbon or water (Burghardt, 2002). In  
52 most cases, they do not result solely from slow pedogenic processes from a parent material  
53 under the influence of climate, vegetation, topography and time (Effland and Pouyat, 1997).

54 Urban soils have a number of common features. They generally have high organic  
55 carbon content due to an accumulation of dust, combustion residues and organic waste. The  
56 high organic carbon, in turn, contributes to their generally high cation exchange capacity  
57 (Lehmann and Stahr, 2007). Urban soils also tend to have higher carbonate contents and  
58 therefore to be more alkaline, due to the presence of construction residues such as plaster or  
59 concrete (Lehmann and Stahr, 2007; Rokia et al., 2014). The modifications of soil pH may  
60 influence the availability of mineral nutrients (Craul, 1992). In addition, many urban soils are  
61 often more compacted than natural ones due to the high levels of foot traffic and the use of  
62 machines to put the soils in place, which can lead to a loss of structure and an increase in bulk  
63 density (Jim, 1998; Morel et al., 2015). Because of this compaction and the decrease in pore  
64 size, urban soils tend to drain more slowly and the diffusion of oxygen and other gases may  
65 be reduced (Kozłowski, 1999). However, the high soil organic carbon content generally found  
66 in urban areas may increase the resistance of the soils to compaction. Indeed, organic matter  
67 improves soil structural stability by increasing soil aggregation and aggregate stability (Leroy  
68 et al., 2008). All these mechanisms and interactions determine urban soils' capacity to store,  
69 supply and recycle mineral nutrients and the movements and availability of water (Nawaz et  
70 al., 2013).

71 Even though it is widely accepted that the various pressures to which soils are  
72 subjected in urban environments can have dramatic effects on their properties (Schwartz et al.,  
73 2001; Norra et al., 2006; Joimel et al., 2016; Vasenev et al., 2018), research is still needed to  
74 fully document these pressures and their consequences for soil functioning. In view of the  
75 likely effect urban soils have on the quality of life of urban populations (Vegter, 2007), this  
76 omission should be addressed. Urban soils are directly or indirectly involved in most

77 ecosystem services provided by urban green spaces, such as the recycling of organic matter or  
78 plant growth (Stroganova et al., 1997; Chiesura, 2004; Morel et al., 2015; Vasenev et al.,  
79 2018). It is therefore critical to understand how urbanization affects their properties.

80 In France, monitoring programs such as the French soil quality-monitoring network  
81 (RMQS) have been carried out to describe and monitor French agricultural, forest and  
82 grassland soils (Arrouays et al., 2011; Saby et al., 2014). However, these programs have  
83 tended to not include urban soils. Our work aims at filling this gap, focusing on the chemical,  
84 physical, and hydrostructural topsoil characteristics along a concentric gradient of  
85 urbanization around the city of Paris (Foti et al., 2017). The study was carried out on soils  
86 from forests and lawns, as these constitute the main vegetation types in the urban area of the  
87 Paris region (ECOMOS, 2003). It was expected that urban forest topsoil have particular  
88 characteristics because of their history and their geology. It was also expected that urban  
89 lawns are subjected to higher foot traffic, resulting in higher compaction than the other kinds  
90 of sites. Indeed lawns are essential to urban green spaces and an important part of city  
91 dwellers' everyday life (Ignatieva et al., 2017), and human density is higher in the urban than  
92 in the rural area (Foti et al., 2017). Ultimately, this study provides a baseline for the long-term  
93 monitoring of the main chemical, physical and hydrostructural topsoil characteristics in the  
94 urban area of the Paris region.

95

## 96 **2- Materials and methods**

### 97 *2.1- Study area*

98 The study area is located in the Ile-de-France region (48°07'N, 1°35'E; 49°07'N,  
99 3°26'E), and covers 12 070 km<sup>2</sup> around the city of Paris (France), which is inhabited by 12.01  
100 million people (18.8% of the metropolitan France population, INSEE, 2013). The region is  
101 relatively uniform in terms of topography, geology, hydrology, and altitude (average of 108  
102 meters above sea level). The bedrock is exclusively sedimentary (Jurassic limestone and marl,

103 Cretaceous chalk, Carbonaceous alluvial deposits, Tertiary quartz sand). The climate is  
104 subatlantic (average temperature of 11°C, rainfall of 600 mm per year). The rainfall regime is  
105 pluvial oceanic (Pomerol and Feugueur, 1968).

106

## 107 *2.2- Determination of Urban-Rural Gradient of the Paris region*

108 Two indices were used to establish the Urban-Rural Gradient (URG): a Socio-  
109 Demographic Index (SDI) and a Heat Island Index (HII). The SDI uses the average values of  
110 the human activity density index per hectare of built surface. It allows the identification of the  
111 areas of a region that are most frequented and that concentrate employment. The HII uses the  
112 minimal temperature recording values of the Paris region. It identifies the areas that are most  
113 affected by human activities and the overall degree of artificial land cover (e.g. tar roads,  
114 buildings) (See Foti et al., 2017).

115 To build the URG map of the Paris region, the data of the two indices were combined  
116 using GIS software (ArcGIS v.10) to obtain one map with a resolution of 2 x 2 km.

117 Finally, the URG was discretized into three classes (rural area, suburban and urban  
118 area; See Foti et al., 2017).

119

## 120 *2.3- Sampling design and protocol*

121 The sampling was stratified following a fully balanced cross factorial scheme with two  
122 factors: the Urban-Rural Gradient (URG, 3 levels) and the Land-use Type (LT, 2 levels). The  
123 URG contained three concentric classes that broadly corresponded to an urban-rural gradient:  
124 a rural class, a suburban class and an urban class. The classes were distinguished based on  
125 population density, built-up area and estimated heat island effects. For a complete description  
126 of the method used to identify the gradient, see Foti et al. (2017). The two-targeted land-uses  
127 were forests and lawns that, respectively, represent 3.5% (419 km<sup>2</sup>) and 22.2% (2670 km<sup>2</sup>) of  
128 the region (ECOMOS, 2003). All the selected green spaces of the study were established after

129 1950, except for the forests of the urban area (IAU, 2013). Sampling took place from  
130 September to October 2015. Each combination of URG and LT was sampled at 30 different  
131 locations, yielding a total of 180 sampling sites ( $n = 3$  levels of URG  $\times$  2 LT  $\times$  30 replicates =  
132 180 sites) (Fig. 1).

133 Soil characteristics were described from one composite soil sample per sampling site.  
134 Each composite sample was made of 3 sub-samples collected within a 1 m<sup>2</sup> square from the  
135 top 10 cm of the organo-mineral layer (after having removed any vegetal or anthropogenic  
136 debris and the humus layer). Each composite sample was homogenized to constitute a  
137 representative sample according to the NF X31-100 standard. Samples were collected with an  
138 8 cm-diameter stainless steel hand auger, immediately placed in polyethylene bags and  
139 subsequently air-dried in the laboratory. In order to measure the water retention curve of the  
140 soils, a single undisturbed sample was also taken from the 0-5 cm surface layer, at the centre  
141 of each 1 m<sup>2</sup> square using the cylinder method (Blake and Hartge, 1986). Roots and rocks  
142 were removed by hand from the base and the top of the cylinder. The undisturbed samples  
143 (100 cm<sup>3</sup>) were stored in sealed bags at a temperature of 4-5°C to reduce biological activity  
144 and preserve the sample structure.

145

#### 146 *2.4- Chemical, physical and hydrostructural soil analysis*

147 International (ISO) or French (NF) standardized methods were used to measure the  
148 chemical and physical soil characteristics: clay, coarse and fine silt (CSi and FSi), coarse and  
149 fine sand (CSa and FSa), organic carbon (OC), total nitrogen (tot N), pH-H<sub>2</sub>O (pH),  
150 carbonates (CaCO<sub>3</sub>), total phosphorus (tot P) and cation exchange capacity (CEC) (Table  
151 A.1). Particle-size distribution was assessed by the dispersion of mineral particles after  
152 destruction of the organic matter using hydrogen peroxide and separation of the particles into  
153 different classes by sedimentation. Soil pH was measured in water in a 1:5 soil-to-solution  
154 ratio at 25°C after shaking the suspension for 1 hour. Total N was measured by dry

155 combustion, after burning samples at 1000°C in the presence of O<sub>2</sub> using a CHN auto-  
156 analyzer (CHN 1500, Carlo Erba). Organic carbon was quantified by sulfochromic oxidation  
157 using an auto-analyzer (Technicon III, Brian and Luebbe, Axflow). The soil organic carbon  
158 stocks (OCS in kg m<sup>-2</sup>) in the first 10 cm were estimated using the equation:  
159  $OCS_{(n)}=0.1 \times BD_{(n)} \times OC_{(n)}$ , where 0.1 is the sampling depth in meters, and BD the bulk density.  
160 The soil carbonate concentration was determined by measuring the volume of CO<sub>2</sub> released  
161 by reaction with HCl, using a Bernard calcimeter. Total P was measured by the molybdenum  
162 blue method, and quantified using an auto-analyzer (Technicon III, Brian and Luebbe,  
163 Axflow). CEC was determined after percolation of 1.0M ammonium acetate solution at pH 7.

164 The water retention of the soils was measured following classical methods (Table A.1;  
165 Pansu and Gautheyrou, 2006). Samples were saturated from the bottom using a sandbox  
166 suction table until equilibrium at 0 kPa matric potential at the bottom of the samples and -0.5  
167 kPa at the top was reached. Subsequently, a pressure plate apparatus was used to equilibrate  
168 each soil sample at -33 kPa (field capacity). After the equilibrium was reached, an aliquot of  
169 each soil sample was used to determine the water content. The remainder of the samples was  
170 immediately enclosed in brass rings of 5.35 cm diameter and 3.0 cm height and placed on a  
171 pressure membrane apparatus to determine the water retained at -1500 kPa matric potential  
172 (permanent wilting point). The volumetric water content at each matric potential was  
173 determined from the gravimetric water contents and the bulk density (Table A.1). The pore-  
174 neck diameters of the maximum water-filled pores radius corresponding to the three-selected  
175 matric potentials were 600 μm (-0.5 kPa), 9 μm (-33 kPa), and 0.2 μm (-1500 kPa). They were  
176 determined in accordance with Jurin's law:  $r = 149/h$ , where  $r$  is the equivalent pore radius in  
177 μm and  $h$  is the matric potential in kPa. They delimited the macropores (600-9 μm),  
178 mesopores (9-0.2 μm), and micropores ( $r < 0.2$  μm). The megapores ( $r > 600$  μm) represent  
179 the quasi-permanent air filled soil porosity. The megaposity (Meg), macroporosity (Mac),  
180 mesoporosity (Mes), microporosity (Mic) and the available water storage capacity (AWS in

181 mm) were calculated following equations given in Table A.1. The soil water retention  
182 measurements were performed at 20°C. The pressure vessels, plates, and sandbox suction  
183 table used were manufactured by Soil Moisture Equipment Corp. The sandbox suction table  
184 was by Eijkerkamp.

185

186

## 187 *2.5- Statistical analysis*

188 All statistical analyses were performed using the R 3.4 (R Core Team, 2016). First, a  
189 between-group multivariate analysis (Bati et al., 2006) was used to detect the effect of the  
190 urban-rural gradient (URG) and land-use type (LT) on all the soil variables. This analysis was  
191 performed using a combination of the two factors (URG and LT, 6 combinations) as the  
192 explanatory variable. The significance of the composite factor (URG/LT) was tested using a  
193 Monte-Carlo permutation test (1000 permutations).

194 The effects of URG, LT, and their interaction (URGxLT) on each chemical, physical,  
195 and hydrological soil characteristics were then analyzed using ANOVA. Variables that were  
196 not normally distributed were log-transformed prior to analyses, except for the megaporosity  
197 (square root transformation), and pH (exponential transformation). Bulk density, saturation  
198 point, field capacity, and the available water storage capacity were not transformed.  
199 Combinations of the different factors were compared using multiple comparisons of means  
200 (Tukey's honest significant difference, multcomp package, Hothorn et al., 2008). The  
201 residuals were checked for spatial autocorrelation using Moran's I correlogram (spdep  
202 package; Bivand, 2012). Since the Moran's I values (permutation test, n=1000) were never  
203 significant, the autocorrelation term was not included in models.

204

## 205 **3- Results**

### 206 *3.1- Chemical, physical and hydrostructural soil typology of the Paris region*

207           The clay content was low in all the samples analyzed: soil texture ranged from sand to  
208 silt loam (Fig. 2). The urban forest soils exhibited a specific textural pattern when compared  
209 to soils of other land-use types, which were relatively homogeneous. The urban forest soils  
210 were generally classified as sandy loam, whilst the other sites were loamy soils (Fig. 2).

211           The between-group analysis (Fig. 3) performed on the chemical, physical and  
212 hydrostructural variables, grouped as a function of the URG and LT, explained 19.94% of the  
213 total variance. A Monte-Carlo permutation test showed that the URG and LT significantly  
214 affected the chemical, physical and hydrostructural soil characteristics ( $P = 0.001$ ). The first  
215 and second axes of the between-group analysis ordination accounted for 65.42% and 24.47%  
216 of the variance, respectively. The organic carbon, total nitrogen, coarse sand concentrations  
217 and macroporosity positively contributed to axis 1, while clay and mesoporosity contributed  
218 negatively. Axis 1 discriminated urban forest soils from all the other soils. The bulk density  
219 and megaporosity were the main explanatory variables in the discrimination of the LT along  
220 Axis 2.

221

### 222 *3.2- Effects of land-use types and urban-rural gradient on chemical, physical, and* 223 *hydrostructural soil characteristics*

224           The URG, LT and their interaction had a significant impact on all chemical, physical,  
225 and hydrostructural variables. However, no factor was significant for the saturation point. In  
226 addition, URG had no effect on the pH, and LT had no effect on the cation exchange capacity.  
227 Neither LT nor URGxLT had a significant effect on the proportion of fine sand. Finally,  
228 URGxLT showed no effect on the permanent wilting point and the microporosity (Table 1).

229           Multiple comparisons of means showed that the effect of URGxLT on chemical,  
230 physical, and hydrostructural variables was mainly due to the differences between the urban  
231 forests and all other types of sites. Urban forest exhibited either the highest (organic carbon  
232 concentration, total nitrogen, cation exchange capacity, carbonate, coarse sand, soil organic

233 carbon stock and macroporosity) or the lowest (coarse silt, the fine silt, the clay, the field  
234 capacity, the mesoporosity, the microporosity and the available water storage capacity)  
235 measured values for most of the studied variables. In addition, urban lawns had higher coarse  
236 silt concentrations than the suburban forests (22.2 and 15.6%, respectively). The C/N ratio  
237 was the lowest in the rural lawns (8.41), and the other kinds of sites showed no difference  
238 (10.09 on the average). Suburban lawns were significantly more alkaline (pH of 7.6) than all  
239 of the forest sites (pH of 6.8 on the average). Total phosphorus increased from rural to urban  
240 area in forests. The urban forests and all lawn types had higher total P concentration (urban  
241 forests: 1351.1 mg kg<sup>-1</sup>, urban lawns: 1199.9 mg kg<sup>-1</sup>, suburban lawns: 1014.7, rural lawns:  
242 787.9 mg kg<sup>-1</sup>) than rural forests (444.4 mg kg<sup>-1</sup> means, respectively). The megaporosity  
243 showed a specific pattern with a lower value (0.04 cm<sup>3</sup> cm<sup>-3</sup>) in the urban lawns than in all  
244 other kinds of sites. Finally, bulk density was highest in urban lawn soils (1.27 g cm<sup>-3</sup>), and  
245 lowest in suburban forest soils (0.98 g cm<sup>-3</sup>), with an intermediate value in suburban lawn  
246 soils (1.13 g cm<sup>-3</sup>) (Fig. 4-5, Table A.2, Fig. A.1-A.2).

247

### 248 **3- Discussion**

#### 249 *3.1- Impact of urban-rural gradient on forest topsoil characteristics*

250 The higher organic carbon, the higher total nitrogen and the lower pH in forest soils  
251 compared to lawn soils may be partially due to differences between the two vegetation types.  
252 Indeed, the high inputs of tree leaf litter can lead to acidification and an accumulation of  
253 organic carbon and nitrogen in forest soils (Rout and Gupta, 1989). It is widely recognized  
254 that forest soils accumulate more organic matter than the other temperate terrestrial  
255 ecosystems, especially in topsoil (Guo et al., 2002; Innangi et al., 2017). However, this should  
256 not explain the differences between the urban forest soils and the suburban and rural forest  
257 soils. A possible explanation may be related to the age of the green spaces. Indeed, urban  
258 forests existed long before the other green spaces (see Fig. A.3). Urban forests are all that



259 remains of the old “forest of Rouvray” that surrounded “Lutèce” in the Gallo-Roman era,  
260 while all the other kinds of sites were established after 1950 (IAU, 2013). Consequently, the  
261 higher organic matter concentration (SOM) found in urban forest soils than in other forests  
262 and in lawns could be simply due to a longer accumulation of organic matter.

263         These soils were also subjected to a longer period of exposure to urban conditions and  
264 anthropogenic chemical inputs, *e.g.* incomplete combustion of fossil fuel or biomass, which  
265 may have affected the composition of SOM and enhanced its recalcitrance to decomposition  
266 (Marschner et al., 2008; Schmidt et al., 2011). In addition, the higher concentrations of trace  
267 elements found in urban forest soils compared to the other kinds of sites (Foti et al., 2017)  
268 could also be influential. When they are in excess, trace elements can induce a change in soil  
269 microbial community structure and activity, and thus in C utilization (Moynahan et al., 2002;  
270 Kandeler et al., 2008; Chen et al., 2014). This can cause a reduction in SOM decomposition  
271 rate (Bian et al., 2015). Furthermore, the shading effects of the tree canopy on soil  
272 temperature may result in urban lawn topsoil being hotter than that of urban forests (Hamada  
273 and Ohta, 2010). Thus, SOM decomposition could be higher in urban lawns than in urban  
274 forests since it is generally accepted that high temperatures stimulate soil respiration rates  
275 (Jandl et al., 2007). Nevertheless, the response of SOM decomposition to temperature is still a  
276 controversial subject, in particular because SOM pools with different recalcitrance have  
277 diverse sensitivities to temperature (Billings and Ballantyne, 2013). All these factors  
278 (anthropogenic carbon inputs, trace elements, shading effects on soil temperature) would lead  
279 to a higher SOM accumulation through time in urban forest soils compared to other land-use  
280 types in the three classes of urban pressure. It must be noted that the soil organic carbon stock  
281 of urban forest soils is 1.16 times higher on average than the recorded regional means of  
282 natural forest soils (Saby et al., 2014), which is consistent with our results.

283         Besides showing the highest SOM concentrations, urban forests showed the highest  
284 carbonate concentrations. This could also be explained by their long exposure to urban

285 conditions, especially to the construction waste materials such as concrete and cement  
286 (Washbourne et al., 2012). Indeed, a large proportion of calcium in urban soils comes from  
287 artificial calcium silicate and hydroxide minerals within concrete and cement by erosion  
288 through time (*e.g.* building erosion). This allows the formation of pedogenic carbonates by  
289 carbonation reaction (Jorat et al., 2015).

290       Urban forests also showed a sandy loam texture, while the texture of the soils of the  
291 other forests and lawns was loamy. This is probably due to the fact that the soils of the two  
292 main urban forests sampled, the Bois de Boulogne and Vincennes, were formed from  
293 Carbonaceous alluvial deposits and Tertiary quartz sand (Fig. A.4). Thus, the high sand  
294 (especially coarse sand) and the low clay concentrations of urban forest soils likely explain  
295 the relatively high macroporosity and the smaller mesoporosity and microporosity  
296 (FitzPatrick, 2012). In the same way, the high coarse sand concentration of urban forest soils,  
297 linked to the geological origin of these soils, should explain their low available water storage  
298 capacity. Given the relatively similar textures in non-urban forests and all lawns (loamy soils),  
299 these sites have similar water storage capacities. Nevertheless, the available water storage  
300 capacity of urban forest soils is within the normal range of values recorded in the forest soils  
301 of the region (from the national network monitoring of the soil quality data base – RMQS).  
302 Note that despite the lower clay content, urban forests tended to have higher cation exchange  
303 capacity than other types of sites, which is probably due to their high organic carbon  
304 concentration (Christensen 1996; McCauley et al., 2009). In addition, the higher organic  
305 carbon concentration found in urban forests may also explain their lower bulk density  
306 compared to the urban lawns. Indeed, organic carbon is known to improve soil aggregation  
307 (*i.e.* increasing of total pore space) and to lower the degree of soil compaction (Leroy et al.,  
308 2008).

309       The historical and present day soil management practices of the Paris region have also  
310 probably influenced soil characteristics. Local urban forests, and particularly the sampled

311 Bois de Boulogne and Bois de Vincennes, have undergone profound restructuration during the  
312 Haussmann period, from 1852 to 1870, when Paris and its green spaces were refurbished  
313 (Gandy, 1999, Forrest and Konijnendijk, 2005). At this time, market garden soils at the  
314 periphery of Paris were seen as particularly fertile (sandy texture, high organic carbon, high  
315 total nitrogen, high total phosphorus soil concentrations) and using these soils was probably  
316 seen as a cheap way to reorganize urban green spaces, among which the Bois de Boulogne  
317 and Vincennes: some market garden soils were turned into forests as recreation areas for the  
318 city dwellers (Nold, 2011; Paris Green Space and Environmental Division – DEVE, pers.  
319 comm.). The soil of market gardens had often been translocated to new green spaces.

320 Furthermore, during this period, wastewater was considered as a very efficient mean  
321 of fertilization and has been used, probably in large quantities, to irrigate urban public green  
322 spaces and urban and non-urban market gardens (Moreau et al., 1846, Barles, 1999). This  
323 irrigation practice was applied to urban public green spaces until 1950 (DEVE, pers. comm.),  
324 e.g. in parts of the Bois de Boulogne and Bois de Vincennes. Moreover, the application of  
325 charcoal and liming was a common practice to increase soil fertility, and would have been  
326 also largely used in the urban market gardens of the region (DEVE, pers. comm., Museum of  
327 market gardening of the Paris region, pers. comm.). Consequently, the higher urban forest  
328 SOM concentration may also be partly explained by the legacy of the urban forest soil  
329 management, especially by charcoal and wastewater application. Indeed, it is widely  
330 recognized that charcoal C is resistant to biological soil decomposition due to its degree of  
331 aromatic condensation, which can lead to the accumulation of recalcitrant C over time  
332 (Skjemstad et al., 2002; Schmidt et al., 2011), and wastewater irrigation can lead to the long  
333 term organic matter accumulation in soils (Friedel et al., 2000). In addition, liming could  
334 explain the high carbonate concentration of urban forests, and both charcoal application and  
335 liming may explain their tendency to be slightly more alkaline than the other forests (Haynes  
336 and Naidu, 1998; Glaser et al., 2002).

337

338 *3.2- Impact of the urban-rural gradient on lawn topsoil characteristics*

339 As with the forest soils, the historical and present day practices of soil management  
340 should explain some of the topsoil characteristics of the lawns along the urban-rural gradient  
341 in the Paris region. Despite uncertainties about the history of green spaces, arable soils  
342 excavated during roadworks or construction have been resold as substrate for public green  
343 spaces since 1950 (Nold, 2011; Paris Green Space and Environmental Division – DEVE, pers.  
344 comm.). Furthermore, the quality of these soils (*e.g.* organic carbon, nutrients and carbonates  
345 concentration, soil texture) is constrained since 2004 by the NF U 44-551 standard that  
346 imposes strict ranges for the main soil properties (*e.g.* texture, C and N contents). Thus, these  
347 practices and the creation of the urban and suburban public green spaces from 1950 onwards  
348 have likely led in the three categories of lawns to relatively homogenous soils and of their  
349 chemical and physical characteristics (*e.g.* organic carbon, total nitrogen, total phosphorus,  
350 carbonates and texture). Furthermore, the urban and suburban lawns of the region tended to  
351 have lower organic carbon and total nitrogen soil concentrations than rural lawns and all types  
352 of forests. The mowing regime is more intensive, *i.e.* up to 15 cuts per year, in urban and  
353 suburban than in rural lawns and the mowed biomass is always exported (DEVE, pers.  
354 comm.). This type of management can explain the lower organic carbon and total nitrogen  
355 concentrations in urban and suburban lawn soils (Hassink, 1994). It should be noted that lawn  
356 soils have carbon contents 1.51 times lower than the carbon content of agricultural soils of the  
357 region (Saby et al., 2014) from which they stem. This suggests that these soils have lost  
358 carbon since they have been imported into urban green spaces.

359 The phosphorus fertilization of lawns (*e.g.* monoammonium and diammonium  
360 phosphate) was until recently common practice in the Paris region (DEVE, pers. comm.),  
361 which can cause P accumulation in soils when applied in excess (Carpenter et al., 1998). This  
362 likely explains the high P concentrations observed in the urban and suburban lawn soils when

363 compared to the rural and suburban forests, and the similar concentrations observed in urban  
364 forests. Moreover, since human activities increase from the rural to the urban area,  
365 atmospheric P deposition to soils likely follows this trend, which can contribute to the  
366 observed phosphorus concentration trend. Indeed, fuel combustion (fossil fuel, biomass  
367 burning, biofuels) is recognized to release phosphorus that is then deposited by dry and wet  
368 deposition (Mahowald et al., 2008).

369 Urban green spaces provide city dwellers with an accessible connection with nature  
370 (Miller, 2005). This depends, among other things, on the distance between the place of  
371 residence and green spaces that is often mentioned as the most crucial determinant of the  
372 frequency of green space visits (Bertram et al., 2017). In a city with a high population density  
373 such as Paris (21 067 inhabitant km<sup>-2</sup>; INSEE, 2014), this means that the green space lawns  
374 are certainly subjected to high foot traffic, depending on the local human population density,  
375 resulting in compaction, the loss of the largest pores and an increase of the bulk density of the  
376 surface soils (Supuka et al., 2009). This is supported by the decrease we observed in  
377 megaposity and the increase in bulk density from rural to urban lawns.

378

### 379 *3.3- Synthesis of underlying factors and study limits*

380 We have identified only one true effect of urbanization on topsoil: urbanization leads  
381 to high human densities in town centers, resulting in soil compaction in green spaces,  
382 especially urban lawns. The other effects we have detected do not pertain to urbanization *per*  
383 *se* but more to the history of soil management, the past land-uses and past soil manipulations  
384 in the Paris region. Furthermore, because soils have often been imported from the rural area,  
385 the local bedrock is likely to have much less influence on the green space topsoil  
386 characteristics, than the choice of soil type used for their construction and their subsequent  
387 management. Nevertheless, a part of urban forests grow on natural soils originating from  
388 sandy soils, which likely explains their textures. It remains difficult to accurately determine

389 the relative influence of these different factors on topsoil characteristics, since the detailed  
390 chronology of soil management history of the Paris region, especially for urban forests, is not  
391 available. This should be clarified by further historical research. Soil management history  
392 strongly depends on the age of green space creation in the region (Nold, 2011; DEVE, pers.  
393 comm.). Thus, comparing soils of green spaces with different ages should allow a better  
394 analysis of the consequences of soil management history on their characteristics, and their  
395 local evolution in green spaces of the Paris region.

396 The urban-rural gradient does not explain a high proportion of the variability found in  
397 the chemical, physical and hydrostructural soil characteristics (~ 20%). This suggests that  
398 other factors explaining their variability have not been taken into account. These  
399 characteristics might depend on the precise origin of imported soils that has probably changed  
400 over time and between the cities of the Paris region.

401 Finally, the trampling effect we have detected on the urban lawn topsoil has already  
402 been identified in many towns (Jim, 1998; Meuser, 2010) and is probably generalizable to  
403 most towns of the world. We can also expect to find the other types of effect we have  
404 identified in Paris region in most towns of the world because of the universality of soil  
405 manipulations in urban areas (*e.g.* textural homogenization; Salbitano et al., 2016). However,  
406 because towns have diverse histories that likely interact in complex ways with local soil  
407 contexts, the amplitude and direction of these effects cannot be predicted without local studies  
408 (Hazelton and Murphy, 2011). Nevertheless, in cities that have developed more recently, such  
409 as many cities in developing countries, the historical aspects are likely less influential for soil  
410 green space characteristics than in Paris.

411

#### 412 **4- Conclusion**

413 Taken together, our results show that studying the soils of Paris region could be  
414 misleading without taking into account town and soil histories and their consequences for soil

415 characteristics. Interpreting our results with more certainty would require better documenting  
416 each sampling site and in particular collecting data on the history and management of each  
417 lawn and each forest. Such an effort would probably also be important for optimizing current  
418 soil management in towns and the ecosystem services they provide. For example, our results  
419 suggest that urban forests may have stored an important quantity of carbon in their topsoil  
420 layer but the mechanisms behind this storage of carbon remain to be thoroughly studied.  
421 Similarly, the implications of the mowing regime and the exportation of grass clippings for  
422 the long-term storage of carbon in lawn topsoil should be further studied. One of the  
423 shortcomings of our study is that we have only documented the 0-10 soil layers while, clearly,  
424 other patterns could be found in deeper soil layers, and the provision of soil services also  
425 depends on soil functioning below 10 cm.

426 Overall, new research is necessary to study the functioning of the soils of the Paris  
427 region and to test more thoroughly the hypothesis that urban conditions (*e.g.* carbon and  
428 nitrogen depositions, trace element pollutants, trampling, urban heat island) and the gradient  
429 of urban pressure alter soil functioning. Potentially, comparing the details of soil functioning  
430 along urban-rural gradient, especially in a rather homogeneous land use such as lawns would  
431 reveal differences in microbial communities (composition and abundance) or microbial  
432 activities (*e.g.* mineralization and nitrification) that would be due to urban pressures *per se*.

433

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443

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1 **Topsoil characteristics of forests and lawns along an urban-rural gradient in the Paris**  
2 **region (France)**

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21 characteristics, physical urban soil characteristics, hydrostructural urban soil characteristics

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## 25 **Abstract**

26           Urban soils are a crucial component of urban ecosystems, especially in public green  
27 spaces, because of the ecosystem services they provide (*e.g.* public recreation, urban cooling  
28 or water infiltration). In this study we describe the chemical, physical and hydrostructural  
29 characteristics of 180 forest and lawn surface soil samples, taken along an urban-rural  
30 gradient in the Paris region. This was done in order to identify how these soils have been  
31 affected by urbanization. Forests and lawns are the main vegetation types found in this region,  
32 and represent 21% and 22.2% of the territory's surface area, respectively. Many of the  
33 properties of urban forest soils differed from those of other sites (*e.g.* texture, organic carbon  
34 content, total nitrogen and carbonate contents), possibly because the urban forests are much  
35 older than the lawns and because of the legacy of the historical management of soils in this  
36 region (Haussmann period). Urban lawn soils were more compacted than urban forests,  
37 probably due to higher foot traffic. The effects of urbanization were, at times, confounded  
38 with other factors (*e.g.* sandier texture of urban forests), which suggests that surface soil  
39 characteristics were influenced by past urban planning. Finally, this study constitutes a  
40 baseline analysis for the monitoring of soil quality in the region.

41

## 42 **1- Introduction**

43           Cities and towns exert significant pressures on both urban and surrounding  
44 environments (Kaushal et al., 2014; Chambers et al., 2016). Urban soils are particularly  
45 impacted, in that they are heavily managed, with whole soil profiles often being  
46 anthropogenic. For example, fertile agricultural soils from rural areas are often imported for  
47 use in constructing urban green spaces (Yang et al., 2015). Furthermore, they are subjected to  
48 the addition of waste materials, pollutants from numerous point and diffuse sources,  
49 atmospheric deposition of carbon and nitrogen, or heat island effects. Town planning and  
50 landscaping decisions can also result in rapid changes in land-use, which modify soil



51 properties in a complex manner, *e.g.* capacity to store carbon or water (Wang et al., 2020). In  
52 most cases, they do not result solely from slow pedogenic processes from a parent material  
53 under the influence of climate, vegetation, topography and time (Effland and Pouyat, 1997;  
54 Vialle et al., 2020).

55 Urban soils have a number of common features. They generally have high organic  
56 carbon content due to an accumulation of dust, combustion residues and organic waste. The  
57 high organic carbon, in turn, contributes to their generally high cation exchange capacity  
58 (Lehmann and Stahr, 2007). Urban soils also tend to have higher carbonate contents and  
59 therefore to be more alkaline, due to the presence of construction residues such as plaster or  
60 concrete (Rokia et al., 2014; Yang et al., 2015). The modifications of soil pH may influence  
61 the availability of mineral nutrients (Craul, 1992). In addition, many urban soils are often  
62 more compacted than natural soils due to the high levels of foot traffic and the use of  
63 machines to put the soils in place, which can lead to a loss of structure and an increase in bulk  
64 density (Jim, 1998; Morel et al., 2015). Because of this compaction and the decrease in pore  
65 size, urban soils tend to drain more slowly and the diffusion of oxygen and other gases may  
66 be reduced (Yang et al., 2011; Huong and Pathirana 2013; Cheon et al. 2014). However, the  
67 high soil organic carbon content generally found in urban areas may increase the resistance of  
68 the soils to compaction. Indeed, organic matter improves soil structural stability by increasing  
69 soil aggregation and aggregate stability (Leroy et al., 2008). All these mechanisms and  
70 interactions determine urban soils capacity to store, supply and recycle mineral nutrients and  
71 the movements and availability of water (Nawaz et al., 2013).

72 Even though it is widely accepted that the various pressures to which soils are  
73 subjected in urban environments can have dramatic effects on their properties (Joimel et al.,  
74 2016; Liu et al., 2016; Vasenev et al., 2018; Wang et al., 2020), research is still needed to  
75 fully document these pressures and their consequences for soil functioning. Although urban  
76 soils have attracted the attention of soil scientists in recent decades, particularly in Central

77 Europe and North America (Burghardt et al., 2015), urban and industrial areas generally do  
78 not figure on traditional soil maps, as they are not within the area of interest of national soil  
79 survey campaigns. Furthermore, these soil maps are likely already outdated with respect to  
80 urban soils due to rapid urban expansion in recent decades (De Vijver et al., 2020). In view of  
81 the likely effect urban soils have on the quality of life of urban populations, and for  
82 maintaining the habitability of cities (Vegter, 2007; Kumar et al., 2016; Economic and Social  
83 Council, 2019), these shortcomings should be overcome. Indeed, urban soils are directly or  
84 indirectly involved in most ecosystem services provided by urban green spaces, such as the  
85 recycling of organic matter or plant growth (Stroganova et al., 1997; Chiesura, 2004; Morel et  
86 al., 2015; Vasenev et al., 2018). It is therefore critical to understand how urbanization affects  
87 their properties.

88 In France, monitoring programs such as the French soil quality-monitoring network  
89 (RMQS) have been carried out to describe and monitor French agricultural, forest and  
90 grassland soils (Arrouays et al., 2011; Saby et al., 2014). However, these programs have  
91 tended to not include urban soils. Our work aims at filling this gap, focusing on the chemical,  
92 physical, and hydrostructural topsoil characteristics along a concentric gradient of  
93 urbanization around the city of Paris (Foti et al., 2017). The study was carried out on soils  
94 from forests and lawns, as these constitute the main vegetation types in the urban area of the  
95 Paris region (ECOMOS, 2003). It was expected that urban forest topsoil have particular  
96 characteristics because of their history and their geology. It was also expected that urban  
97 lawns are subjected to higher foot traffic, resulting in higher compaction than the other kinds  
98 of sites. Indeed lawns are essential to urban green spaces and an important part of city  
99 dwellers' everyday life (Ignatieva et al., 2017), and human density is higher in the urban than  
100 in the rural area (Foti et al., 2017). Ultimately, this study provides a baseline for the long-term  
101 monitoring of the main chemical, physical and hydrostructural topsoil characteristics in the  
102 urban area of the Paris region.

## 103 **2- Materials and methods**

### 104 *2.1- Study area*

105 The study area is located in the Ile-de-France region (48°07'N, 1°35'E; 49°07'N,  
106 3°26'E), and covers 12 070 km<sup>2</sup> around the city of Paris (France), which is inhabited by 12.01  
107 million people (18.8% of the metropolitan France population, INSEE, 2013). The region is  
108 relatively uniform in terms of topography, geology, hydrology, and altitude (average of 108  
109 meters above sea level). The bedrock is exclusively sedimentary (Jurassic limestone and marl,  
110 Cretaceous chalk, Carbonaceous alluvial deposits, Tertiary quartz sand). The climate is  
111 subatlantic (average temperature of 11°C, rainfall of 600 mm per year). The rainfall regime is  
112 pluvial oceanic (Pomerol and Feugueur, 1968).

113

### 114 *2.2- Determination of Urban-Rural Gradient of the Paris region*

115 Two indices were used to establish the Urban-Rural Gradient (URG): a Socio-  
116 Demographic Index (SDI) and a Heat Island Index (HII). The SDI uses the average values of  
117 the human activity density index per hectare of built surface. It allows the identification of the  
118 areas of a region that are most frequented and that concentrate employment. The HII uses the  
119 minimal temperature recording **values**. It identifies the areas that are most affected by human  
120 activities and the overall degree of artificial land cover (e.g. tar roads, buildings) (Foti et al.,  
121 2017).

122 To build the URG map, the data of the two indices were combined using GIS software  
123 (ArcGIS v.10) to obtain one map with a resolution of 2 x 2 km.

124 Finally, the URG was discretized into three classes (rural area, suburban and urban  
125 area; See Foti et al., 2017).

126

### 127 *2.3- Sampling design and protocol*

128 The sampling was stratified following a fully balanced cross factorial scheme with two

129 factors: the Urban-Rural Gradient (URG, 3 levels) and the Land-use Type (LT, 2 levels). The  
130 URG contained three concentric classes that broadly corresponded to an urban-rural gradient:  
131 a rural class, a suburban class and an urban class. The classes were distinguished based on  
132 population density, built-up area and estimated heat island effects. For a complete description  
133 of the method used to identify the gradient (Foti et al., 2017). The two-targeted land-uses  
134 were forests and lawns that, respectively, represent 21% (2525 km<sup>2</sup>) and 22.2% (2670 km<sup>2</sup>) of  
135 the region (ECOMOS, 2003). All the selected green spaces of the study were established after  
136 1950, except for the forests of the urban area (IAU, 2013). Sampling took place from  
137 September to October 2015. Each combination of URG and LT was sampled at 30 different  
138 locations, yielding a total of 180 sampling sites ( $n = 3 \text{ levels of URG} \times 2 \text{ LT} \times 30 \text{ replicates} =$   
139 180 sites) (Fig. 1).

140 Soil characteristics were described from one composite soil sample per sampling site.  
141 Each composite sample was made of 3 sub-samples collected within a 1 m<sup>2</sup> square from the  
142 top 10 cm of the organo-mineral layer (after having removed any vegetal or anthropogenic  
143 debris and the humus layer). Each composite sample was homogenized to constitute a  
144 representative sample according to the NF X31-100 standard. Samples were collected with an  
145 8 cm-diameter stainless steel hand auger, immediately placed in polyethylene bags and  
146 subsequently air-dried in the laboratory. In order to measure the water retention curve of the  
147 soils, a single undisturbed sample was also taken from the 0-5 cm surface layer, at the centre  
148 of each 1 m<sup>2</sup> square using the cylinder method (Blake and Hartge, 1986). Roots and rocks  
149 were removed by hand from the base and the top of the cylinder. The undisturbed samples  
150 (100 cm<sup>3</sup>) were stored in sealed bags at a temperature of 4-5°C to reduce biological activity  
151 and preserve the sample structure.

152

153 *2.4- Chemical, physical and hydrostructural soil analysis*

154 International (ISO) or French (NF) standardized methods were used to measure the  
155 chemical and physical soil characteristics: clay, coarse and fine silt (CSi and FSi), coarse and  
156 fine sand (CSa and FSa), organic carbon (OC), total nitrogen (tot N), pH-H<sub>2</sub>O (pH),  
157 carbonates (CaCO<sub>3</sub>), total phosphorus (tot P) and cation exchange capacity (CEC) (Table  
158 A.1). Particle-size distribution was assessed by the dispersion of mineral particles after  
159 destruction of the organic matter using hydrogen peroxide and separation of the particles into  
160 different classes by sedimentation. Soil pH was measured in water in a 1:5 soil-to-solution  
161 ratio at 25°C after shaking the suspension for 1 hour. Total N was measured by dry  
162 combustion, after burning samples at 1000°C in the presence of O<sub>2</sub> using a CHN auto-  
163 analyzer (CHN 1500, Carlo Erba). Organic carbon was quantified by sulfochromic oxidation  
164 using an auto-analyzer (Technicon III, Brian and Luebbe, Axflow). The soil organic carbon  
165 stocks (OCS in kg m<sup>-2</sup>) in the first 10 cm were estimated using the equation:  
166  $OCS_{(n)}=0.1 \times BD_{(n)} \times OC_{(n)}$ , where 0.1 is the sampling depth in meters, and BD the bulk density.  
167 The soil carbonate concentration was determined by measuring the volume of CO<sub>2</sub> released  
168 by reaction with HCl, using a Bernard calcimeter. **Total phosphorus** was measured by the  
169 molybdenum blue method, and quantified using an auto-analyzer (Technicon III, Brian and  
170 Luebbe, Axflow). CEC was determined after percolation of 1.0M ammonium acetate solution  
171 at pH 7.

172 **The water retention of the soils was measured following classical methods (Pansu and**  
173 **Gautheyrou, 2006). Samples were saturated from the bottom using a sandbox suction table**  
174 **until equilibrium at 0 kPa matric potential at the bottom of the samples and -0.5 kPa at the top**  
175 **was reached. A pressure plate apparatus was used to equilibrate each soil sample at -33 kPa**  
176 **(field capacity). The remainder of the samples was immediately enclosed in brass rings of**  
177 **5.35 cm diameter and 3.0 cm height and placed on a pressure membrane apparatus to**  
178 **determine the water retained at -1500 kPa matric potential (permanent wilting point). The**  
179 **volumetric water content at each matric potential was determined from the gravimetric water**

180 contents and the bulk density (Table A.1). The pore-neck diameters of the maximum water-  
181 filled pores radius corresponding to the three-selected matric potentials were 600  $\mu\text{m}$  (-0.5  
182 kPa), 9  $\mu\text{m}$  (-33 kPa), and 0.2  $\mu\text{m}$  (-1500 kPa), which were determined in accordance with  
183 Jurin's law. They delimited the macropores (600-9  $\mu\text{m}$ ), mesopores (9-0.2  $\mu\text{m}$ ), and  
184 micropores ( $r < 0.2 \mu\text{m}$ ). The megapores ( $r > 600 \mu\text{m}$ ) represent the quasi-permanent air filled  
185 soil porosity (See Table A.1). The soil water retention measurements were performed at 20°C.  
186 The pressure vessels, plates, and sandbox suction table used were manufactured by Soil  
187 Moisture Equipment Corp. The sandbox suction table was by Eijkerkamp.

188

### 189 2.5- Statistical analysis

190 All statistical analyses were performed using the R 3.4 (R Core Team, 2016). First, a  
191 between-group multivariate analysis (Bati et al., 2006) was used to detect the effect of the  
192 urban-rural gradient (URG) and land-use type (LT) on all the soil variables. This analysis was  
193 performed using a combination of the two factors (URG and LT, 6 combinations) as the  
194 explanatory variable. The significance of the composite factor (URG/LT) was tested using a  
195 Monte-Carlo permutation test (1000 permutations).

196 The effects of URG, LT, and their interaction (URGxLT) on each chemical, physical,  
197 and hydrological soil characteristics were then analyzed using ANOVA. Variables that were  
198 not normally distributed were log-transformed prior to analyses, except for the megaporosity  
199 (square root transformation), and pH (exponential transformation). Bulk density, saturation  
200 point, field capacity, and the available water storage capacity were not transformed.  
201 Combinations of the different factors were compared using multiple comparisons of means  
202 (Tukey's honest significant difference, multcomp package, Hothorn et al., 2008). The  
203 residuals were checked for spatial autocorrelation using Moran's I correlogram (spdep  
204 package; Bivand, 2012). Since the Moran's I values (permutation test, n=1000) were never  
205 significant, the autocorrelation term was not included in models.

## 206 3- Results

### 207 3.1- Chemical, physical and hydrostructural soil typology of the Paris region

208 The clay content was low in all the samples analyzed: soil texture ranged from sand to  
209 silt loam (Fig. 2). The urban forest soils exhibited a specific textural pattern when compared  
210 to soils of other land-use types, which were relatively homogeneous. The urban forest soils  
211 were generally classified as sandy loam, whilst the other sites were loamy soils (Fig. 2).

212 The between-group analysis performed on the chemical, physical and hydrostructural  
213 variables, grouped as a function of the URG and LT, explained 19.94% of the total variance  
214 (Fig. 3). A Monte-Carlo permutation test showed that the URG and LT significantly affected  
215 the chemical, physical and hydrostructural soil characteristics ( $P = 0.001$ ). The first and  
216 second axes of the between-group analysis ordination accounted for 65.42% and 24.47% of  
217 the variance, respectively. The organic carbon, total nitrogen, coarse sand concentrations and  
218 macroporosity positively contributed to axis 1, while clay and mesoporosity contributed  
219 negatively. Axis 1 discriminated urban forest soils from all the other soils. The bulk density  
220 and megaporosity were the main explanatory variables in the discrimination of the LT along  
221 Axis 2.

222

### 223 3.2- Effects of land-use types and urban-rural gradient on chemical, physical, and 224 hydrostructural soil characteristics

225 The URG, LT and their interaction had a significant impact on all chemical, physical,  
226 and hydrostructural variables. However, no factor significant affected the saturation point. In  
227 addition, URG had no effect on the pH, and LT had no effect on the cation exchange capacity.  
228 Neither LT nor URGxLT had a significant effect on the proportion of fine sand. Finally,  
229 URGxLT showed no effect on the permanent wilting point and the microporosity (Table 1).

230 Multiple comparisons of means showed that the effect of URGxLT on chemical,  
231 physical, and hydrostructural variables was mainly due to the differences between the urban

232 forests and all other types of sites. Urban forest exhibited either the highest (organic carbon  
233 concentration, total nitrogen, cation exchange capacity, carbonate, coarse sand, soil organic  
234 carbon stock and macroporosity) or the lowest (coarse silt, the fine silt, the clay, the field  
235 capacity, the mesoporosity, the microporosity and the available water storage capacity)  
236 measured values for most of the studied variables. In addition, urban lawns had higher coarse  
237 silt concentrations than the suburban forests. The C/N ratio was the lowest in the rural lawns,  
238 and the other kinds of sites showed no difference. Suburban lawns were significantly more  
239 alkaline than all of the forest sites. Total phosphorus increased from rural to urban areas in  
240 forests. The urban forests and all lawn types had higher total phosphorus concentrations than  
241 rural forests. The megaporosity showed a specific pattern with a lower value in the urban  
242 lawns than in all other sites. Finally, bulk density was highest in urban lawn soils, and lowest  
243 in suburban forest soils, with an intermediate value in suburban lawn soils (See Fig. 4-5,  
244 Table A.2, Fig. A.1-A.2).

245

## 246 **4- Discussion**

### 247 *4.1- Impact of urban-rural gradient on forest topsoil characteristics*

248 The higher organic carbon, the higher total nitrogen and the lower pH in forest soils  
249 compared to lawn soils may be partially due to differences between the two vegetation types.  
250 Indeed, the high inputs of tree leaf litter can lead to acidification and an accumulation of  
251 organic carbon and nitrogen in forest soils (Rout and Gupta, 1989). It is widely recognized  
252 that forest soils accumulate more organic matter than the other temperate terrestrial  
253 ecosystems, especially in topsoil (Guo et al., 2002; Innangi et al., 2017). However, **this does**  
254 not explain the differences between the urban forest soils and the suburban and rural forest  
255 soils. A possible explanation may be related to the age of the green spaces. Indeed, urban  
256 forests existed long before the other green spaces (see Fig. A.3). Urban forests are all that  
257 remains of the old “forest of Rouvray” that surrounded “Lutèce” in the Gallo-Roman era,



258 while all the other kinds of sites were established after 1950 (IAU, 2013). Consequently, the  
259 higher organic matter concentration (SOM) found in urban forest soils than in other forests  
260 and in lawns could be simply due to a longer accumulation of organic matter.

261 These soils were also subjected to a longer period of exposure to urban conditions and  
262 anthropogenic chemical inputs, *e.g.* incomplete combustion of fossil fuel or biomass, which  
263 may have affected the composition of SOM and enhanced its recalcitrance to decomposition  
264 (Marschner et al., 2008; Schmidt et al., 2011). In addition, the higher concentrations of trace  
265 elements found in urban forest soils compared to the other sites (Foti et al., 2017) could also  
266 be influential. When they are in excess, trace elements can induce a change in soil microbial  
267 community structure and activity, and thus in C utilization (Moynahan et al., 2002; Kandeler  
268 et al., 2008; Chen et al., 2014). This can cause a reduction in SOM decomposition rate (Bian  
269 et al., 2015). Furthermore, the shading effects of the tree canopy on soil temperature may  
270 result in urban lawn topsoil being hotter than that of urban forests (Hamada and Ohta, 2010).  
271 Thus, SOM decomposition may be higher in urban lawns than in urban forests since it is  
272 generally accepted that high temperatures stimulate soil respiration rates (Jandl et al., 2007).  
273 Nevertheless, the response of SOM decomposition to temperature is still a controversial  
274 subject, in particular because SOM pools with different recalcitrance have diverse sensitivities  
275 to temperature (Billings and Ballantyne, 2013). Anthropogenic carbon inputs, trace elements,  
276 and shading effects on soil temperature would lead to a higher SOM accumulation through  
277 time in urban forest soils compared to other land-use types in the three classes of urban  
278 pressure. It should be noted that the soil organic carbon stock of urban forest soils is 1.16  
279 times higher on average than the recorded regional means of natural forest soils (Saby et al.,  
280 2014), which is consistent with our results.

281 Besides showing the highest SOM concentrations, urban forests showed the highest  
282 carbonate concentrations. This could also be explained by their long exposure to urban  
283 conditions, especially to the construction waste materials such as concrete and cement

284 (Washbourne et al., 2012). Indeed, a large proportion of calcium in urban soils comes from  
285 artificial calcium silicate and hydroxide minerals within concrete and cement by erosion  
286 through time (*e.g.* building erosion). This allows the formation of pedogenic carbonates by  
287 carbonation reaction (Jorat et al., 2015).

288 Urban forests also showed a sandy loam texture, while the texture of the soils of the  
289 other forests and lawns was loamy. This is probably due to the fact that the soils of the two  
290 main urban forests sampled, the Bois de Boulogne and Vincennes, were formed from  
291 Carbonaceous alluvial deposits and Tertiary quartz sand (Fig. A.4). Thus, **the high coarse sand**  
292 and the low clay concentrations of urban forest soils likely explain the relatively high  
293 macroporosity and the smaller mesoporosity and microporosity (FitzPatrick, 2012). In the  
294 same way, the high coarse sand concentration of urban forest soils, linked to the geological  
295 origin of these soils, should explain their low available water storage capacity. Given the  
296 relatively similar textures in non-urban forests and all lawns (*e.g.* loamy soils), these sites  
297 have similar water storage capacities. Nevertheless, the available water storage capacity of  
298 urban forest soils is within the normal range of values recorded in the forest soils of the region  
299 (from the national network monitoring of the soil quality data base – RMQS). Note that  
300 despite the lower clay content, urban forests tended to have higher cation exchange capacity  
301 than other types of sites, which is probably due to their high organic carbon concentration  
302 (Christensen 1996; McCauley et al., 2009). In addition, the higher organic carbon  
303 concentration found in urban forests may also explain their lower bulk density compared to  
304 the urban lawns. Indeed, organic carbon is known to improve soil aggregation (*i.e.* increasing  
305 of total pore space) and to lower the degree of soil compaction (Leroy et al., 2008).

306 The historical and present day soil management practices of the Paris region have also  
307 probably influenced soil characteristics. Local urban forests, and particularly the sampled  
308 Bois de Boulogne and Bois de Vincennes, have undergone profound restructuration during the  
309 Haussmann period, from 1852 to 1870, when Paris and its green spaces were refurbished

310 (Gandy, 1999, Forrest and Konijnendijk, 2005). At this time, market garden soils at the  
311 periphery of Paris were seen as particularly fertile with their sandy texture, high organic  
312 carbon, high total nitrogen, and with high total phosphorus soil concentrations. Thus, using  
313 these soils was probably seen as a cheap way to reorganize urban green spaces, among which  
314 the Bois de Boulogne and Vincennes: some market garden soils were turned into forests as  
315 recreation areas for the city dwellers (Nold, 2011; Paris Green Space and Environmental  
316 Division – DEVE, pers. comm.). The soil of market gardens had often been translocated to  
317 new green spaces.

318 Furthermore, during this period, wastewater was considered as a very efficient mean  
319 of fertilization and has been used, probably in large quantities, to irrigate urban public green  
320 spaces and urban and non-urban market gardens (Moreau et al., 1846, Barles, 1999). This  
321 irrigation practice was applied to urban public green spaces until 1950, in parts of the Bois de  
322 Boulogne and Bois de Vincennes (DEVE, pers. comm.). Moreover, the application of  
323 charcoal and liming was a common practice to increase soil fertility, and would have been  
324 also largely used in the urban market gardens of the region (DEVE, pers. comm., Museum of  
325 market gardening of the Paris region, pers. comm.). Consequently, the higher urban forest  
326 SOM concentration may also be partly explained by the legacy of the urban forest soil  
327 management, especially by charcoal and wastewater application. Indeed, it is widely  
328 recognized that charcoal C is resistant to biological soil decomposition due to its degree of  
329 aromatic condensation, which can lead to the accumulation of recalcitrant C over time  
330 (Skjemstad et al., 2002; Schmidt et al., 2011), and wastewater irrigation can lead to the long  
331 term organic matter accumulation in soils (Friedel et al., 2000). In addition, liming could  
332 explain the high carbonate concentration of urban forests, and both charcoal application and  
333 liming may explain their tendency to be slightly more alkaline than the other forests (Haynes  
334 and Naidu, 1998; Glaser et al., 2002).

335

#### 336 4.2- Impact of the urban-rural gradient on lawn topsoil characteristics

337 As with the forest soils, the historical and present day practices of soil management  
338 should explain some of the topsoil characteristics of the lawns along the urban-rural gradient  
339 in the Paris region. Despite uncertainties about the history of green spaces, arable soils  
340 excavated during roadworks or construction have been resold as substrate for public green  
341 spaces since 1950 (Nold, 2011; Paris Green Space and Environmental Division – DEVE, pers.  
342 comm.). Furthermore, the quality of these soils is constrained since 2004 by the NF U 44-551  
343 standard that imposes strict ranges for the main soil properties (e.g. texture, C and N contents,  
344 etc.). Thus, these practices and the creation of the urban and suburban public green spaces  
345 from 1950 onwards have likely led in the three categories of lawns to relatively homogenous  
346 soils and of their chemical and physical characteristics (e.g. organic carbon, total nitrogen,  
347 total phosphorus, carbonates and texture). Furthermore, the urban and suburban lawns of the  
348 region tended to have lower organic carbon and total nitrogen soil concentrations than rural  
349 lawns and all types of forests. The mowing regime is more intensive, *i.e.* up to 15 cuts per  
350 year, in urban and suburban than in rural lawns and the mowed biomass is always exported  
351 (DEVE, pers. comm.). This type of management can explain the lower organic carbon and  
352 total nitrogen concentrations in urban and suburban lawn soils (Hassink, 1994). It should be  
353 noted that lawn soils have carbon contents 1.51 times lower than the carbon content of  
354 agricultural soils of the region (Saby et al., 2014) from which they stem. This suggests that  
355 these soils have lost carbon since they have been imported into urban green spaces.

356 The phosphorus fertilization of lawns was until recently common practice in the Paris  
357 region (e.g. monoammonium and diammonium phosphate DEVE, pers. comm.), which can  
358 cause phosphorus accumulation in soils when applied in excess (Carpenter et al., 1998). This  
359 likely explains the high phosphorus concentrations observed in the urban and suburban lawn  
360 soils when compared to the rural and suburban forests, and the similar concentrations  
361 observed in urban forests. Moreover, since human activities increase from the rural to the

362 urban area, atmospheric P deposition to soils likely follows this trend, which can contribute to  
363 the observed phosphorus concentration trend. Indeed, fuel combustion **such as fossil fuel,**  
364 **biomass burning, or biofuels** is recognized to release phosphorus that is then deposited by dry  
365 and wet deposition (Mahowald et al., 2008).

366 Urban green spaces provide city dwellers with an accessible connection with nature  
367 (Miller, 2005). This depends, among other things, on the distance between the place of  
368 residence and green spaces that is often mentioned as the most crucial determinant of the  
369 frequency of green space visits (Bertram et al., 2017). In a city with a high population density  
370 such as Paris (21 067 inhabitant km<sup>-2</sup>; INSEE, 2014), this means that the green space lawns  
371 are certainly subjected to high foot traffic, depending on the local human population density,  
372 resulting in compaction, the loss of the largest pores and an increase of the bulk density of the  
373 surface soils (Supuka et al., 2009). This is supported by the decrease we observed in  
374 megaporosity and the increase in bulk density from rural to urban lawns.

375

#### 376 *4.3- Synthesis of underlying factors and study limits*

377 We have identified only one true effect of urbanization on topsoil: urbanization leads  
378 to high human densities in town centers, resulting in soil compaction in green spaces,  
379 especially urban lawns. The other effects we have detected do not pertain to urbanization *per*  
380 *se* but more to the history of soil management, the past land-uses and **past soil uses.**  
381 Furthermore, because soils have often been imported from the rural area, the local bedrock is  
382 likely to have much less influence on the green space topsoil characteristics, than the choice  
383 of soil type used for their construction and their subsequent management. Nevertheless, a part  
384 of urban forests grow on natural soils originating from sandy soils, which likely explains their  
385 textures. It remains difficult to accurately determine the relative influence of these different  
386 factors on topsoil characteristics, since the detailed chronology of soil management history of  
387 the Paris region, especially for urban forests, is not available. This should be clarified by

388 further historical research. Soil management history strongly depends on the age of green  
389 space creation in the region (Nold, 2011; DEVE, pers. comm.). Thus, comparing soils of  
390 green **spaces of different** ages should allow a better analysis of the consequences of soil  
391 management history on their characteristics, and their local evolution in green spaces of the  
392 Paris region.

393 The urban-rural gradient does not explain a high proportion of the variability found in  
394 the chemical, physical and hydrostructural soil characteristics (~ 20%). This suggests that  
395 other factors explaining their variability have not been taken into account. These  
396 characteristics might depend on the precise origin of imported soils that has probably changed  
397 over time and between the cities of the Paris region.

398 Finally, the trampling effect we have detected on the urban lawn topsoil has already  
399 been identified in many towns (Jim, 1998; Meuser, 2010) and is probably generalizable to  
400 most towns of the world. We can also expect to find the other types of effect we have  
401 identified in Paris region in most towns of the world because of the universality of soil  
402 manipulations in urban areas (*e.g.* textural homogenization; Salbitano et al., 2016). However,  
403 because towns have diverse histories that likely interact in complex ways with local soil  
404 contexts, the amplitude and direction of these effects cannot be predicted without local studies  
405 (Hazelton and Murphy, 2011). Nevertheless, in cities that have developed more recently, such  
406 as many cities in developing countries, the historical aspects are likely less influential for soil  
407 green space characteristics than in Paris.

408

## 409 **5- Conclusion**

410 **Whilst the results presented here are consistent with those of the literature on urban**  
411 **soil characteristics, it was difficult to identify precisely the effect of urbanization on the soil**  
412 **characteristics. We identified only one true effect of urbanization on soils, which is the**  
413 **compaction phenomenon due to the high human densities in town centers, especially on urban**

414 lawns. The other effects we have detected were not due to urbanization *per se* but more to the  
415 history of soil management, the past land-uses and past soil changes in the Paris region.

416 Taken together, our results suggest that studying urban soil can be misleading if urban  
417 and soil histories, and their consequences for soil characteristics, are not taken into account.  
418 Interpreting our results with more certainty would require better documenting each sampling  
419 site and, in particular, collecting data on the history and management of each lawn and each  
420 forest. Such an effort would probably also be useful for optimizing current soil management  
421 in towns and the ecosystem services they provide. For example, our results suggest that urban  
422 forests may have stored a large quantity of carbon in their topsoil layer, but the mechanisms  
423 behind this storage of carbon remain to be thoroughly identified. Similarly, the implications of  
424 the mowing regime and the exportation of grass clippings for the long-term storage of carbon  
425 in lawn topsoil should be further studied. One of the shortcomings of our study is that we  
426 have only documented the 0-10 soil layers while, clearly, other patterns could emerge in  
427 deeper soil layers, and the provision of soil services also depends on soil functioning below  
428 10 cm.

429

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439

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1 **Topsoil characteristics of forests and lawns along an urban-rural gradient in the Paris**  
2 **region (France)**

3

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19

20 **Keywords:** Anthrosols, Forests, lawns, urban-rural gradient, chemical urban soil  
21 characteristics, physical urban soil characteristics, hydrostructural urban soil characteristics

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## 25 **Abstract**

26           Urban soils are a crucial component of urban ecosystems, especially in public green  
27 spaces, because of the ecosystem services they provide (*e.g.* public recreation, urban cooling  
28 or water infiltration). In this study we describe the chemical, physical and hydrostructural  
29 characteristics of 180 forest and lawn surface soil samples, taken along an urban-rural  
30 gradient in the Paris region. This was done in order to identify how these soils have been  
31 affected by urbanization. Forests and lawns are the main vegetation types found in this region,  
32 and represent 21% and 22.2% of the territory's surface area, respectively. Many of the  
33 properties of urban forest soils differed from those of other sites (*e.g.* texture, organic carbon  
34 content, total nitrogen and carbonate contents), possibly because the urban forests are much  
35 older than the lawns and because of the legacy of the historical management of soils in this  
36 region (Haussmann period). Urban lawn soils were more compacted than urban forests,  
37 probably due to higher foot traffic. The effects of urbanization were, at times, confounded  
38 with other factors (*e.g.* sandier texture of urban forests), which suggests that surface soil  
39 characteristics were influenced by past urban planning. Finally, this study constitutes a  
40 baseline analysis for the monitoring of soil quality in the region.

41

## 42 **1- Introduction**

43           Cities and towns exert significant pressures on both urban and surrounding  
44 environments (Kaushal et al., 2014; Chambers et al., 2016). Urban soils are particularly  
45 impacted, in that they are heavily managed, with whole soil profiles often being  
46 anthropogenic. For example, fertile agricultural soils from rural areas are often imported for  
47 use in constructing urban green spaces (Yang et al., 2015). Furthermore, they are subjected to  
48 the addition of waste materials, pollutants from numerous point and diffuse sources,  
49 atmospheric deposition of carbon and nitrogen, or heat island effects. Town planning and  
50 landscaping decisions can also result in rapid changes in land-use, which modify soil

51 properties in a complex manner, *e.g.* capacity to store carbon or water (Wang et al., 2020). In  
52 most cases, they do not result solely from slow pedogenic processes from a parent material  
53 under the influence of climate, vegetation, topography and time (Effland and Pouyat, 1997;  
54 Vialle et al., 2020).

55 Urban soils have a number of common features. They generally have high organic  
56 carbon content due to an accumulation of dust, combustion residues and organic waste. The  
57 high organic carbon, in turn, contributes to their generally high cation exchange capacity  
58 (Lehmann and Stahr, 2007). Urban soils also tend to have higher carbonate contents and  
59 therefore to be more alkaline, due to the presence of construction residues such as plaster or  
60 concrete (Rokia et al., 2014; Yang et al., 2015). The modifications of soil pH may influence  
61 the availability of mineral nutrients (Craul, 1992). In addition, many urban soils are often  
62 more compacted than natural soils due to the high levels of foot traffic and the use of  
63 machines to put the soils in place, which can lead to a loss of structure and an increase in bulk  
64 density (Jim, 1998; Morel et al., 2015). Because of this compaction and the decrease in pore  
65 size, urban soils tend to drain more slowly and the diffusion of oxygen and other gases may  
66 be reduced (Yang et al., 2011; Huong and Pathirana 2013; Cheon et al. 2014). However, the  
67 high soil organic carbon content generally found in urban areas may increase the resistance of  
68 the soils to compaction. Indeed, organic matter improves soil structural stability by increasing  
69 soil aggregation and aggregate stability (Leroy et al., 2008). All these mechanisms and  
70 interactions determine urban soils capacity to store, supply and recycle mineral nutrients and  
71 the movements and availability of water (Nawaz et al., 2013).

72 Even though it is widely accepted that the various pressures to which soils are  
73 subjected in urban environments can have dramatic effects on their properties (Joimel et al.,  
74 2016; Liu et al., 2016; Vasenev et al., 2018; Wang et al., 2020), research is still needed to  
75 fully document these pressures and their consequences for soil functioning. Although urban  
76 soils have attracted the attention of soil scientists in recent decades, particularly in Central

77 Europe and North America (Burghardt et al., 2015), urban and industrial areas generally do  
78 not figure on traditional soil maps, as they are not within the area of interest of national soil  
79 survey campaigns. Furthermore, these soil maps are likely already outdated with respect to  
80 urban soils due to rapid urban expansion in recent decades (De Vijver et al., 2020). In view of  
81 the likely effect urban soils have on the quality of life of urban populations, and for  
82 maintaining the habitability of cities (Vegter, 2007; Kumar et al., 2016; Economic and Social  
83 Council, 2019), these shortcomings should be overcome. Indeed, urban soils are directly or  
84 indirectly involved in most ecosystem services provided by urban green spaces, such as the  
85 recycling of organic matter or plant growth (Stroganova et al., 1997; Chiesura, 2004; Morel et  
86 al., 2015; Vasenev et al., 2018). It is therefore critical to understand how urbanization affects  
87 their properties.

88 In France, monitoring programs such as the French soil quality-monitoring network  
89 (RMQS) have been carried out to describe and monitor French agricultural, forest and  
90 grassland soils (Arrouays et al., 2011; Saby et al., 2014). However, these programs have  
91 tended to not include urban soils. Our work aims at filling this gap, focusing on the chemical,  
92 physical, and hydrostructural topsoil characteristics along a concentric gradient of  
93 urbanization around the city of Paris (Foti et al., 2017). The study was carried out on soils  
94 from forests and lawns, as these constitute the main vegetation types in the urban area of the  
95 Paris region (ECOMOS, 2003). It was expected that urban forest topsoil have particular  
96 characteristics because of their history and their geology. It was also expected that urban  
97 lawns are subjected to higher foot traffic, resulting in higher compaction than the other kinds  
98 of sites. Indeed lawns are essential to urban green spaces and an important part of city  
99 dwellers' everyday life (Ignatieva et al., 2017), and human density is higher in the urban than  
100 in the rural area (Foti et al., 2017). Ultimately, this study provides a baseline for the long-term  
101 monitoring of the main chemical, physical and hydrostructural topsoil characteristics in the  
102 urban area of the Paris region.

## 103 **2- Materials and methods**

### 104 *2.1- Study area*

105 The study area is located in the Ile-de-France region (48°07'N, 1°35'E; 49°07'N,  
106 3°26'E), and covers 12 070 km<sup>2</sup> around the city of Paris (France), which is inhabited by 12.01  
107 million people (18.8% of the metropolitan France population, INSEE, 2013). The region is  
108 relatively uniform in terms of topography, geology, hydrology, and altitude (average of 108  
109 meters above sea level). The bedrock is exclusively sedimentary (Jurassic limestone and marl,  
110 Cretaceous chalk, Carbonaceous alluvial deposits, Tertiary quartz sand). The climate is  
111 subatlantic (average temperature of 11°C, rainfall of 600 mm per year). The rainfall regime is  
112 pluvial oceanic (Pomerol and Feugueur, 1968).

113

### 114 *2.2- Determination of Urban-Rural Gradient of the Paris region*

115 Two indices were used to establish the Urban-Rural Gradient (URG): a Socio-  
116 Demographic Index (SDI) and a Heat Island Index (HII). The SDI uses the average values of  
117 the human activity density index per hectare of built surface. It allows the identification of the  
118 areas of a region that are most frequented and that concentrate employment. The HII uses the  
119 minimal temperature recording values. It identifies the areas that are most affected by human  
120 activities and the overall degree of artificial land cover (e.g. tar roads, buildings) (Foti et al.,  
121 2017).

122 To build the URG map, the data of the two indices were combined using GIS software  
123 (ArcGIS v.10) to obtain one map with a resolution of 2 x 2 km.

124 Finally, the URG was discretized into three classes (rural area, suburban and urban  
125 area; See Foti et al., 2017).

126

### 127 *2.3- Sampling design and protocol*

128 The sampling was stratified following a fully balanced cross factorial scheme with two

129 factors: the Urban-Rural Gradient (URG, 3 levels) and the Land-use Type (LT, 2 levels). The  
130 URG contained three concentric classes that broadly corresponded to an urban-rural gradient:  
131 a rural class, a suburban class and an urban class. The classes were distinguished based on  
132 population density, built-up area and estimated heat island effects. For a complete description  
133 of the method used to identify the gradient (Foti et al., 2017). The two-targeted land-uses  
134 were forests and lawns that, respectively, represent 21% (2525 km<sup>2</sup>) and 22.2% (2670 km<sup>2</sup>) of  
135 the region (ECOMOS, 2003). All the selected green spaces of the study were established after  
136 1950, except for the forests of the urban area (IAU, 2013). Sampling took place from  
137 September to October 2015. Each combination of URG and LT was sampled at 30 different  
138 locations, yielding a total of 180 sampling sites ( $n = 3$  levels of URG  $\times$  2 LT  $\times$  30 replicates =  
139 180 sites) (Fig. 1).

140 Soil characteristics were described from one composite soil sample per sampling site.  
141 Each composite sample was made of 3 sub-samples collected within a 1 m<sup>2</sup> square from the  
142 top 10 cm of the organo-mineral layer (after having removed any vegetal or anthropogenic  
143 debris and the humus layer). Each composite sample was homogenized to constitute a  
144 representative sample according to the NF X31-100 standard. Samples were collected with an  
145 8 cm-diameter stainless steel hand auger, immediately placed in polyethylene bags and  
146 subsequently air-dried in the laboratory. In order to measure the water retention curve of the  
147 soils, a single undisturbed sample was also taken from the 0-5 cm surface layer, at the centre  
148 of each 1 m<sup>2</sup> square using the cylinder method (Blake and Hartge, 1986). Roots and rocks  
149 were removed by hand from the base and the top of the cylinder. The undisturbed samples  
150 (100 cm<sup>3</sup>) were stored in sealed bags at a temperature of 4-5°C to reduce biological activity  
151 and preserve the sample structure.

152

153 *2.4- Chemical, physical and hydrostructural soil analysis*

154 International (ISO) or French (NF) standardized methods were used to measure the  
155 chemical and physical soil characteristics: clay, coarse and fine silt (CSi and FSi), coarse and  
156 fine sand (CSa and FSa), organic carbon (OC), total nitrogen (tot N), pH-H<sub>2</sub>O (pH),  
157 carbonates (CaCO<sub>3</sub>), total phosphorus (tot P) and cation exchange capacity (CEC) (Table  
158 A.1). Particle-size distribution was assessed by the dispersion of mineral particles after  
159 destruction of the organic matter using hydrogen peroxide and separation of the particles into  
160 different classes by sedimentation. Soil pH was measured in water in a 1:5 soil-to-solution  
161 ratio at 25°C after shaking the suspension for 1 hour. Total N was measured by dry  
162 combustion, after burning samples at 1000°C in the presence of O<sub>2</sub> using a CHN auto-  
163 analyzer (CHN 1500, Carlo Erba). Organic carbon was quantified by sulfochromic oxidation  
164 using an auto-analyzer (Technicon III, Brian and Luebbe, Axflow). The soil organic carbon  
165 stocks (OCS in kg m<sup>-2</sup>) in the first 10 cm were estimated using the equation:  
166  $OCS_{(n)}=0.1 \times BD_{(n)} \times OC_{(n)}$ , where 0.1 is the sampling depth in meters, and BD the bulk density.  
167 The soil carbonate concentration was determined by measuring the volume of CO<sub>2</sub> released  
168 by reaction with HCl, using a Bernard calcimeter. Total phosphorus was measured by the  
169 molybdenum blue method, and quantified using an auto-analyzer (Technicon III, Brian and  
170 Luebbe, Axflow). CEC was determined after percolation of 1.0M ammonium acetate solution  
171 at pH 7.

172 The water retention of the soils was measured following classical methods (Pansu and  
173 Gautheyrou, 2006). Samples were saturated from the bottom using a sandbox suction table  
174 until equilibrium at 0 kPa matric potential at the bottom of the samples and -0.5 kPa at the top  
175 was reached. A pressure plate apparatus was used to equilibrate each soil sample at -33 kPa  
176 (field capacity). The remainder of the samples was immediately enclosed in brass rings of  
177 5.35 cm diameter and 3.0 cm height and placed on a pressure membrane apparatus to  
178 determine the water retained at -1500 kPa matric potential (permanent wilting point). The  
179 volumetric water content at each matric potential was determined from the gravimetric water

180 contents and the bulk density (Table A.1). The pore-neck diameters of the maximum water-  
181 filled pores radius corresponding to the three-selected matric potentials were 600  $\mu\text{m}$  (-0.5  
182 kPa), 9  $\mu\text{m}$  (-33 kPa), and 0.2  $\mu\text{m}$  (-1500 kPa), which were determined in accordance with  
183 Jurin's law. They delimited the macropores (600-9  $\mu\text{m}$ ), mesopores (9-0.2  $\mu\text{m}$ ), and  
184 micropores ( $r < 0.2 \mu\text{m}$ ). The megapores ( $r > 600 \mu\text{m}$ ) represent the quasi-permanent air filled  
185 soil porosity (See Table A.1). The soil water retention measurements were performed at 20°C.  
186 The pressure vessels, plates, and sandbox suction table used were manufactured by Soil  
187 Moisture Equipment Corp. The sandbox suction table was by Eijkerkamp.

188

### 189 *2.5- Statistical analysis*

190 All statistical analyses were performed using the R 3.4 (R Core Team, 2016). First, a  
191 between-group multivariate analysis (Bati et al., 2006) was used to detect the effect of the  
192 urban-rural gradient (URG) and land-use type (LT) on all the soil variables. This analysis was  
193 performed using a combination of the two factors (URG and LT, 6 combinations) as the  
194 explanatory variable. The significance of the composite factor (URG/LT) was tested using a  
195 Monte-Carlo permutation test (1000 permutations).

196 The effects of URG, LT, and their interaction (URGxLT) on each chemical, physical,  
197 and hydrological soil characteristics were then analyzed using ANOVA. Variables that were  
198 not normally distributed were log-transformed prior to analyses, except for the megaporosity  
199 (square root transformation), and pH (exponential transformation). Bulk density, saturation  
200 point, field capacity, and the available water storage capacity were not transformed.  
201 Combinations of the different factors were compared using multiple comparisons of means  
202 (Tukey's honest significant difference, multcomp package, Hothorn et al., 2008). The  
203 residuals were checked for spatial autocorrelation using Moran's I correlogram (spdep  
204 package; Bivand, 2012). Since the Moran's I values (permutation test, n=1000) were never  
205 significant, the autocorrelation term was not included in models.

## 206 **3- Results**

### 207 *3.1- Chemical, physical and hydrostructural soil typology of the Paris region*

208 The clay content was low in all the samples analyzed: soil texture ranged from sand to  
209 silt loam (Fig. 2). The urban forest soils exhibited a specific textural pattern when compared  
210 to soils of other land-use types, which were relatively homogeneous. The urban forest soils  
211 were generally classified as sandy loam, whilst the other sites were loamy soils (Fig. 2).

212 The between-group analysis performed on the chemical, physical and hydrostructural  
213 variables, grouped as a function of the URG and LT, explained 19.94% of the total variance  
214 (Fig. 3). A Monte-Carlo permutation test showed that the URG and LT significantly affected  
215 the chemical, physical and hydrostructural soil characteristics ( $P = 0.001$ ). The first and  
216 second axes of the between-group analysis ordination accounted for 65.42% and 24.47% of  
217 the variance, respectively. The organic carbon, total nitrogen, coarse sand concentrations and  
218 macroporosity positively contributed to axis 1, while clay and mesoporosity contributed  
219 negatively. Axis 1 discriminated urban forest soils from all the other soils. The bulk density  
220 and megaporosity were the main explanatory variables in the discrimination of the LT along  
221 Axis 2.

222

### 223 *3.2- Effects of land-use types and urban-rural gradient on chemical, physical, and* 224 *hydrostructural soil characteristics*

225 The URG, LT and their interaction had a significant impact on all chemical, physical,  
226 and hydrostructural variables. However, no factor significant affected the saturation point. In  
227 addition, URG had no effect on the pH, and LT had no effect on the cation exchange capacity.  
228 Neither LT nor URGxLT had a significant effect on the proportion of fine sand. Finally,  
229 URGxLT showed no effect on the permanent wilting point and the microporosity (Table 1).

230 Multiple comparisons of means showed that the effect of URGxLT on chemical,  
231 physical, and hydrostructural variables was mainly due to the differences between the urban



232 forests and all other types of sites. Urban forest exhibited either the highest (organic carbon  
233 concentration, total nitrogen, cation exchange capacity, carbonate, coarse sand, soil organic  
234 carbon stock and macroporosity) or the lowest (coarse silt, the fine silt, the clay, the field  
235 capacity, the mesoporosity, the microporosity and the available water storage capacity)  
236 measured values for most of the studied variables. In addition, urban lawns had higher coarse  
237 silt concentrations than the suburban forests. The C/N ratio was the lowest in the rural lawns,  
238 and the other kinds of sites showed no difference. Suburban lawns were significantly more  
239 alkaline than all of the forest sites. Total phosphorus increased from rural to urban areas in  
240 forests. The urban forests and all lawn types had higher total phosphorus concentrations than  
241 rural forests. The megaporosity showed a specific pattern with a lower value in the urban  
242 lawns than in all other sites. Finally, bulk density was highest in urban lawn soils, and lowest  
243 in suburban forest soils, with an intermediate value in suburban lawn soils (See Fig. 4-5,  
244 Table A.2, Fig. A.1-A.2).

245

## 246 **4- Discussion**

### 247 *4.1- Impact of urban-rural gradient on forest topsoil characteristics*

248 The higher organic carbon, the higher total nitrogen and the lower pH in forest soils  
249 compared to lawn soils may be partially due to differences between the two vegetation types.  
250 Indeed, the high inputs of tree leaf litter can lead to acidification and an accumulation of  
251 organic carbon and nitrogen in forest soils (Rout and Gupta, 1989). It is widely recognized  
252 that forest soils accumulate more organic matter than the other temperate terrestrial  
253 ecosystems, especially in topsoil (Guo et al., 2002; Innangi et al., 2017). However, this does  
254 not explain the differences between the urban forest soils and the suburban and rural forest  
255 soils. A possible explanation may be related to the age of the green spaces. Indeed, urban  
256 forests existed long before the other green spaces (see Fig. A.3). Urban forests are all that  
257 remains of the old “forest of Rouvray” that surrounded “Lutèce” in the Gallo-Roman era,

258 while all the other kinds of sites were established after 1950 (IAU, 2013). Consequently, the  
259 higher organic matter concentration (SOM) found in urban forest soils than in other forests  
260 and in lawns could be simply due to a longer accumulation of organic matter.

261         These soils were also subjected to a longer period of exposure to urban conditions and  
262 anthropogenic chemical inputs, *e.g.* incomplete combustion of fossil fuel or biomass, which  
263 may have affected the composition of SOM and enhanced its recalcitrance to decomposition  
264 (Marschner et al., 2008; Schmidt et al., 2011). In addition, the higher concentrations of trace  
265 elements found in urban forest soils compared to the other sites (Foti et al., 2017) could also  
266 be influential. When they are in excess, trace elements can induce a change in soil microbial  
267 community structure and activity, and thus in C utilization (Moynahan et al., 2002; Kandeler  
268 et al., 2008; Chen et al., 2014). This can cause a reduction in SOM decomposition rate (Bian  
269 et al., 2015). Furthermore, the shading effects of the tree canopy on soil temperature may  
270 result in urban lawn topsoil being hotter than that of urban forests (Hamada and Ohta, 2010).  
271 Thus, SOM decomposition may be higher in urban lawns than in urban forests since it is  
272 generally accepted that high temperatures stimulate soil respiration rates (Jandl et al., 2007).  
273 Nevertheless, the response of SOM decomposition to temperature is still a controversial  
274 subject, in particular because SOM pools with different recalcitrance have diverse sensitivities  
275 to temperature (Billings and Ballantyne, 2013). Anthropogenic carbon inputs, trace elements,  
276 and shading effects on soil temperature would lead to a higher SOM accumulation through  
277 time in urban forest soils compared to other land-use types in the three classes of urban  
278 pressure. It should be noted that the soil organic carbon stock of urban forest soils is 1.16  
279 times higher on average than the recorded regional means of natural forest soils (Saby et al.,  
280 2014), which is consistent with our results.

281         Besides showing the highest SOM concentrations, urban forests showed the highest  
282 carbonate concentrations. This could also be explained by their long exposure to urban  
283 conditions, especially to the construction waste materials such as concrete and cement

284 (Washbourne et al., 2012). Indeed, a large proportion of calcium in urban soils comes from  
285 artificial calcium silicate and hydroxide minerals within concrete and cement by erosion  
286 through time (*e.g.* building erosion). This allows the formation of pedogenic carbonates by  
287 carbonation reaction (Jorat et al., 2015).

288 Urban forests also showed a sandy loam texture, while the texture of the soils of the  
289 other forests and lawns was loamy. This is probably due to the fact that the soils of the two  
290 main urban forests sampled, the Bois de Boulogne and Vincennes, were formed from  
291 Carbonaceous alluvial deposits and Tertiary quartz sand (Fig. A.4). Thus, the high coarse sand  
292 and the low clay concentrations of urban forest soils likely explain the relatively high  
293 macroporosity and the smaller mesoporosity and microporosity (FitzPatrick, 2012). In the  
294 same way, the high coarse sand concentration of urban forest soils, linked to the geological  
295 origin of these soils, should explain their low available water storage capacity. Given the  
296 relatively similar textures in non-urban forests and all lawns (*e.g.* loamy soils), these sites  
297 have similar water storage capacities. Nevertheless, the available water storage capacity of  
298 urban forest soils is within the normal range of values recorded in the forest soils of the region  
299 (from the national network monitoring of the soil quality data base – RMQS). Note that  
300 despite the lower clay content, urban forests tended to have higher cation exchange capacity  
301 than other types of sites, which is probably due to their high organic carbon concentration  
302 (Christensen 1996; McCauley et al., 2009). In addition, the higher organic carbon  
303 concentration found in urban forests may also explain their lower bulk density compared to  
304 the urban lawns. Indeed, organic carbon is known to improve soil aggregation (*i.e.* increasing  
305 of total pore space) and to lower the degree of soil compaction (Leroy et al., 2008).

306 The historical and present day soil management practices of the Paris region have also  
307 probably influenced soil characteristics. Local urban forests, and particularly the sampled  
308 Bois de Boulogne and Bois de Vincennes, have undergone profound restructuration during the  
309 Haussmann period, from 1852 to 1870, when Paris and its green spaces were refurbished

310 (Gandy, 1999, Forrest and Konijnendijk, 2005). At this time, market garden soils at the  
311 periphery of Paris were seen as particularly fertile with their sandy texture, high organic  
312 carbon, high total nitrogen, and with high total phosphorus soil concentrations. Thus, using  
313 these soils was probably seen as a cheap way to reorganize urban green spaces, among which  
314 the Bois de Boulogne and Vincennes: some market garden soils were turned into forests as  
315 recreation areas for the city dwellers (Nold, 2011; Paris Green Space and Environmental  
316 Division – DEVE, pers. comm.). The soil of market gardens had often been translocated to  
317 new green spaces.

318         Furthermore, during this period, wastewater was considered as a very efficient mean  
319 of fertilization and has been used, probably in large quantities, to irrigate urban public green  
320 spaces and urban and non-urban market gardens (Moreau et al., 1846, Barles, 1999). This  
321 irrigation practice was applied to urban public green spaces until 1950, in parts of the Bois de  
322 Boulogne and Bois de Vincennes (DEVE, pers. comm.). Moreover, the application of  
323 charcoal and liming was a common practice to increase soil fertility, and would have been  
324 also largely used in the urban market gardens of the region (DEVE, pers. comm., Museum of  
325 market gardening of the Paris region, pers. comm.). Consequently, the higher urban forest  
326 SOM concentration may also be partly explained by the legacy of the urban forest soil  
327 management, especially by charcoal and wastewater application. Indeed, it is widely  
328 recognized that charcoal C is resistant to biological soil decomposition due to its degree of  
329 aromatic condensation, which can lead to the accumulation of recalcitrant C over time  
330 (Skjemstad et al., 2002; Schmidt et al., 2011), and wastewater irrigation can lead to the long  
331 term organic matter accumulation in soils (Friedel et al., 2000). In addition, liming could  
332 explain the high carbonate concentration of urban forests, and both charcoal application and  
333 liming may explain their tendency to be slightly more alkaline than the other forests (Haynes  
334 and Naidu, 1998; Glaser et al., 2002).

335

336 4.2- *Impact of the urban-rural gradient on lawn topsoil characteristics*

337 As with the forest soils, the historical and present day practices of soil management  
338 should explain some of the topsoil characteristics of the lawns along the urban-rural gradient  
339 in the Paris region. Despite uncertainties about the history of green spaces, arable soils  
340 excavated during roadworks or construction have been resold as substrate for public green  
341 spaces since 1950 (Nold, 2011; Paris Green Space and Environmental Division – DEVE, pers.  
342 comm.). Furthermore, the quality of these soils is constrained since 2004 by the NF U 44-551  
343 standard that imposes strict ranges for the main soil properties (*e.g.* texture, C and N contents,  
344 etc.). Thus, these practices and the creation of the urban and suburban public green spaces  
345 from 1950 onwards have likely led in the three categories of lawns to relatively homogenous  
346 soils and of their chemical and physical characteristics (*e.g.* organic carbon, total nitrogen,  
347 total phosphorus, carbonates and texture). Furthermore, the urban and suburban lawns of the  
348 region tended to have lower organic carbon and total nitrogen soil concentrations than rural  
349 lawns and all types of forests. The mowing regime is more intensive, *i.e.* up to 15 cuts per  
350 year, in urban and suburban than in rural lawns and the mowed biomass is always exported  
351 (DEVE, pers. comm.). This type of management can explain the lower organic carbon and  
352 total nitrogen concentrations in urban and suburban lawn soils (Hassink, 1994). It should be  
353 noted that lawn soils have carbon contents 1.51 times lower than the carbon content of  
354 agricultural soils of the region (Saby et al., 2014) from which they stem. This suggests that  
355 these soils have lost carbon since they have been imported into urban green spaces.

356 The phosphorus fertilization of lawns was until recently common practice in the Paris  
357 region (*e.g.* monoammonium and diammonium phosphate DEVE, pers. comm.), which can  
358 cause phosphorus accumulation in soils when applied in excess (Carpenter et al., 1998). This  
359 likely explains the high phosphorus concentrations observed in the urban and suburban lawn  
360 soils when compared to the rural and suburban forests, and the similar concentrations  
361 observed in urban forests. Moreover, since human activities increase from the rural to the

362 urban area, atmospheric P deposition to soils likely follows this trend, which can contribute to  
363 the observed phosphorus concentration trend. Indeed, fuel combustion such as fossil fuel,  
364 biomass burning, or biofuels is recognized to release phosphorus that is then deposited by dry  
365 and wet deposition (Mahowald et al., 2008).

366 Urban green spaces provide city dwellers with an accessible connection with nature  
367 (Miller, 2005). This depends, among other things, on the distance between the place of  
368 residence and green spaces that is often mentioned as the most crucial determinant of the  
369 frequency of green space visits (Bertram et al., 2017). In a city with a high population density  
370 such as Paris (21 067 inhabitant km<sup>-2</sup>; INSEE, 2014), this means that the green space lawns  
371 are certainly subjected to high foot traffic, depending on the local human population density,  
372 resulting in compaction, the loss of the largest pores and an increase of the bulk density of the  
373 surface soils (Supuka et al., 2009). This is supported by the decrease we observed in  
374 megaposity and the increase in bulk density from rural to urban lawns.

375

#### 376 *4.3- Synthesis of underlying factors and study limits*

377 We have identified only one true effect of urbanization on topsoil: urbanization leads  
378 to high human densities in town centers, resulting in soil compaction in green spaces,  
379 especially urban lawns. The other effects we have detected do not pertain to urbanization *per*  
380 *se* but more to the history of soil management, the past land-uses and past soil uses.  
381 Furthermore, because soils have often been imported from the rural area, the local bedrock is  
382 likely to have much less influence on the green space topsoil characteristics, than the choice  
383 of soil type used for their construction and their subsequent management. Nevertheless, a part  
384 of urban forests grow on natural soils originating from sandy soils, which likely explains their  
385 textures. It remains difficult to accurately determine the relative influence of these different  
386 factors on topsoil characteristics, since the detailed chronology of soil management history of  
387 the Paris region, especially for urban forests, is not available. This should be clarified by

388 further historical research. Soil management history strongly depends on the age of green  
389 space creation in the region (Nold, 2011; DEVE, pers. comm.). Thus, comparing soils of  
390 green spaces of different ages should allow a better analysis of the consequences of soil  
391 management history on their characteristics, and their local evolution in green spaces of the  
392 Paris region.

393 The urban-rural gradient does not explain a high proportion of the variability found in  
394 the chemical, physical and hydrostructural soil characteristics (~ 20%). This suggests that  
395 other factors explaining their variability have not been taken into account. These  
396 characteristics might depend on the precise origin of imported soils that has probably changed  
397 over time and between the cities of the Paris region.

398 Finally, the trampling effect we have detected on the urban lawn topsoil has already  
399 been identified in many towns (Jim, 1998; Meuser, 2010) and is probably generalizable to  
400 most towns of the world. We can also expect to find the other types of effect we have  
401 identified in Paris region in most towns of the world because of the universality of soil  
402 manipulations in urban areas (*e.g.* textural homogenization; Salbitano et al., 2016). However,  
403 because towns have diverse histories that likely interact in complex ways with local soil  
404 contexts, the amplitude and direction of these effects cannot be predicted without local studies  
405 (Hazelton and Murphy, 2011). Nevertheless, in cities that have developed more recently, such  
406 as many cities in developing countries, the historical aspects are likely less influential for soil  
407 green space characteristics than in Paris.

408

## 409 **5- Conclusion**

410 Whilst the results presented here are consistent with those of the literature on urban  
411 soil characteristics, it was difficult to identify precisely the effect of urbanization on the soil  
412 characteristics. We identified only one true effect of urbanization on soils, which is the  
413 compaction phenomenon due to the high human densities in town centers, especially on urban

414 lawns. The other effects we have detected were not due to urbanization *per se* but more to the  
415 history of soil management, the past land-uses and past soil changes in the Paris region.

416 Taken together, our results suggest that studying urban soil can be misleading if urban  
417 and soil histories, and their consequences for soil characteristics, are not taken into account.  
418 Interpreting our results with more certainty would require better documenting each sampling  
419 site and, in particular, collecting data on the history and management of each lawn and each  
420 forest. Such an effort would probably also be useful for optimizing current soil management  
421 in towns and the ecosystem services they provide. For example, our results suggest that urban  
422 forests may have stored a large quantity of carbon in their topsoil layer, but the mechanisms  
423 behind this storage of carbon remain to be thoroughly identified. Similarly, the implications of  
424 the mowing regime and the exportation of grass clippings for the long-term storage of carbon  
425 in lawn topsoil should be further studied. One of the shortcomings of our study is that we  
426 have only documented the 0-10 soil layers while, clearly, other patterns could emerge in  
427 deeper soil layers, and the provision of soil services also depends on soil functioning below  
428 10 cm.

429

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439



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Table 1- Effect of the Urban-Rural Gradient (URG), Land-use Types (LT), and their interactions (URGxLT) on the chemical, physical and hydrostructural soil characteristics of the Paris region (OCS: *soil organic carbon stock*, OC: *organic carbon*, tot N: *total nitrogen*, tot P: *total phosphorus*, pH: *pH-H<sub>2</sub>O*, CEC: *Cation Exchange Capacity*, C/N ratio, CaCO<sub>3</sub>: *carbonates*, Clay, CSi and FSi: *coarse and fine silt*, CSa and FSa: *coarse and fine sand*, BD: *bulk density*,  $\theta_{0.7}$ : *saturation point*,  $\theta_{2.5}$ : *field capacity*, Meg: *megaporosity*, Mac: *macroporosity*, Mes: *mesoporosity*, AWS: *available water storage capacity*,  $\theta_{4.2}=\text{Mic}$ : *permanent wilting point=microporosity*). Results of linear models (degrees of freedom (df) (total residual df=174), F values) (\*p-value<0.05, \*\*p-value<0.01, \*\*\*p-value<0.001). All chemical, physical and hydrostructural soil variables were log-transformed, except Meg (square root) and pH (exponential). BD,  $\theta_{0.7}$ ,  $\theta_{2.5}$  and AWS were not transformed.

	URG	LT	URGxLT	R <sup>2</sup> adjusted
df	2	1	2	
<b>Chemical and physical soil characteristics</b>				
<b>OCS</b>	12.57***	15.71***	4.54**	0.20
<b>OC</b>	4.68*	29.52***	6.81**	0.21
<b>tot N</b>	5.64**	15.64***	10.09***	0.19
<b>tot P</b>	14.74***	21.23***	4.66*	0.23
<b>pH</b>	0.81	17.54***	3.88*	0.11
<b>CEC</b>	8.86***	0.23	7.00**	0.13
<b>C/N</b>	5.49**	15.15***	4.29*	0.14
<b>CaCO<sub>3</sub></b>	3.53*	5.23*	10.43***	0.14
<b>Clay</b>	7.12**	19.38***	8.21***	0.20
<b>CSi</b>	6.48**	31.21***	14.42***	0.27
<b>FSi</b>	5.17**	25.33***	7.56***	0.20
<b>CSa</b>	7.98***	6.00*	9.30***	0.17
<b>FSa</b>	3.48*	2.42	0.97	0.03
<b>BD</b>	9.64***	24.66***	8.93**	0.24
<b>Hydrostructural soil characteristics</b>				
<b><math>\theta_{0.7}</math></b>	0.54	0.01	2.30	0.004
<b><math>\theta_{2.5}</math></b>	8.70***	15.23***	5.84**	0.18
<b>Meg</b>	11.21***	18.76***	3.83*	0.20
<b>Mac</b>	10.13***	13.08***	7.84***	0.20
<b>Mes</b>	3.33*	18.16***	7.45***	0.16
<b>AWS</b>	3.17*	14.14***	6.34**	0.14
<b><math>\theta_{4.2}=\text{Mic}</math></b>	9.80***	11.19**	2.64	0.15

Table 1- Effect of the Urban-Rural Gradient (URG), Land-use Types (LT), and their interactions (URGxLT) on the chemical, physical and hydrostructural soil characteristics of the Paris region

	URG	LT	URGxLT	R <sup>2</sup> adjusted
df	2	1	2	
<b>Chemical and physical soil characteristics</b>				
<b>OCS</b>	12.57***	15.71***	4.54**	0.20
<b>OC</b>	4.68*	29.52***	6.81**	0.21
<b>tot N</b>	5.64**	15.64***	10.09***	0.19
<b>tot P</b>	14.74***	21.23***	4.66*	0.23
<b>pH</b>	0.81	17.54***	3.88*	0.11
<b>CEC</b>	8.86***	0.23	7.00**	0.13
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<b>CaCO<sub>3</sub></b>	3.53*	5.23*	10.43***	0.14
<b>Clay</b>	7.12**	19.38***	8.21***	0.20
<b>CSi</b>	6.48**	31.21***	14.42***	0.27
<b>FSi</b>	5.17**	25.33***	7.56***	0.20
<b>CSa</b>	7.98***	6.00*	9.30***	0.17
<b>FSa</b>	3.48*	2.42	0.97	0.03
<b>BD</b>	9.64***	24.66***	8.93**	0.24
<b>Hydrostructural soil characteristics</b>				
<b>θ<sub>0.7</sub></b>	0.54	0.01	2.30	0.004
<b>θ<sub>2.5</sub></b>	8.70***	15.23***	5.84**	0.18
<b>Meg</b>	11.21***	18.76***	3.83*	0.20
<b>Mac</b>	10.13***	13.08***	7.84***	0.20
<b>Mes</b>	3.33*	18.16***	7.45***	0.16
<b>AWS</b>	3.17*	14.14***	6.34**	0.14
<b>θ<sub>4.2</sub>=Mic</b>	9.80***	11.19**	2.64	0.15

**Results of linear models (degrees of freedom (df) (total residual df=174), F values) (\*p-value<0.05, \*\*p-value<0.01, \*\*\*p-value<0.001). All chemical, physical and hydrostructural soil variables were log-transformed, except Meg (square root) and pH (exponential). BD, θ<sub>0.7</sub>, θ<sub>2.5</sub> and AWS were not transformed.**

(**OCS**: soil organic carbon stock, **OC**: organic carbon, **tot N**: total nitrogen, **tot P**: total phosphorus, **pH**: pH-H<sub>2</sub>O, **CEC**: Cation Exchange Capacity, **C/N ratio**, **CaCO<sub>3</sub>**: carbonates, **Clay**, **CSi** and **FSi**: coarse and fine silt, **CSa** and **FSa**: coarse and fine sand, **BD**: bulk density, **θ<sub>0.7</sub>**: saturation point, **θ<sub>2.5</sub>**: field capacity, **Meg**: megaporosity, **Mac**: macroporosity, **Mes**: mesoporosity, **AWS**: available water storage capacity, **θ<sub>4.2</sub>=Mic**: permanent wilting point=microporosity)

1 Fig. 1- Map of the sampled sites (n=180) located between 48°07'N, 1°35'E and 49°07'N,  
2 3°26'E in the Île-de-France region around Paris City. Department delineation is displayed (75:  
3 Paris, 77: Seine et Marne, 78: Yvelines, 91: Essonne, 92: Hauts-de-Seine, 93: Seine-Saint-  
4 Denis, 94: Val de Marne, 95: Val d'Oise) in the whole Île-de-France region (left) or in urban  
5 area (right). RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural forests, SF:  
6 suburban Forests, UF: urban forests.

7  
8 Fig. 2- Ternary textural diagram (Davis and Bennett, 1927) of the lawn and forest soils in  
9 rural, suburban and urban areas of the Paris region. Labels of the gravity centers correspond  
10 to rural lawns (RL), suburban lawns (SL), urban lawns (UL), rural forests (RF), suburban  
11 forests (SF) and urban forests (UF).

12  
13 Fig. 3- Between-group analysis on the chemical, physical and hydrostructural soil  
14 characteristics of the Paris region with the composite factor URGxLT as explanatory variable.  
15 (a) Correlation circle plot with the soil characteristic vectors (OC: *organic carbon*, tot N: *total*  
16 *nitrogen*, tot P: *total phosphorus*, pH: *pH-H<sub>2</sub>O*, CEC: *cation exchange capacity*, CaCO<sub>3</sub>:  
17 *carbonates*, Clay, CSa and FSa: *coarse and fine sand*, FSi: *fine silt*, BD: *bulk density*, Meg:  
18 *megaporosity*, Mac: *macroporosity*, Mes: *mesoporosity*, Mic: *microporosity*). (b) Projection  
19 of the sampled soils on the factorial map of the first two discriminating axes according to the  
20 combination of URG (Urban-Rural Gradient) and LT (Land-use Type). Labels of the gravity  
21 centers: rural lawns (RL), suburban lawns (SL), urban lawns (UL), rural forests (RF),  
22 suburban forests (SF) and urban forests (UF). Eigen values were 65.42% and 24.47% for axes  
23 1 and 2 respectively. The combination of URGxLT explained 19.94% of the variance  
24 (permutation test, p-value = 0.001).

25  
26 Fig. 4- Mean values of the (a) textural and (b) chemical and physical soil characteristics of  
27 lawn and forest soils in rural, suburban and urban areas of the Paris region. (OC: *organic*

28 *carbon*, tot N: *total nitrogen*, tot P: *total phosphorus*, pH: *pH-H<sub>2</sub>O*, CEC: *cation exchange*  
29 *capacity*, C/N ratio, CaCO<sub>3</sub>: *carbonates*, Clay, CSi and FSi: *coarse and fine silt*, CSa and FSa:  
30 *coarse and fine sand*, BD: *bulk density*). RL: rural lawns, SL: suburban lawns, UL: urban  
31 lawns, RF: rural forests, SF: suburban forests, UF: urban forests. Error bars represent standard  
32 errors. Letters indicate significant differences between means.

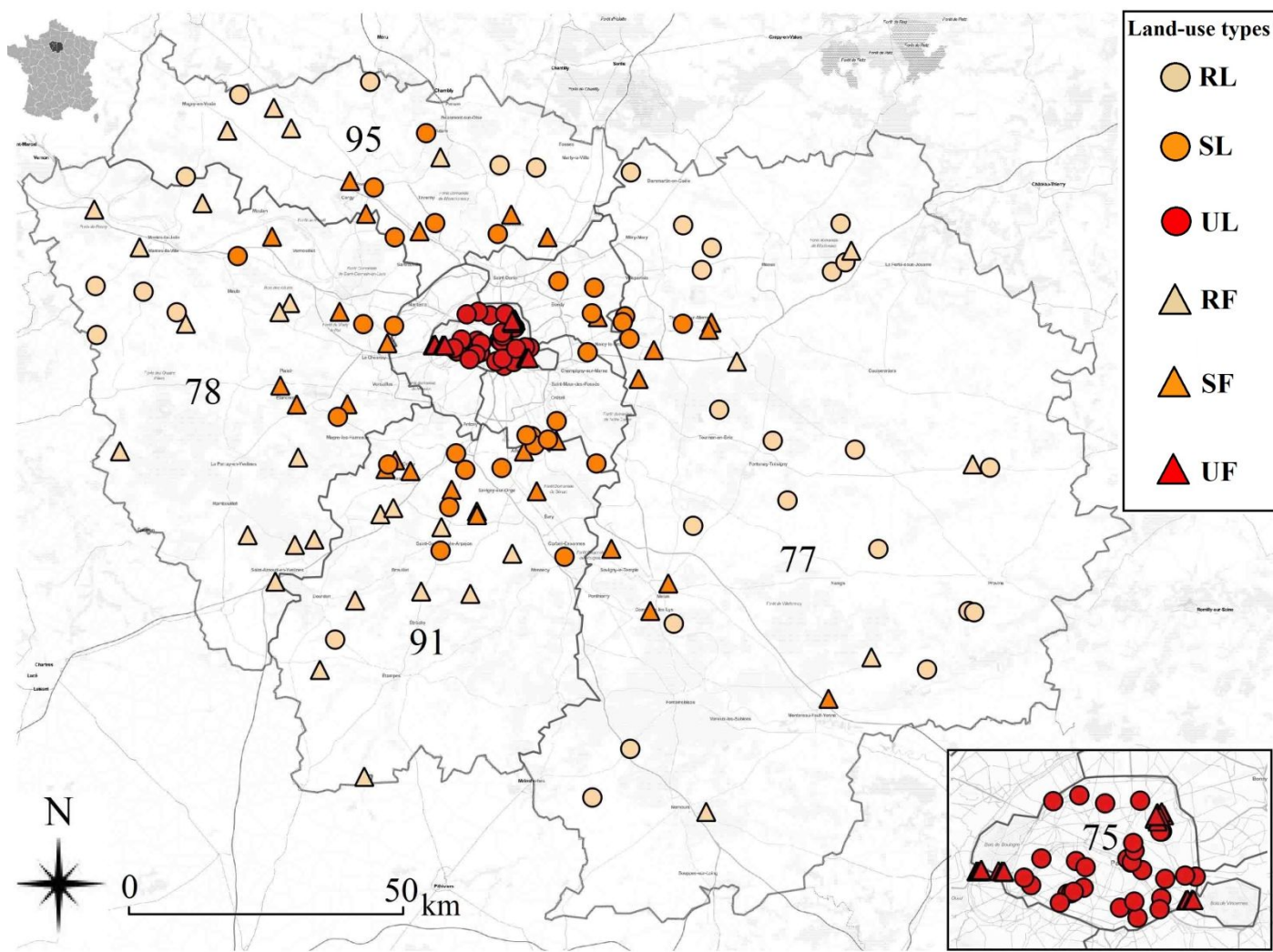
33

34 Fig. 5- Mean values of the hydrostructural soil characteristics of forest and lawn soils in rural,  
35 suburban and urban areas of the Paris region. (megaporosity, macroporosity, mesoporosity,  
36 and microporosity). RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural forests,  
37 SF: suburban forests, UF: urban forests. Error bars represent standard errors. Letters indicate  
38 significant differences between means.

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40 Fig. 1

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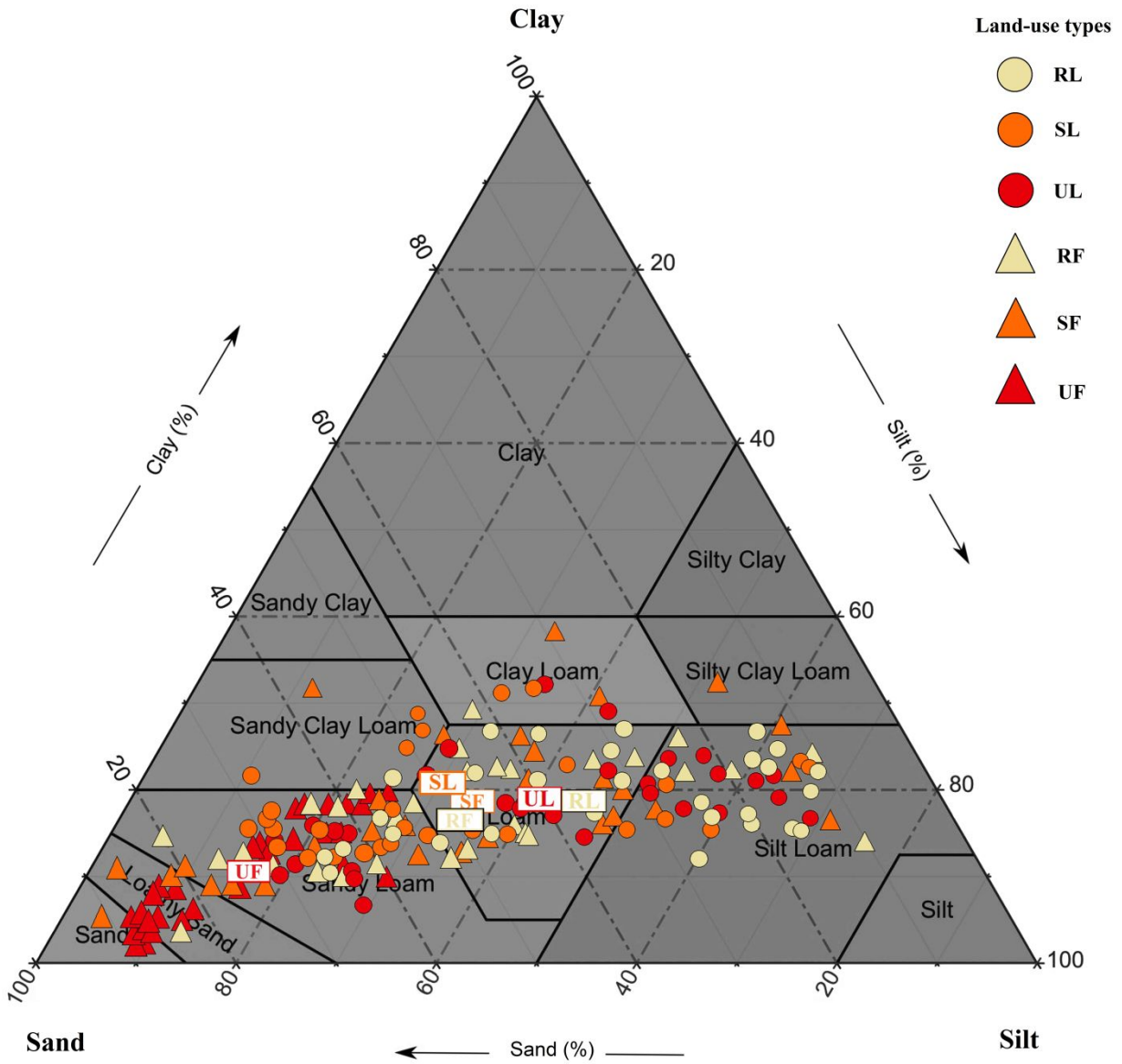
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Fig. 2



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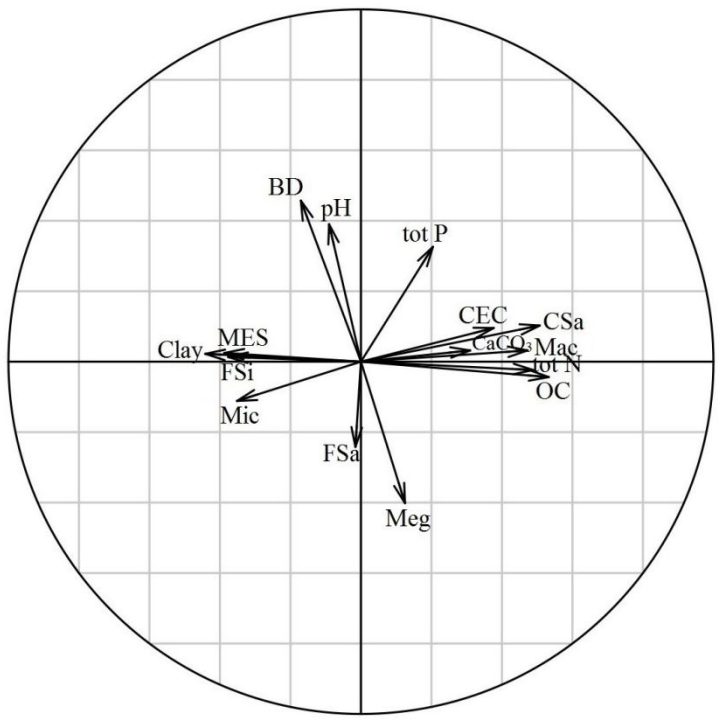
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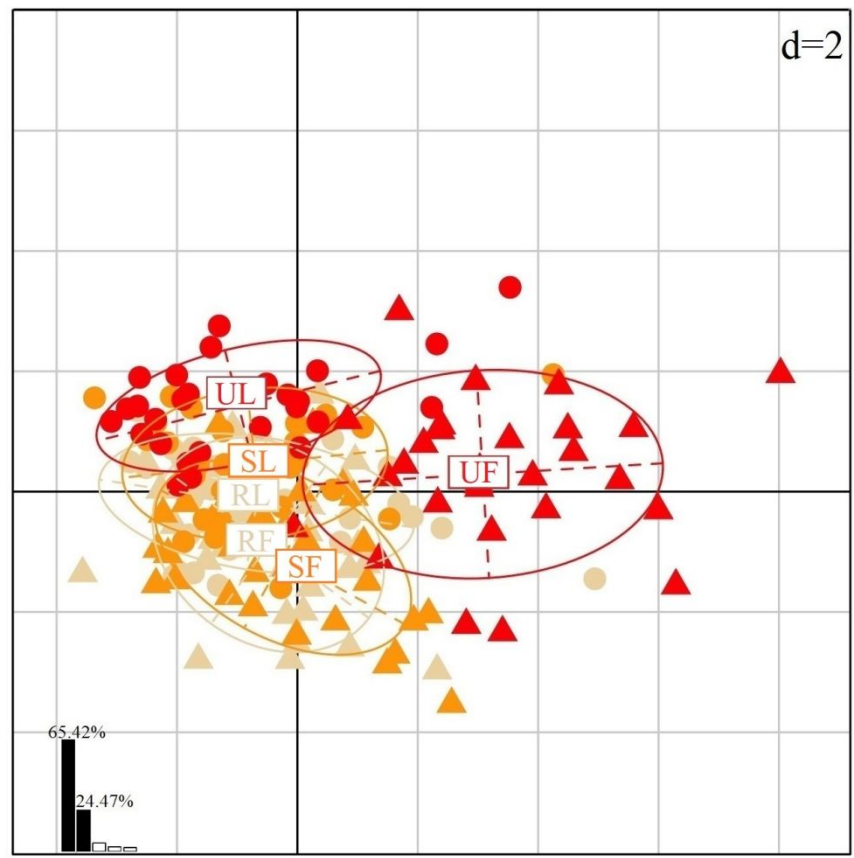
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a)



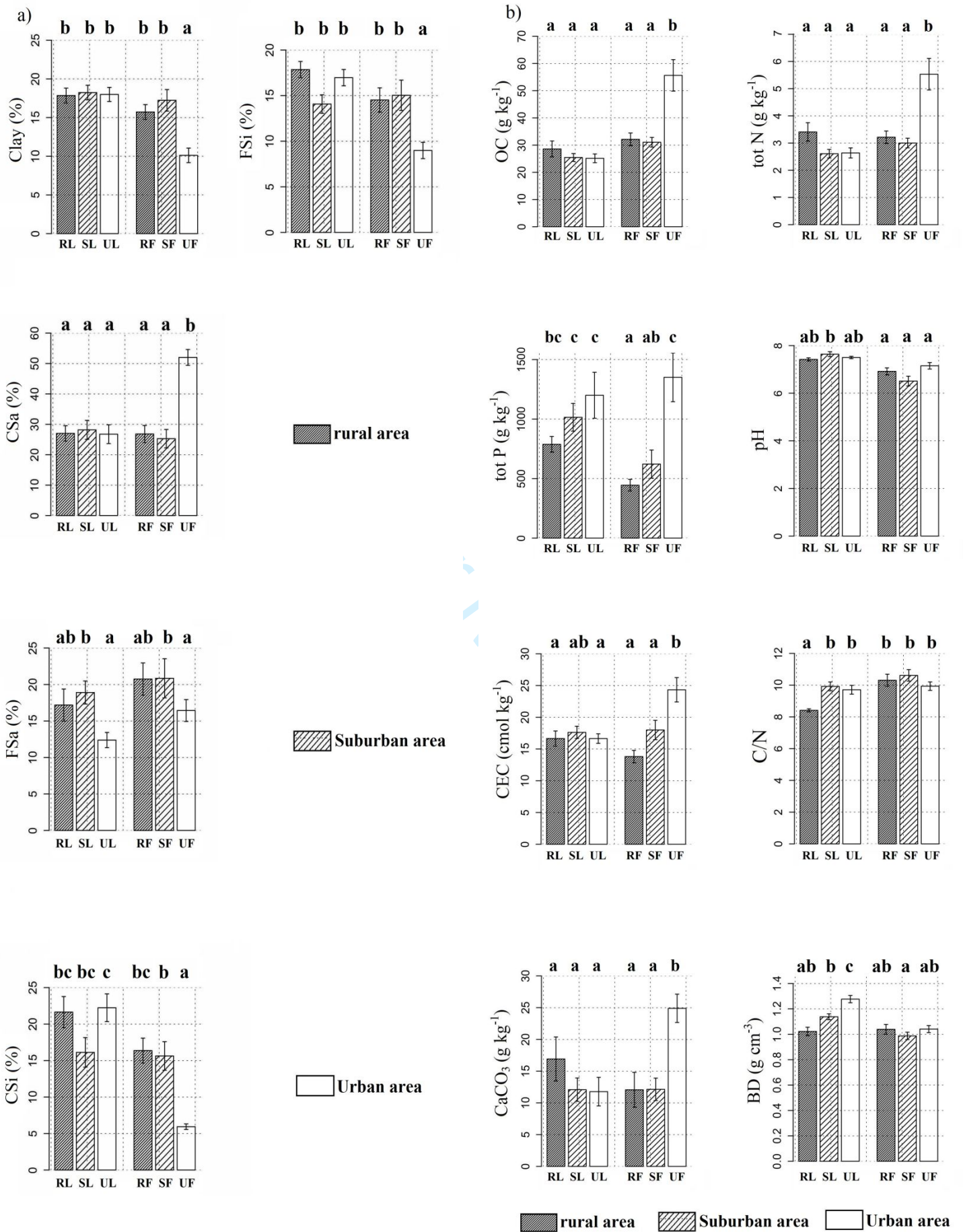
b)



Land-use types

- RL
- SL
- UL
- △ RF
- △ SF
- ▲ UF

Fig. 4





120 Fig. 5

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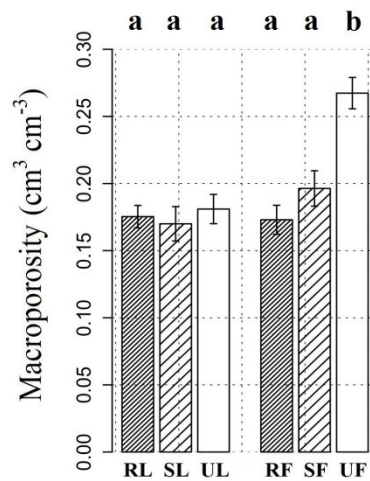
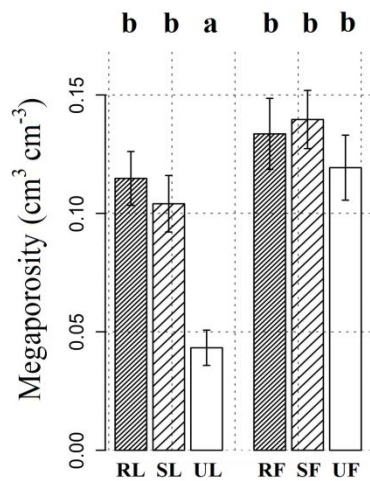
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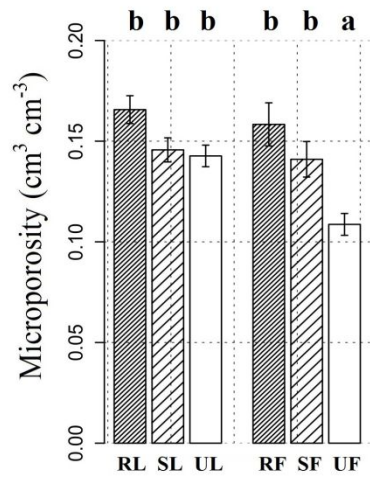
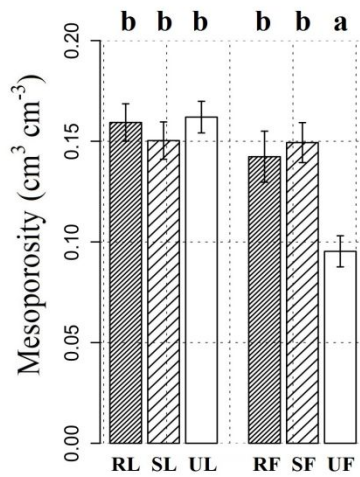
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137 Rural area Suburban area Urban area

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1 Fig. 1- Map of the sampled sites (n=180) located between 48°07'N, 1°35'E and 49°07'N,  
2 3°26'E in the Île-de-France region around Paris City.

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4 Fig. 2- Ternary textural diagram (Davis and Bennett, 1927) of the lawn and forest soils in  
5 rural, suburban and urban areas of the Paris region.

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7 Fig. 3- Between-group analysis on the chemical, physical and hydrostructural soil  
8 characteristics of the Paris region with the composite factor URGxLT as explanatory variable.

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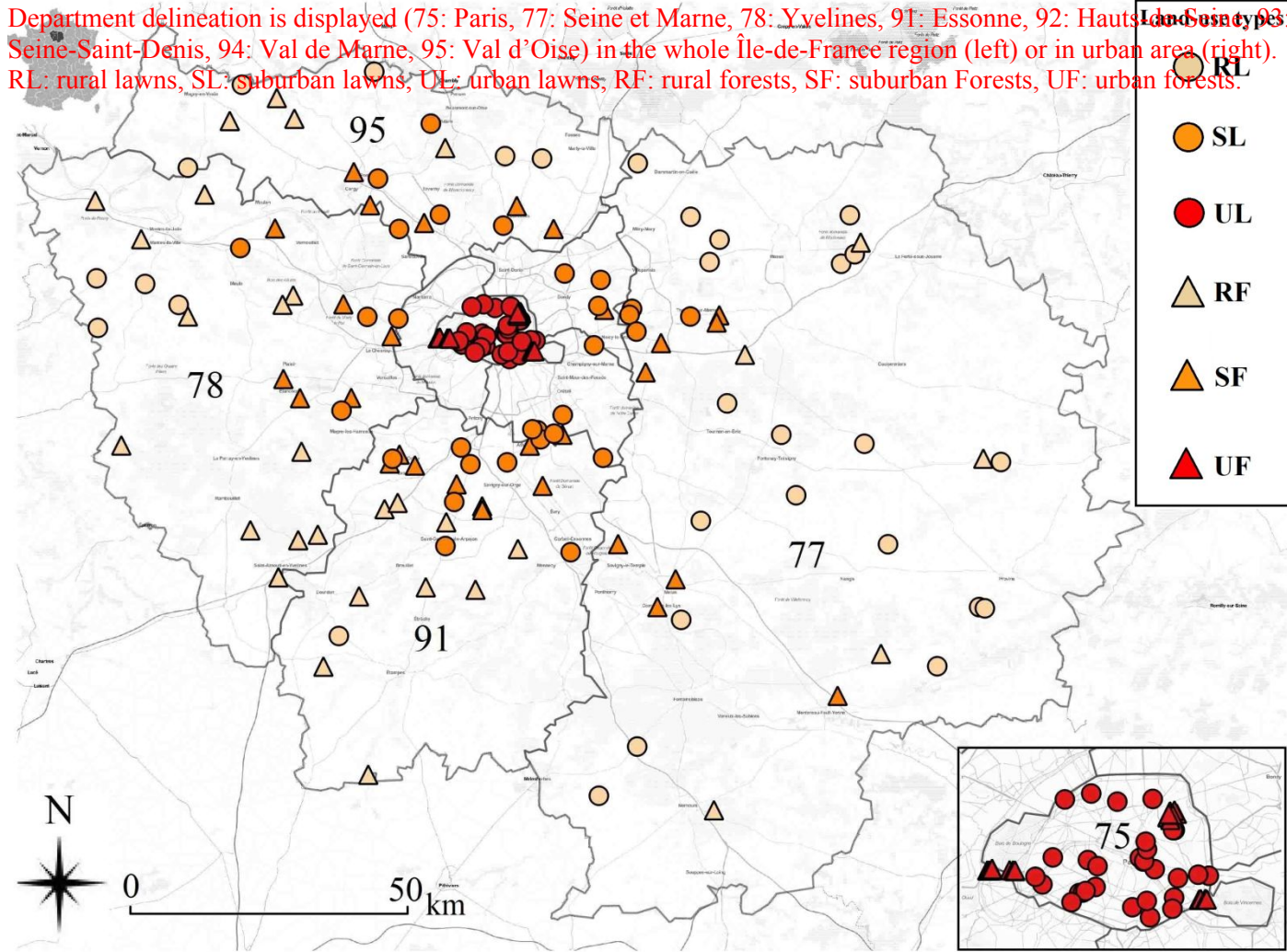
10 Fig. 4- Mean values of the (a) textural and (b) chemical and physical soil characteristics of  
11 lawn and forest soils in rural, suburban and urban areas of the Paris region.

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13 Fig. 5- Mean values of the hydrostructural soil characteristics of forest and lawn soils in rural,  
14 suburban and urban areas of the Paris region.

15 Fig. 1

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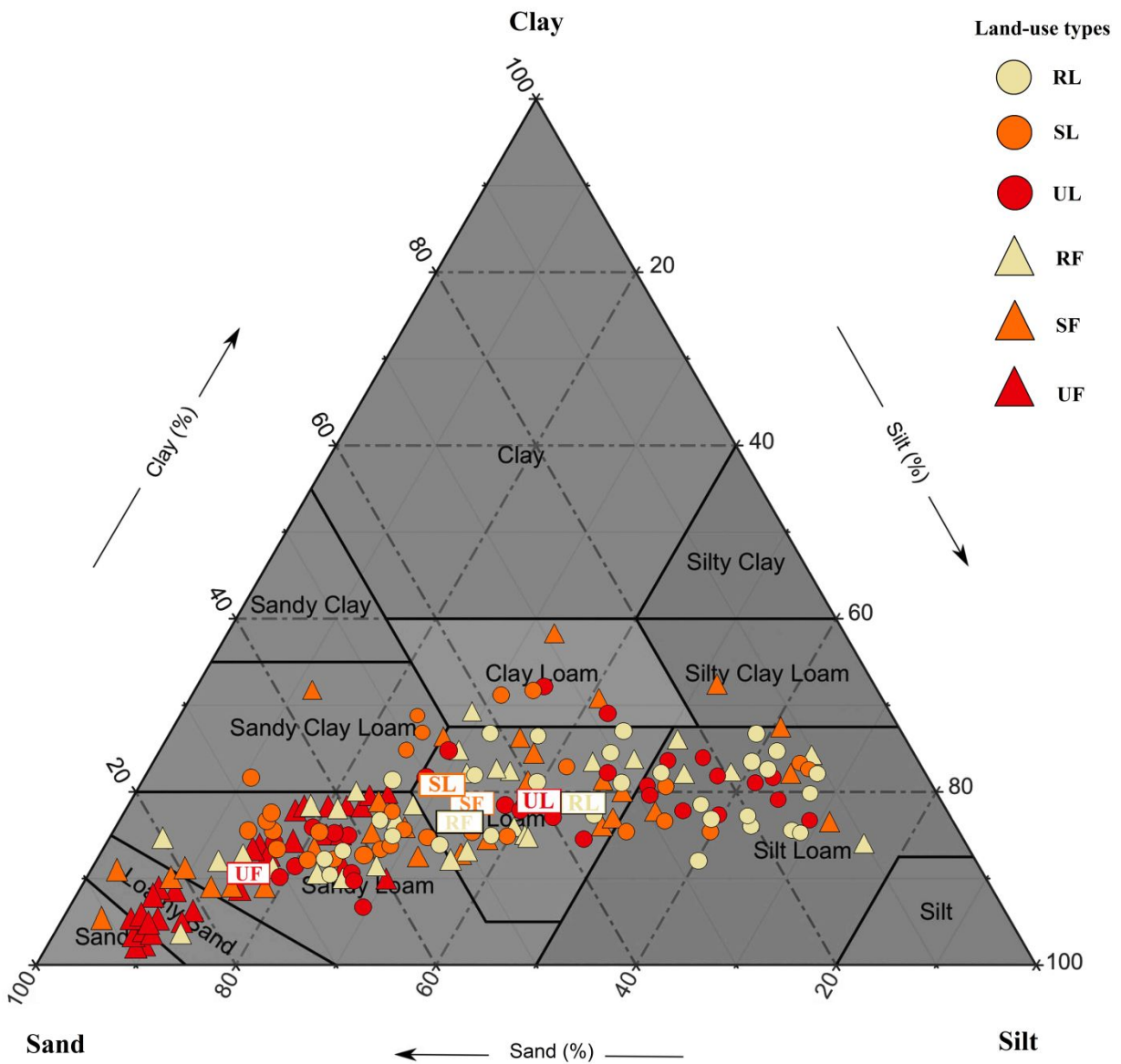
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Fig. 2



Labels of the gravity centers correspond to rural lawns (RL), suburban lawns (SL), urban lawns (UL), rural forests (RF), suburban forests (SF) and urban forests (UF).

49 Fig. 3

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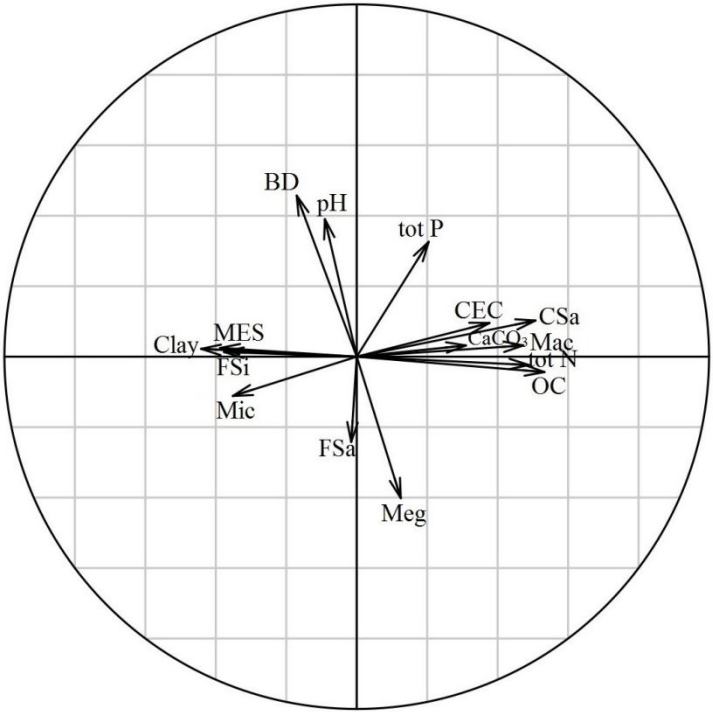
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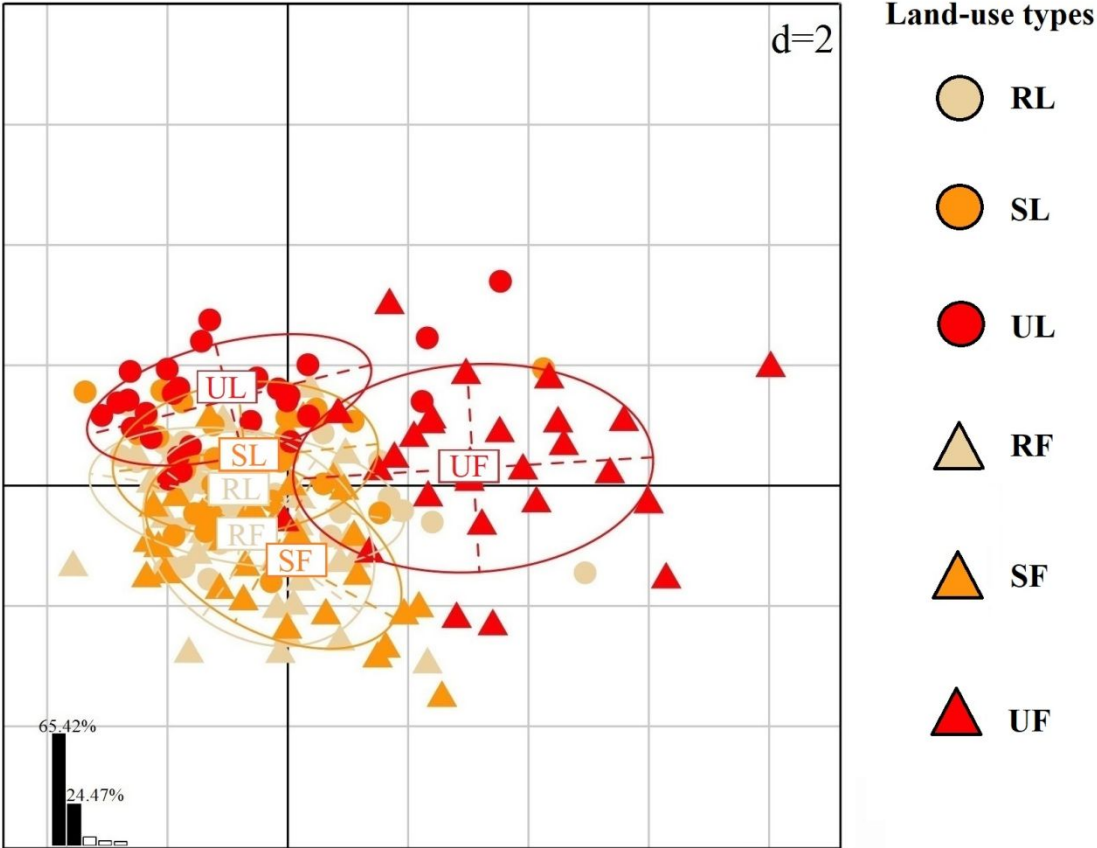
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a)



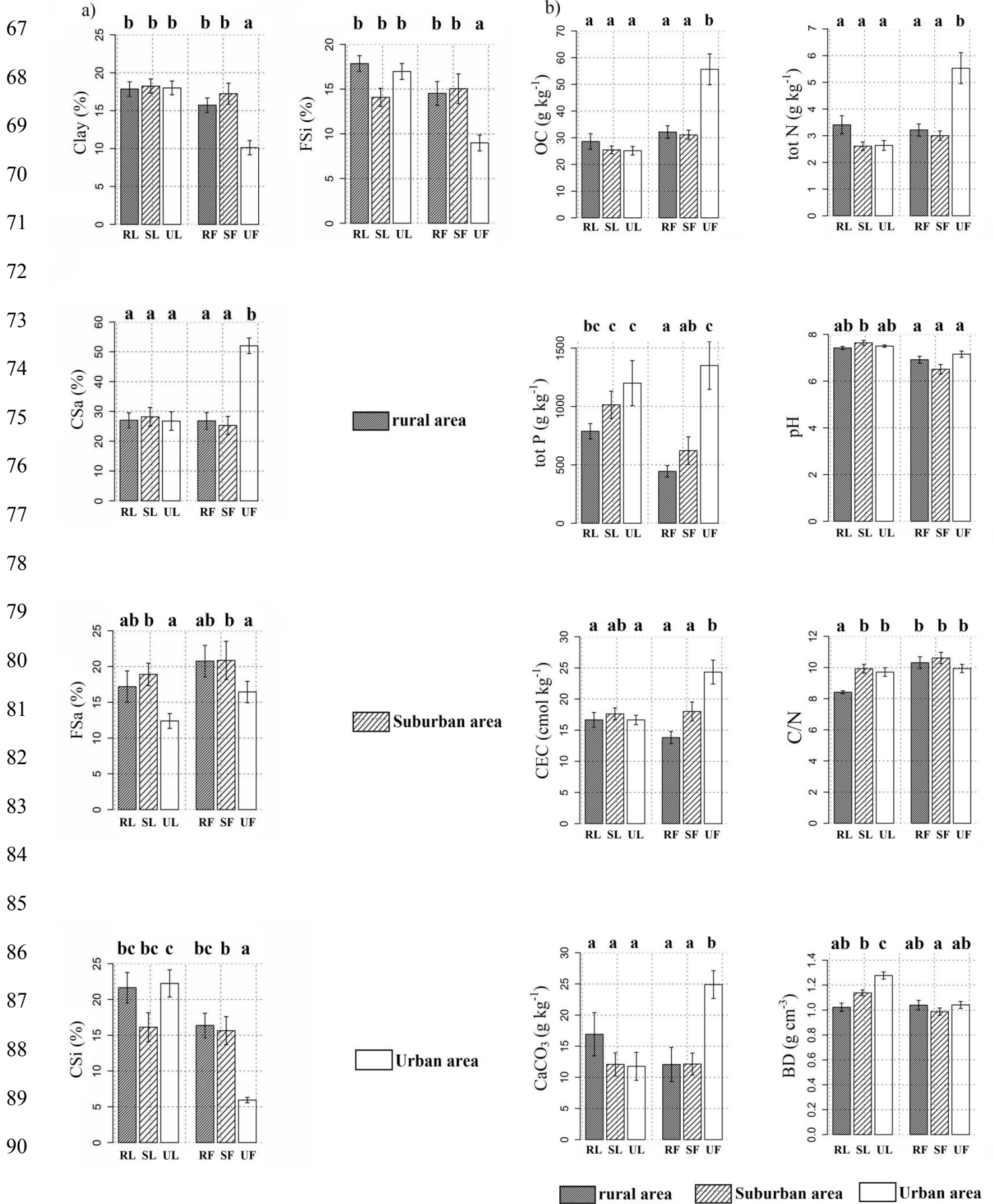
b)



64 (a) Correlation circle plot with the soil characteristic vectors (**OC**: organic carbon, **tot N**: total nitrogen, **tot P**: total phosphorus, **pH**: pH-H<sub>2</sub>O, **CEC**: cation exchange capacity, **CaCO<sub>3</sub>**: carbonates, **Clay**, **CSa** and **FSa**: coarse and fine sand, **FSi**: fine silt, **BD**: bulk density, **Meg**: megaporosity, **Mac**: macroporosity, **Mes**: mesoporosity, **Mic**: microporosity).

65 (b) Projection of the sampled soils on the factorial map of the first two discriminating axes according to the combination of URG (Urban-Rural Gradient) and LT (Land-use Type). Labels of the gravity centers: rural lawns (RL), suburban lawns (SL), urban lawns (UL), rural forests (RF), suburban forests (SF) and urban forests (UF). Eigen values were 65.42% and 24.47% for axes 1 and 2 respectively. The combination of URGxLT explained 19.94% of the variance (permutation test, p-value = 0.001).

66 Fig. 4



OC: organic carbon, tot N: total nitrogen, tot P: total phosphorus, pH: pH-H<sub>2</sub>O, CEC: cation exchange capacity, C/N ratio, CaCO<sub>3</sub>: carbonates, Clay, CSi and FSi: coarse and fine silt, CSa and FSa: coarse and fine sand, BD: bulk density.

RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural forests, SF: suburban forests, UF: urban forests. Error bars represent standard errors. Letters indicate significant differences between means.

91 Fig. 5

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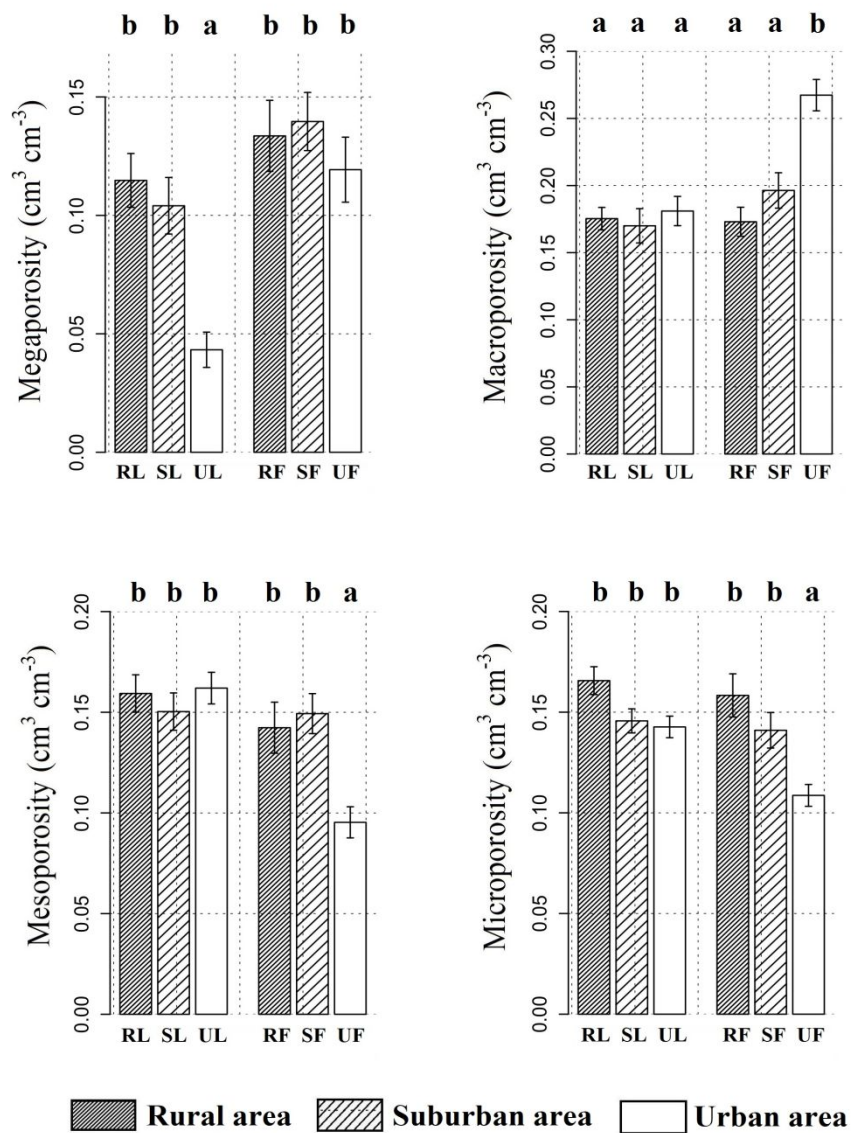
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RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural forests, SF: suburban forests, UF: urban forests. Error bars represent standard errors. Letters indicate significant differences between means.

Table A.1- Physical, chemical and hydrostructural soil characteristics, code, equations, units and standards.

	Parameters	Codes	Equation	Units	Standards
	Composite soil sample preparation	–	–	–	NF ISO 11464 standard
Physical and chemical soil characteristics	Coarse Silt	CSi			
	Fine Silt	FSi			
	Coarse Sand	CSa	–	%	NF X 31-107 standard
	Fine Sand	FSa			
	Clay (<2 µm)	Clay			
	Total Phosphorus	tot P	–	mg kg <sup>-1</sup>	NF ISO 10694 standard
	Organic Carbon	OC			NF ISO 14235 standard
	Total Nitrogen	tot N	–	g kg <sup>-1</sup>	NF ISO 13878 standard
	pH–H <sub>2</sub> O	pH			
	Cation Exchange Capacity	CEC	–	cmol kg <sup>-1</sup>	NF X 31-130 standard
C/N ratio	C/N	$C/N_{(n)} = OC_{(n)}/totN_{(n)}$	–	–	
Carbonates	CaCO <sub>3</sub>	–	g kg <sup>-1</sup>	NF ISO 10693 standard	
Bulk Density	BD	${}^aBD_{(n)} = M_{t(n)}/V_{t(n)}$	g cm <sup>-3</sup>		
Hydrostructural soil characteristics	Saturation point	θ0.7	${}^bθ0.7_{(n)} = W0.7_{(n)} \times BD_{(n)}$		
	Field capacity	θ2.5	${}^bθ2.5_{(n)} = W2.5_{(n)} \times BD_{(n)}$		
	Total Porosity	TP	${}^cTP_{(n)} = 1 - BD_{(n)}/2.65$		
	Megaporosity	Meg	$MEG_{(n)} = TP_{(n)} - θ0.7_{(n)}$	cm <sup>3</sup> cm <sup>-3</sup>	
	Macroporosity	Mac	$MAC_{(n)} = θ0.7_{(n)} - θ2.5_{(n)}$		
	Mesoporosity	Mes	$MES_{(n)} = θ2.5_{(n)} - θ4.2_{(n)}$		
	Permanent wilting point= microporosity	θ4.2= Mic	${}^dθ4.2_{(n)} = W4.2_{(n)} \times BD_{(n)}$		
soil Organic Carbon Sock	OCS	${}^dOCS_{(n)} = 0.1 \times BD_{(n)} \times OC_{(n)}$	kg m <sup>-2</sup>		
Available Water Storage	AWS	${}^dAWS_{(n)} = (W2.5_{(n)} - W4.2_{(n)}) \times BD_{(n)} \times 10$	mm		

<sup>a</sup>M<sub>t</sub> is the total mass of each soil sample from the total wet mass and gravimetric water content of the aliquot at pF2.5 (matric potential: -33 kPa), and V<sub>t</sub> the total volume for each soil sample,

<sup>b</sup>W is the gravimetric water soil content,

<sup>c</sup>2.65 g cm<sup>-3</sup> is the constant particle density,

<sup>d</sup>For the top 10 cm of the organo-mineral soil layer.





9 range) of the topsoil of forests and lawns in urban, suburban and rural areas of the Paris region. (OCS: soil  
 10 organic carbon stock, OC: organic carbon, tot N: total nitrogen, tot P: total phosphorus, pH: pH-H<sub>2</sub>O, CEC:  
 11 cation exchange capacity, C/N ratio, CaCO<sub>3</sub>: carbonates, Clay, CSi and FSi: coarse and fine silt, CSa and FSa:  
 12 coarse and fine sand, BD: bulk density, θ<sub>0.7</sub>: saturation point, θ<sub>2.5</sub>: field capacity, Meg: megaporosity, Mac:  
 13 macroporosity, Mes: mesoporosity, AWS: available water storage capacity, θ<sub>4.2</sub>=Mic: permanent wilting  
 14 point=microporosity).



Chemical, physical, and hydrostructural soil characteristics	Rural area		Suburban area		Urban area		
	Lawns	Forests	Lawns	Forests	Lawns	Forests	
<b>OCS</b> (kg m <sup>-2</sup> )	2.74±0.18 (1.28–5.22)	3.25±0.21 (1.44–5.79)	2.85±0.15 (1.30–4.75)	3.00±0.15 (1.56–4.89)	3.14±0.17 (1.76–4.89)	5.68±0.60 (1.00–15.89)	
<b>OC</b> (g kg <sup>-1</sup> )	28.6±2.9 (12.7–92.3)	32.1±2.3 (14.6–77.7)	25.4±1.4 (10.6–43.3)	31.0±1.8 (12.9–56.3)	25.1±1.5 (12.3–51.5)	55.6±5.8 (9.3–146.9)	
<b>tot N</b> (g kg <sup>-1</sup> )	3.4±0.3 (1.4–10.4)	3.2±0.2 (1.3–5.5)	2.6±0.2 (1.1–4.47)	3.0±0.2 (0.9–5.2)	2.6±0.2 (1.1–6.5)	5.5±0.6 (1.1–16.6)	
<b>tot P</b> (mg kg <sup>-1</sup> )	787.9±65.5 (279.1–1923.2)	444.4±49.2 (103.4–1155.4)	1014.7±116.4 (441.5–2806.0)	621.7±118.0 (175.7–3402.4)	1199.9±193.0 (489.9–4862.8)	1351.1±205.3 (265.5–3997.3)	
<b>pH</b>	7.4±0.1 (6.6–8.0)	6.9±0.1 (4.6–7.9)	7.6±0.1 (6.7–9.7)	6.5±0.2 (4.1–7.9)	7.5±0.05 (7.0–8.0)	7.1±0.1 (5.0–7.8)	
<b>CEC</b> (cmol kg <sup>-1</sup> )	16.6±1.1 (5.8–35.6)	13.8±0.9 (4.9–24.1)	17.6±0.9 (8.5–29.9)	17.9±1.5 (5.4–35.8)	16.6±0.7 (9.7–24.4)	24.3±1.9 (8.6–56.5)	
<b>C/N</b>	8.41±0.09 (7.18–9.36)	10.30±0.37 (6.24–15.80)	9.92±0.27 (7.97–14.52)	10.61±0.36 (6.79–15.04)	9.70±0.27 (5.65–13.41)	9.93±0.26 (7.51–14.82)	
<b>CaCO<sub>3</sub></b> (g kg <sup>-1</sup> )	16.9±3.4 (1.4–69.1)	12.1±2.7 (1.0–69.4)	12.1±1.8 (1.6–37.5)	12.1±1.8 (3.3–38.7)	11.7±2.2 (4.2–49.5)	24.8±2.2 (10.2–57.3)	
<b>Clay</b> (%)	17.8±0.9 (9.8–26.6)	15.7±0.9 (3.7–27.3)	18.2±0.9 (8.7–29.8)	17.2±1.4 (4.6–34.1)	17.9±0.9 (9.9–30.0)	10.1±0.9 (1.7–18.5)	
<b>CSi</b> (%)	21.64±2.8 (5.0–44.9)	16.3±1.7 (2.2–42.2)	16.1±2.0 (1.6–42.3)	15.6±1.9 (1.9–44.2)	22.2±1.8 (5.5–44.6)	5.9±0.37 (3.1–11.1)	
<b>FSi</b> (%)	17.8±0.8 (10.9–29.1)	14.5±1.3 (3.9–32.8)	14.07±1.0 (5.1–29.8)	15.03±1.6 (1.8–46.9)	16.9±0.8 (9.3–24.5)	8.9±0.8 (3.4–20.1)	
<b>CSa</b> (%)	27.0±2.5 (2.7–58.7)	26.8±2.8 (5.5–61.3)	28.1±3.1 (4.8–59.8)	25.2±3.02 (2.8–69.2)	26.7±3.09 (8.1–59.3)	52.0±2.6 (26.4–74.6)	
<b>FSa</b> (%)	17.2±2.1 (6.1–47.8)	20.7±2.2 (3.1–47.0)	18.9±1.5 (6.3–42.6)	20.8±2.6 (4.9–54.7)	12.3±1.04 (4.0–30.4)	16.4±1.4 (5.0–35.6)	
<b>BD</b> (g cm <sup>-3</sup> )	1.02±0.03 (0.48–1.34)	1.03±0.03 (0.61–1.45)	1.13±0.02 (0.76–1.37)	0.98±0.02 (0.62–1.30)	1.27±0.03 (0.87–1.65)	1.04±0.02 (0.75–1.37)	
<b>Hydrostructural soil characteristics</b>	<b>θ<sub>0.7</sub></b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.50±0.01 (0.37–0.61)	0.47±0.01 (0.36–0.59)	0.46±0.01 (0.38–0.65)	0.48±0.01 (0.34–0.60)	0.48±0.01 (0.35–0.61)	0.48±0.01 (0.40–0.62)
	<b>θ<sub>2.5</sub></b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.32±0.01 (0.21–0.46)	0.30±0.01 (0.14–0.50)	0.29±0.01 (0.16–0.42)	0.29±0.01 (0.15–0.44)	0.30±0.01 (0.21–0.41)	0.22±0.01 (0.13–0.36)
	<b>Meg</b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.11±0.01 (0.002–0.22)	0.13±0.01 (0.012–0.35)	0.10±0.01 (0.001–0.27)	0.13±0.01 (0.02–0.38)	0.04±0.01 (0.001–0.12)	0.11±0.01 (0.001–0.23)
	<b>Mac</b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.17±0.01 (0.09–0.26)	0.17±0.01 (0.07–0.33)	0.17±0.01 (0.11–0.49)	0.19±0.01 (0.08–0.35)	0.18±0.01 (0.08–0.32)	0.26±0.01 (0.13–0.39)
	<b>Mes</b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.16±0.01 (0.05–0.28)	0.14±0.01 (0.03–0.33)	0.15±0.01 (0.04–0.26)	0.14±0.01 (0.05–0.24)	0.16±0.01 (0.10–0.27)	0.09±0.01 (0.03–0.26)
	<b>AWS</b> (mm)	159.61±9.23 (50–280)	142.45±12.72 (30–330)	149.68±9.16 (40–260)	149.30±9.86 (50–240)	161.79±7.69 (100–270)	94.63±7.68 (30–250)
	<b>Mic</b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.16±0.01 (0.10–0.25)	0.16±0.01 (0.05–0.31)	0.14±0.01 (0.06–0.20)	0.14±0.01 (0.06–0.24)	0.14±0.01 (0.10–0.21)	0.12±0.01 (0.04–0.19)

16 Fig. A.1- Water soil retention mean curves on both land-uses types (lawns and forests) from the  
 17 urban-rural gradient of the Paris region.  $\theta_{0.7}$ : *Saturation point*,  $\theta_{2.5}$ : *Field capacity*,  $\theta_{4.2}$ :  
 18 *Permanent wilting Point*. RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural  
 19 forests, SF: suburban forests, UF: urban forests. Error bars represent standard errors. Letters  
 20 indicate significant differences among means.

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 22 Fig. A.2- Bubble map of (a) the soil organic carbon stock (OCS in  $\text{kg m}^{-2}$ ), (b) the available  
 23 water storage capacity (AWS in mm), and associated mean values (c and d) in lawn and forest  
 24 soils along the rural, suburban and urban areas of the Paris region. Light yellow: rural area,  
 25 orange: suburban area and red: urban area. Green: lawns, and brown: forests. Each pixel  
 26 represents 2 km x 2 km. RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural forests,  
 27 SF: suburban forests, UF: urban forests. Error bars represent standard errors. Letters indicate  
 28 significant differences among means.

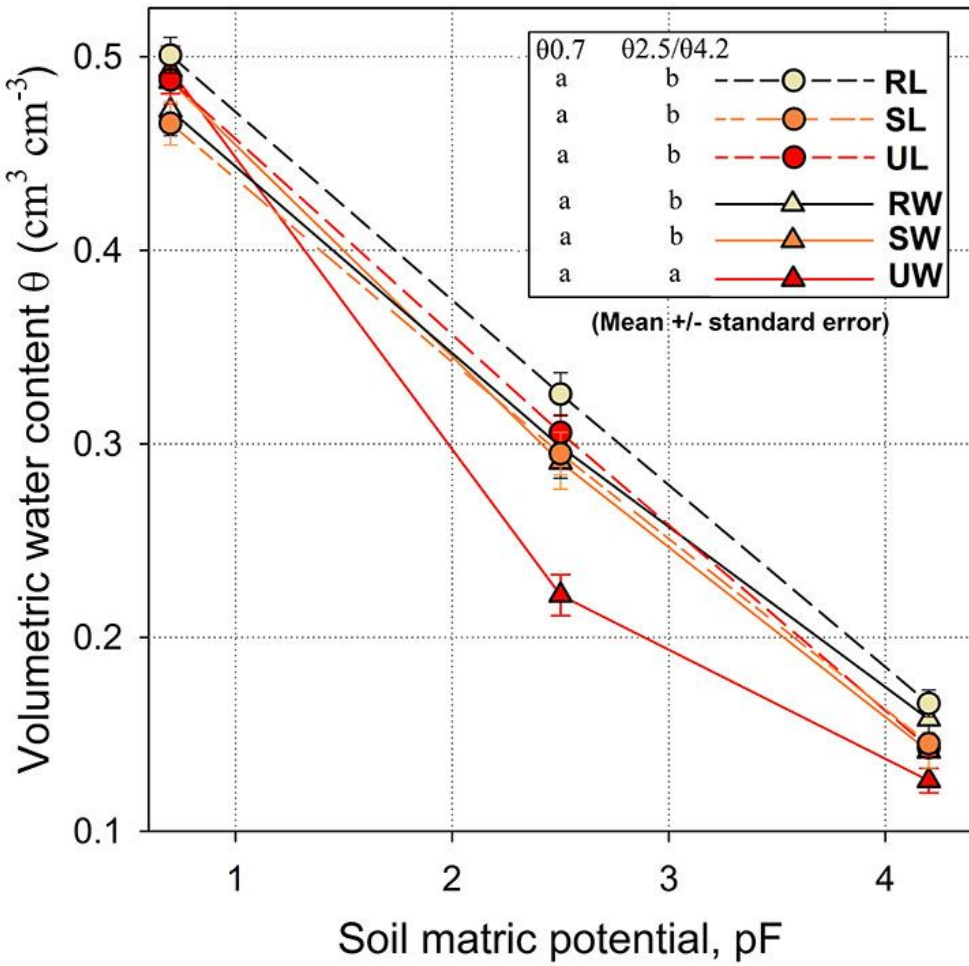
29  
 30 Fig. A.3- Bubble map of (a) the soil organic carbon stock (OCS in  $\text{kg m}^{-2}$ ), (b) the available  
 31 water storage capacity (AWS in mm), and associated mean values (c and d) in lawn and forest  
 32 soils along the rural, suburban and urban areas of the Paris region. Light yellow: rural area,  
 33 orange: suburban area and red: urban area. Green: lawns, and brown: forests. Each pixel  
 34 represents 2 km x 2 km. RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural forests,  
 35 SF: suburban forests, UF: urban forests. Error bars represent standard errors. Letters indicate  
 36 significant differences among means.

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 38 Fig. A.4- (a) Current map of the Paris region in accordance to the sampled sites in the urban area  
 39 of the study vs. historical engraved map (1832) of the same location to 1/92000 from Chapman  
 40 and Hall, 1844. Relief shown by hachures. Urban forests: , urban lawns: .

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 42 Fig. A.5- geological map of the urban area of the Paris region to 1/50000 (Map 2011, provided  
 43 by BRGM – French geological reference platform). Urban forests: , urban lawns: .

44 Fig. A.1

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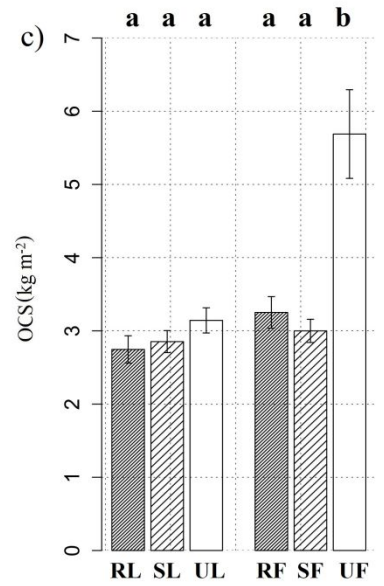
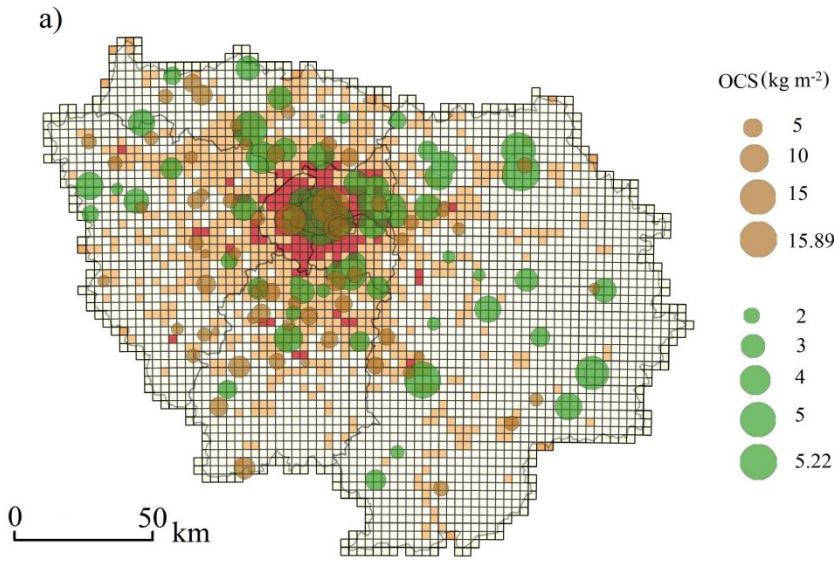
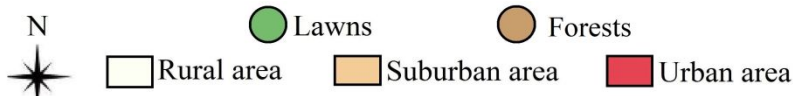
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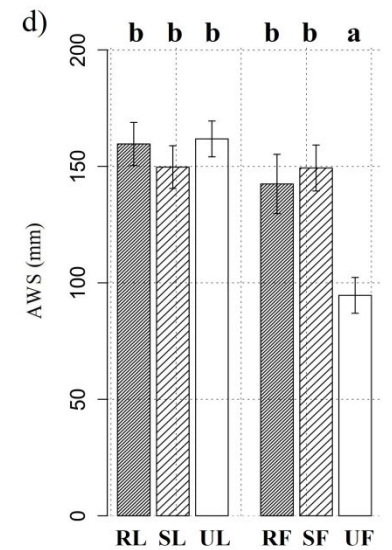
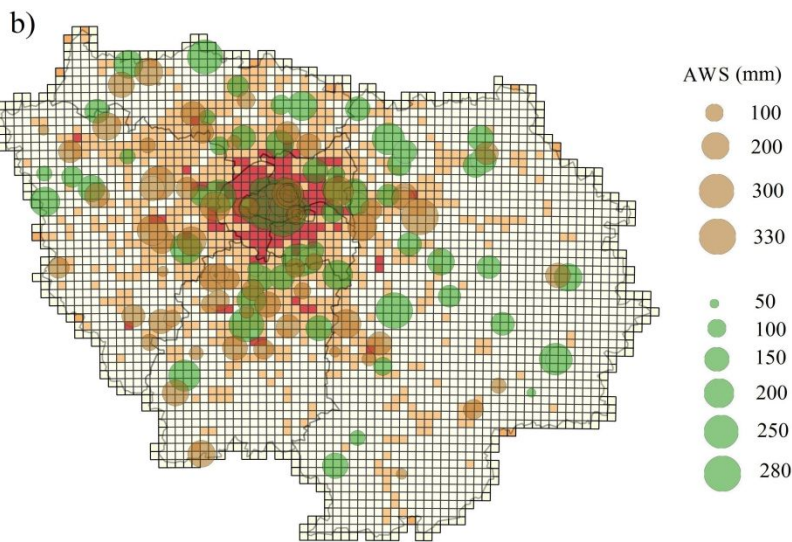
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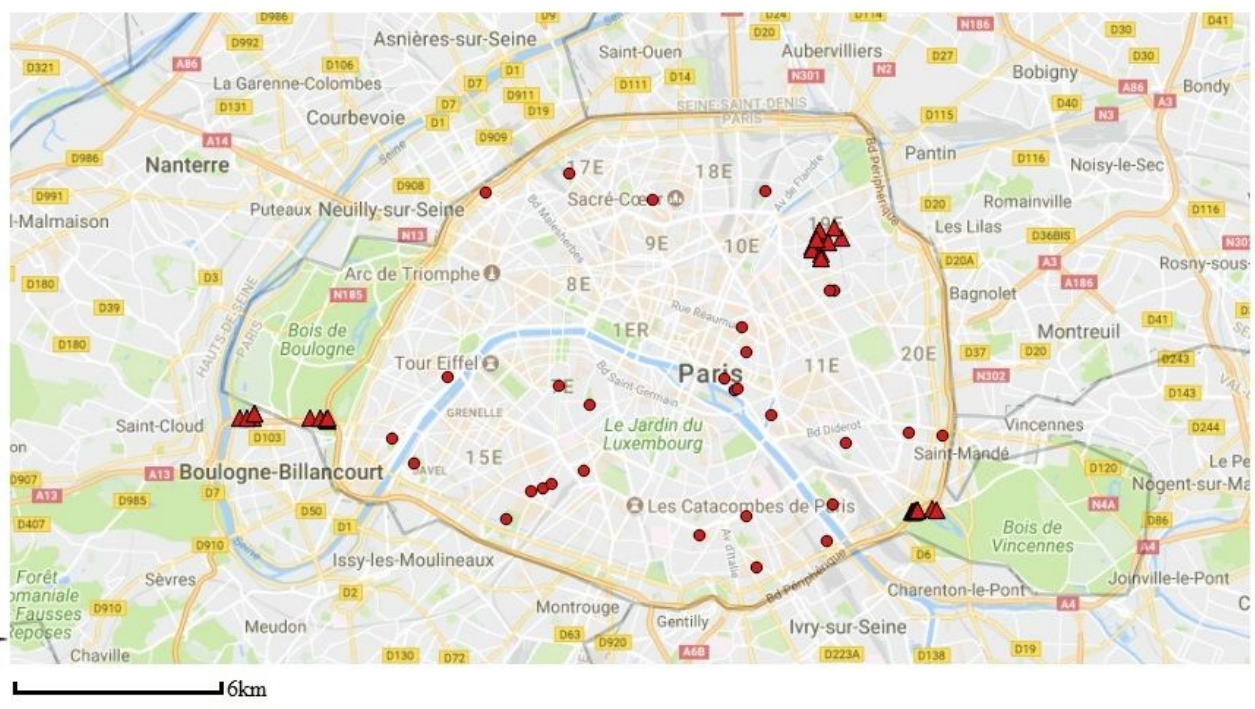
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94 Fig. A.3

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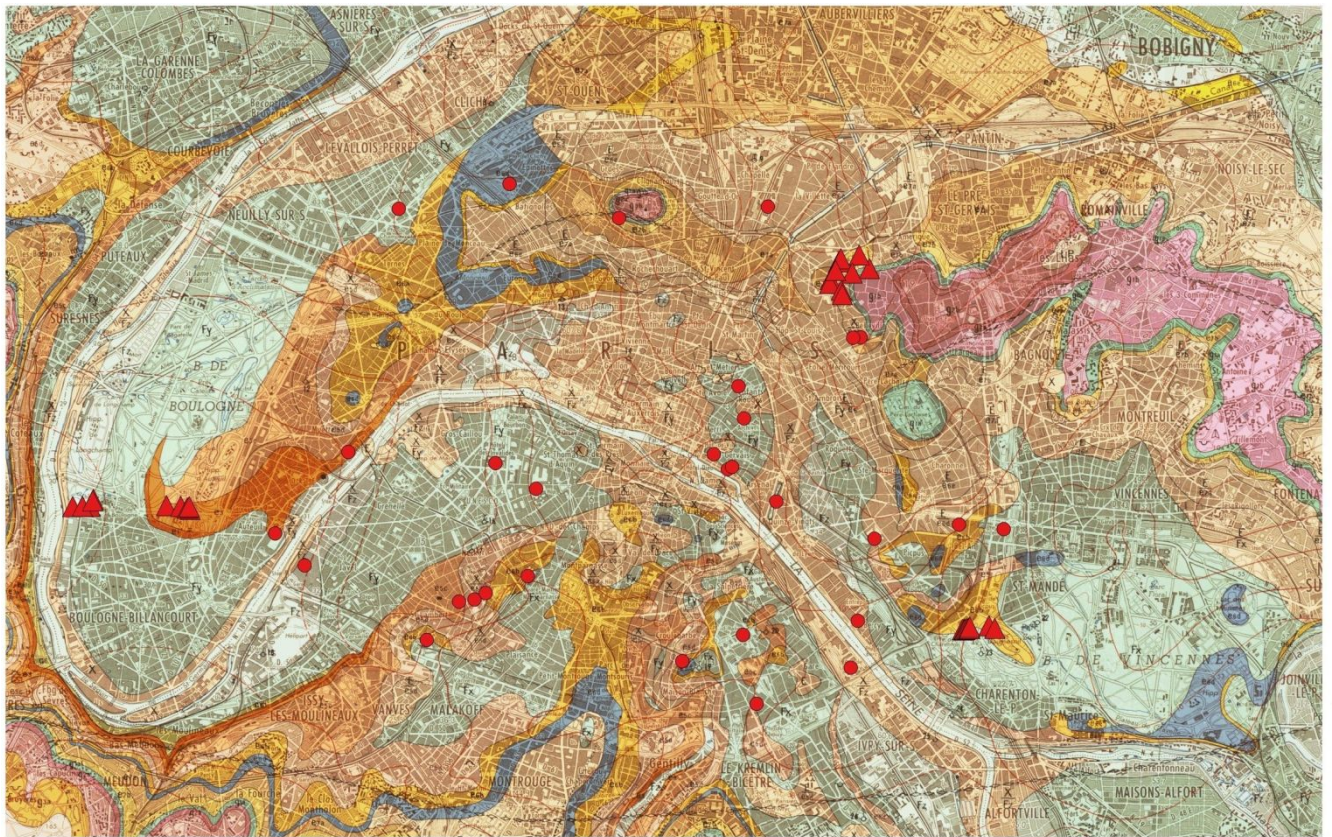
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**Typology:**

 Embankment without substrate indication	 Scree on e5d	 Pholadomyes Marl, fourth mass gypsum, sand of Monceau
 Embankment on modern alluvium	 Scree on Fy-e8	 Limestone of St-Ouen
 Embankment on old alluvium	 Modern alluvium	 Limestone of Ducy
 Embankment on Fx	 Loess	 Sand of Beauchamp
 Embankment on e5c	 Old alluvium	 Marl and loose stone, area IV of Lutecian
 Embankment on e5d	 Old alluvium	 Lutecian, area II
 Embankment on e6a	 Sand of Lozère (Burdigalian)	 Lutecian, areas III and II
 Embankment on e7b	 Milstone of Montmorency (upper Stampian)	 Sparnacian
 Scree	 Sand of Fontainebleau, sandstone sand (average Stampian)	 Montian
 Scree on Fx	 Oyster Marl (average Stampian)	 Campanian
 Scree on e7a	 Limestone of Brie	 Marnes vertes et glaises à Cyrènes sur calcaire de Brie
 Scree on e7b	 Green Marl and Cyrènes clay (lower Stampian)	 Lutecian
 Scree on e6d	 Supragypsum Marl (upper Bartonian)	 Hydro
 Scree on e1c6	 Marl and gypsum Marl	

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	Parameters	Codes	Equation	Units	Standards
	Composite soil sample preparation	–	–	–	NF ISO 11464 standard
Physical and chemical soil characteristics	Coarse Silt	CSi			
	Fine Silt	FSi			
	Coarse Sand	CSa	–	%	NF X 31-107 standard
	Fine Sand	FSa			
	Clay (<2 μm)	Clay			
	Total Phosphorus	tot P	–	mg kg <sup>-1</sup>	NF ISO 10694 standard
	Organic Carbon	OC			NF ISO 14235 standard
	Total Nitrogen	tot N	–	g kg <sup>-1</sup>	NF ISO 13878 standard
	pH–H <sub>2</sub> O	pH			
	Cation Exchange Capacity	CEC	–	cmol kg <sup>-1</sup>	NF X 31-130 standard
C/N ratio	C/N	$C/N_{(n)} = OC_{(n)}/totN_{(n)}$	–	–	
Carbonates	CaCO <sub>3</sub>	–	g kg <sup>-1</sup>	NF ISO 10693 standard	
Bulk Density	BD	${}^aBD_{(n)} = M_{t(n)}/V_{t(n)}$	g cm <sup>-3</sup>		
Hydrostructural soil characteristics	Saturation point	θ0.7	${}^bθ0.7_{(n)} = W0.7_{(n)} \times BD_{(n)}$		
	Field capacity	θ2.5	${}^bθ2.5_{(n)} = W2.5_{(n)} \times BD_{(n)}$		
	Total Porosity	TP	${}^cTP_{(n)} = 1 - BD_{(n)}/2.65$		
	Megaporosity	Meg	$MEG_{(n)} = TP_{(n)} - θ0.7_{(n)}$	cm <sup>3</sup> cm <sup>-3</sup>	
	Macroporosity	Mac	$MAC_{(n)} = θ0.7_{(n)} - θ2.5_{(n)}$		
	Mesoporosity	Mes	$MES_{(n)} = θ2.5_{(n)} - θ4.2_{(n)}$		
	Permanent wilting point= microporosity	θ4.2= Mic	${}^dθ4.2_{(n)} = W4.2_{(n)} \times BD_{(n)}$		
soil Organic Carbon Sock	OCS	${}^dOCS_{(n)} = 0.1 \times BD_{(n)} \times OC_{(n)}$	kg m <sup>-2</sup>		
Available Water Storage	AWS	${}^dAWS_{(n)} = (W2.5_{(n)} - W4.2_{(n)}) \times BD_{(n)} \times 10$	mm		

2 <sup>a</sup>M<sub>t</sub> is the total mass of each soil sample from the total wet mass and gravimetric water content of the aliquot at pF2.5  
3 (matric potential: -33 kPa), and V<sub>t</sub> the total volume for each soil sample,

4 <sup>b</sup>W is the gravimetric water soil content,

5 <sup>c</sup>2.65 g cm<sup>-3</sup> is the constant particle density,

6 <sup>d</sup>For the top 10 cm of the organo-mineral soil layer.

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Chemical, physical, and hydrostructural soil characteristics	Rural area		Suburban area		Urban area		
	Lawns	Forests	Lawns	Forests	Lawns	Forests	
<b>OCS</b> (kg m <sup>-2</sup> )	2.74±0.18 (1.28–5.22)	3.25±0.21 (1.44–5.79)	2.85±0.15 (1.30–4.75)	3.00±0.15 (1.56–4.89)	3.14±0.17 (1.76–4.89)	5.68±0.60 (1.00–15.89)	
<b>OC</b> (g kg <sup>-1</sup> )	28.6±2.9 (12.7–92.3)	32.1±2.3 (14.6–77.7)	25.4±1.4 (10.6–43.3)	31.0±1.8 (12.9–56.3)	25.1±1.5 (12.3–51.5)	55.6±5.8 (9.3–146.9)	
<b>tot N</b> (g kg <sup>-1</sup> )	3.4±0.3 (1.4–10.4)	3.2±0.2 (1.3–5.5)	2.6±0.2 (1.1–4.47)	3.0±0.2 (0.9–5.2)	2.6±0.2 (1.1–6.5)	5.5±0.6 (1.1–16.6)	
<b>tot P</b> (mg kg <sup>-1</sup> )	787.9±65.5 (279.1–1923.2)	444.4±49.2 (103.4–1155.4)	1014.7±116.4 (441.5–2806.0)	621.7±118.0 (175.7–3402.4)	1199.9±193.0 (489.9–4862.8)	1351.1±205.3 (265.5–3997.3)	
<b>pH</b>	7.4±0.1 (6.6–8.0)	6.9±0.1 (4.6–7.9)	7.6±0.1 (6.7–9.7)	6.5±0.2 (4.1–7.9)	7.5±0.05 (7.0–8.0)	7.1±0.1 (5.0–7.8)	
<b>CEC</b> (cmol kg <sup>-1</sup> )	16.6±1.1 (5.8–35.6)	13.8±0.9 (4.9–24.1)	17.6±0.9 (8.5–29.9)	17.9±1.5 (5.4–35.8)	16.6±0.7 (9.7–24.4)	24.3±1.9 (8.6–56.5)	
<b>C/N</b>	8.41±0.09 (7.18–9.36)	10.30±0.37 (6.24–15.80)	9.92±0.27 (7.97–14.52)	10.61±0.36 (6.79–15.04)	9.70±0.27 (5.65–13.41)	9.93±0.26 (7.51–14.82)	
<b>CaCO<sub>3</sub></b> (g kg <sup>-1</sup> )	16.9±3.4 (1.4–69.1)	12.1±2.7 (1.0–69.4)	12.1±1.8 (1.6–37.5)	12.1±1.8 (3.3–38.7)	11.7±2.2 (4.2–49.5)	24.8±2.2 (10.2–57.3)	
<b>Clay</b> (%)	17.8±0.9 (9.8–26.6)	15.7±0.9 (3.7–27.3)	18.2±0.9 (8.7–29.8)	17.2±1.4 (4.6–34.1)	17.9±0.9 (9.9–30.0)	10.1±0.9 (1.7–18.5)	
<b>CSi</b> (%)	21.64±2.8 (5.0–44.9)	16.3±1.7 (2.2–42.2)	16.1±2.0 (1.6–42.3)	15.6±1.9 (1.9–44.2)	22.2±1.8 (5.5–44.6)	5.9±0.37 (3.1–11.1)	
<b>FSi</b> (%)	17.8±0.8 (10.9–29.1)	14.5±1.3 (3.9–32.8)	14.07±1.0 (5.1–29.8)	15.03±1.6 (1.8–46.9)	16.9±0.8 (9.3–24.5)	8.9±0.8 (3.4–20.1)	
<b>CSa</b> (%)	27.0±2.5 (2.7–58.7)	26.8±2.8 (5.5–61.3)	28.1±3.1 (4.8–59.8)	25.2±3.02 (2.8–69.2)	26.7±3.09 (8.1–59.3)	52.0±2.6 (26.4–74.6)	
<b>FSa</b> (%)	17.2±2.1 (6.1–47.8)	20.7±2.2 (3.1–47.0)	18.9±1.5 (6.3–42.6)	20.8±2.6 (4.9–54.7)	12.3±1.04 (4.0–30.4)	16.4±1.4 (5.0–35.6)	
<b>BD</b> (g cm <sup>-3</sup> )	1.02±0.03 (0.48–1.34)	1.03±0.03 (0.61–1.45)	1.13±0.02 (0.76–1.37)	0.98±0.02 (0.62–1.30)	1.27±0.03 (0.87–1.65)	1.04±0.02 (0.75–1.37)	
<b>Hydrostructural soil characteristics</b>	<b>θ<sub>0.7</sub></b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.50±0.01 (0.37–0.61)	0.47±0.01 (0.36–0.59)	0.46±0.01 (0.38–0.65)	0.48±0.01 (0.34–0.60)	0.48±0.01 (0.35–0.61)	0.48±0.01 (0.40–0.62)
	<b>θ<sub>2.5</sub></b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.32±0.01 (0.21–0.46)	0.30±0.01 (0.14–0.50)	0.29±0.01 (0.16–0.42)	0.29±0.01 (0.15–0.44)	0.30±0.01 (0.21–0.41)	0.22±0.01 (0.13–0.36)
	<b>Meg</b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.11±0.01 (0.002–0.22)	0.13±0.01 (0.012–0.35)	0.10±0.01 (0.001–0.27)	0.13±0.01 (0.02–0.38)	0.04±0.01 (0.001–0.12)	0.11±0.01 (0.001–0.23)
	<b>Mac</b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.17±0.01 (0.09–0.26)	0.17±0.01 (0.07–0.33)	0.17±0.01 (0.11–0.49)	0.19±0.01 (0.08–0.35)	0.18±0.01 (0.08–0.32)	0.26±0.01 (0.13–0.39)
	<b>Mes</b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.16±0.01 (0.05–0.28)	0.14±0.01 (0.03–0.33)	0.15±0.01 (0.04–0.26)	0.14±0.01 (0.05–0.24)	0.16±0.01 (0.10–0.27)	0.09±0.01 (0.03–0.26)
	<b>AWS</b> (mm)	159.61±9.23 (50–280)	142.45±12.72 (30–330)	149.68±9.16 (40–260)	149.30±9.86 (50–240)	161.79±7.69 (100–270)	94.63±7.68 (30–250)
	<b>Mic</b> (cm <sup>3</sup> cm <sup>-3</sup> )	0.16±0.01 (0.10–0.25)	0.16±0.01 (0.05–0.31)	0.14±0.01 (0.06–0.20)	0.14±0.01 (0.06–0.24)	0.14±0.01 (0.10–0.21)	0.12±0.01 (0.04–0.19)



OCS: soil organic carbon stock, OC: organic carbon, tot N: total nitrogen, tot P: total phosphorus, pH: pH-H<sub>2</sub>O, CEC: cation exchange capacity, C/N ratio, CaCO<sub>3</sub>: carbonates, Clay, CSi and FSi: coarse and fine silt, CSa and FSa: coarse and fine sand, BD: bulk density, θ<sub>0.7</sub>: saturation point, θ<sub>2.5</sub>: field capacity, Meg: megaporosity, Mac: macroporosity, Mes: mesoporosity, AWS: available water storage capacity, θ<sub>4.2</sub>=Mic: permanent wilting point=microporosity.



15 Fig. A.1- Water soil retention mean curves on both land-uses types (lawns and forests) from the  
16 urban-rural gradient of the Paris region.

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18 Fig. A.2- Bubble map of (a) the soil organic carbon stock (OCS in  $\text{kg m}^{-2}$ ), (b) the available  
19 water storage capacity (AWS in mm), and associated mean values (c and d) in lawn and forest  
20 soils along the rural, suburban and urban areas of the Paris region.

21  
22 Fig. A.4- (a) Current map of the Paris region in accordance to the sampled sites in the urban area  
23 of the study vs. historical engraved map (1832) of the same location to 1/92000 from Chapman  
24 and Hall, 1844. Relief shown by hachures. Urban forests:  , urban lawns:  .

25  
26 Fig. A.5- geological map of the urban area of the Paris region to 1/50000 (Map 2011, provided  
27 by BRGM – French geological reference platform). Urban forests:  , urban lawns: .

For Peer Review

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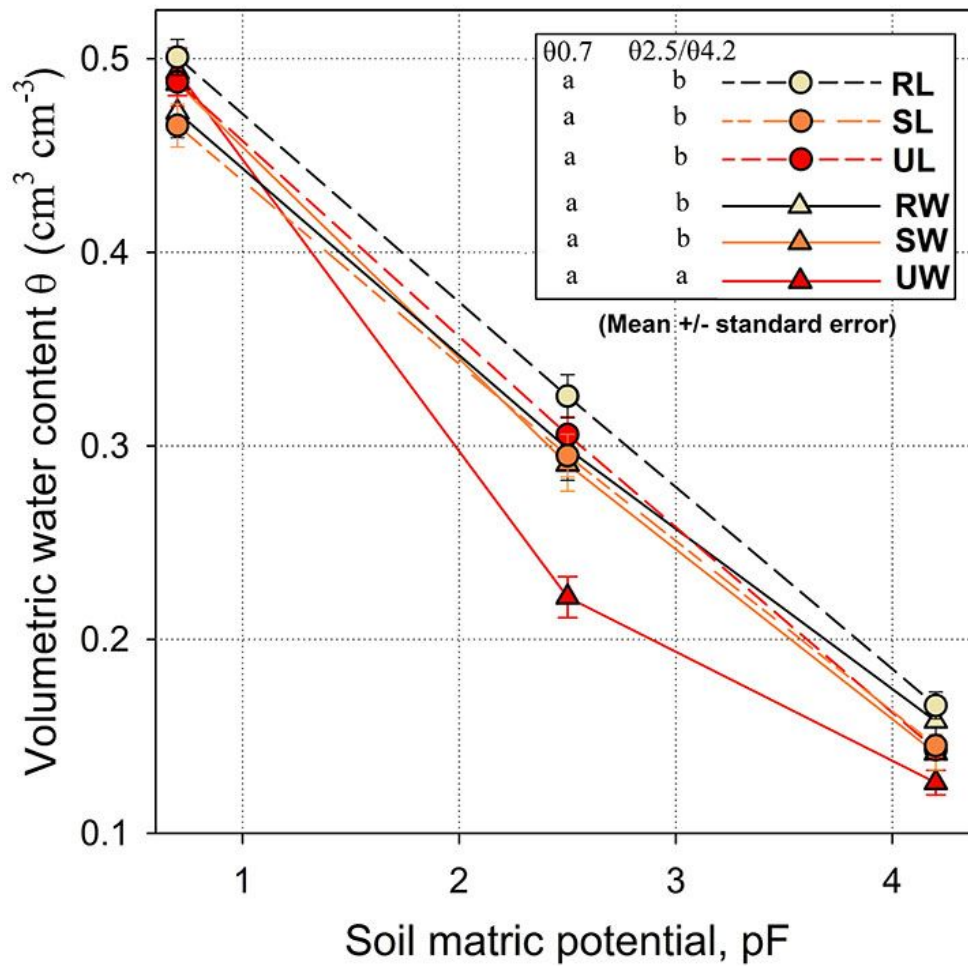
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47 00.7: Saturation point, 02.5: Field capacity, 04.2: Permanent wilting Point. RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural forests, SF: suburban forests, UF: urban forests. Error bars represent standard errors. Letters indicate significant differences among means.

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51 Fig. A.2

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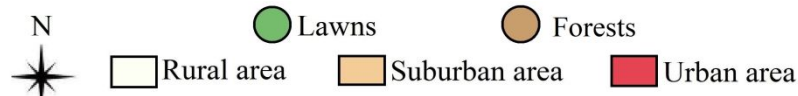
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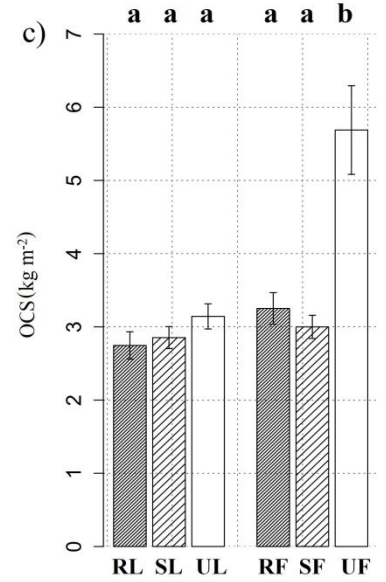
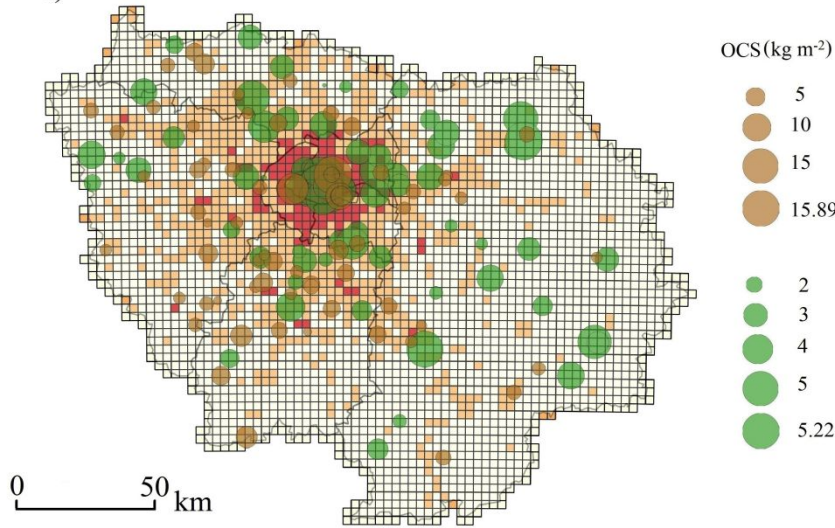
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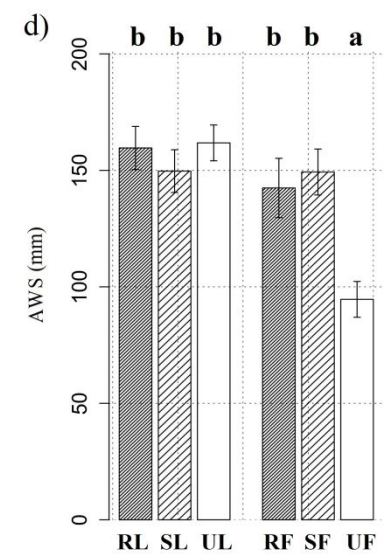
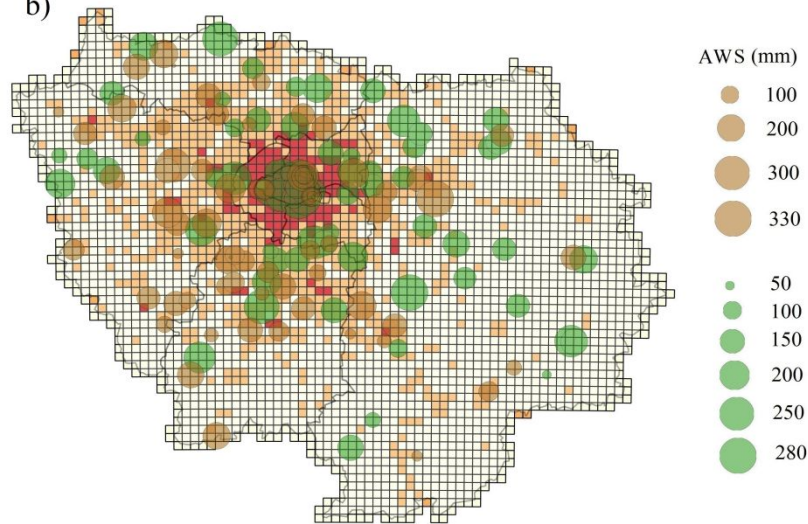
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Light yellow: rural area, orange: suburban area and red: urban area. Green: lawns, and brown: forests. Each pixel represents 2 km x 2 km. RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural forests, SF: suburban forests, UF: urban forests. Error bars represent standard errors. Letters indicate significant differences among means.

78 Fig. A.3

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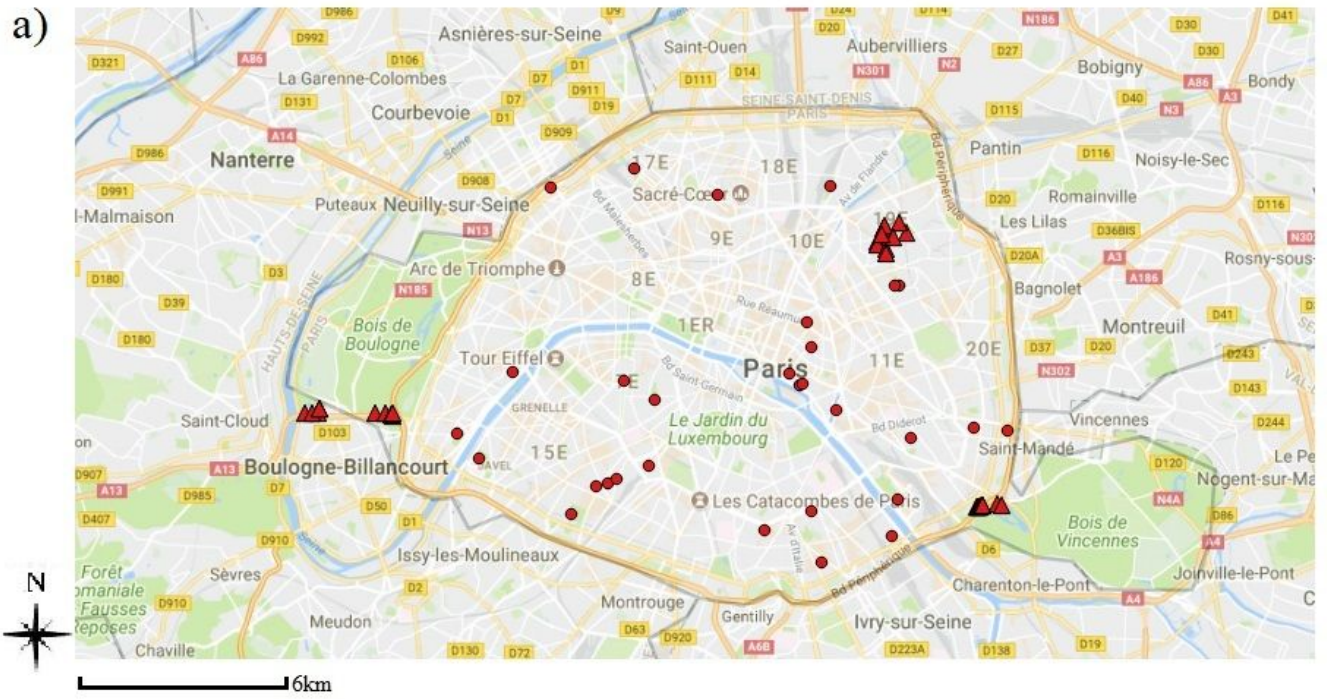
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105 Fig. A.4

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**Typology:**

 Embankment without substrate indication	 Scree on e5d	 Pholadomyes Marl, fourth mass gypsum, sand of Monceau
 Embankment on modern alluvium	 Scree on Fy-e8	 Limestone of St-Ouen
 Embankment on old alluvium	 Modern alluvium	 Limestone of Ducy
 Embankment on Fx	 Loess	 Sand of Beauchamp
 Embankment on e5c	 Old alluvium	 Marl and loose stone, area IV of Lutecian
 Embankment on e5d	 Old alluvium	 Lutecian, area II
 Embankment on e6a	 Sand of Lozère (Burdigalian)	 Lutecian, areas III and II
 Embankment on e7b	 Milstone of Montmorency (upper Stampian)	 Sparnacian
 Scree	 Sand of Fontainebleau, sandstone sand (average Stampian)	 Montian
 Scree on Fx	 Oyster Marl (average Stampian)	 Campanian
 Scree on e7a	 Limestone of Brie	 Marnes vertes et glaises à Cyrènes sur calcaire de Brie
 Scree on e7b	 Green Marl and Cyrènes clay (lower Stampian)	 Lutecian
 Scree on e6d	 Supragypsum Marl (upper Bartonian)	 Hydro
 Scree on e1c6	 Marl and gypsum Marl	

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