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

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Complete List of Authors:	FOTI, Ludovic; Sorbonne Universite, Institute of Ecology and Environmental Sciences Barot, Sebastien; Sorbonne Universite, Institute of Ecology and Environmental Sciences Gignoux, Jacques; Sorbonne Universite, Institute of Ecology and Environmental Sciences Grimaldi, Michel; Sorbonne Universite, Institute of Ecology and Environmental Sciences Lata, Jean-Christophe; Sorbonne Universite, Institute of Ecology and Environmental Sciences Lerch, Thomas; Sorbonne Universite, Institute of Ecology and Environmental Sciences Nold, Francois; Sorbonne Universite, Institute of Ecology and Environmental Sciences Nunan, Naoise; Sorbonne Universite, Institute of Ecology and Environmental Sciences Raynaud, Xavier; Sorbonne Universite, Institute of Ecology and Environmental Sciences Abbadie, Luc; Sorbonne Universite, Institute of Ecology and Environmental Sciences Dubs, Florence; Sorbonne Universite, Institute of Ecology and Environmental Sciences
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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 This paper is well organized and concise, but the literature review is insufficient and some references are outdated.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 As a result, we have replaced the outdated references (Lines 47, 51, 54, 60, 66, 74, 77, 80, 82, 83 and line 86).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 μm (-0.5 kPa), 9 μm (-33 kPa), and 0.2 μm (-1500 kPa), which were determined in accordance with Jurin’s law. They delimited the macropores (600-9 μm), mesopores (9-0.2 μm), 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**

4 Ludovic Foti^{ab1}, Sébastien Barot^a, Jacques Gignoux^a, Michel Grimaldi^a, Jean-Christophe
5 Lata^{ac}, Thomas Lerch Z^a, François Nold^d, Naoise Nunan^a, Xavier Raynaud^a, Luc Abbadie^a,
6 Florence Dubs^a

7

8 ^aSorbonne Université, Université de Paris, UPEC, CNRS, IRD, INRA, UMR 7618, Institute
9 of Ecology and Environmental Sciences - Paris, iEES Paris, 4 place Jussieu, 75005 Paris,
10 France

11

12 ^bRegional Agency for Biodiversity Île-de-France, 15 rue Falguière, 75015 Paris, France

13

14 ^cDepartment of Geocology and Geochemistry, Institute of Natural Resources, Tomsk
15 Polytechnic University, 30, Lenin Street, Tomsk 634050, Russia

16

17 ^dLaboratory of agronomy of the Paris city, Paris Green Space and Environmental Division
18 (DEVE), Parc Floral - Pavillon 5 - Rond Point de la Pyramide, 75012 Paris, France

19

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

22

23

24

1 Corresponding author: ludovic.foti@gmail.com

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 km² 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 km²) and 22.2% (2670 km²) 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 m² 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 m² 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 cm³) 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-H₂O (pH),
150 carbonates (CaCO₃), 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 O₂ 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⁻²) 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 CO₂ 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⁻¹, urban lawns: 1199.9 mg kg⁻¹, suburban lawns: 1014.7, rural lawns:
 242 787.9 mg kg⁻¹) than rural forests (444.4 mg kg⁻¹ means, respectively). The megaporosity
 243 showed a specific pattern with a lower value (0.04 cm³ cm⁻³) 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⁻³), and
 245 lowest in suburban forest soils (0.98 g cm⁻³), with an intermediate value in suburban lawn
 246 soils (1.13 g cm⁻³) (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⁻²; 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)**

3

4 Ludovic Foti^{ab1}, Sébastien Barot^a, Jacques Gignoux^a, Michel Grimaldi^a, Jean-Christophe
5 Lata^{ac}, Thomas Lerch Z^a, François Nold^d, Naoise Nunan^a, Xavier Raynaud^a, Luc Abbadie^a,
6 Florence Dubs^a

7

8 ^aSorbonne Université, Université de Paris, UPEC, CNRS, IRD, INRA, UMR 7618, Institute
9 of Ecology and Environmental Sciences - Paris, iEES Paris, 4 place Jussieu, 75005 Paris,
10 France

11

12 ^bRegional Agency for Biodiversity Île-de-France, 15 rue Falguière, 75015 Paris, France

13

14 ^cDepartment of Geocology and Geochemistry, Institute of Natural Resources, Tomsk
15 Polytechnic University, 30, Lenin Street, Tomsk 634050, Russia

16

17 ^dLaboratory of agronomy of the Paris city, Paris Green Space and Environmental Division
18 (DEVE), Parc Floral - Pavillon 5 - Rond Point de la Pyramide, 75012 Paris, France

19

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

22

23

24

1 Corresponding author: ludovic.foti@gmail.com

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 km² 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 km²) and 22.2% (2670 km²) 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 m² 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 m² 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 cm³) 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-H₂O (pH),
157 carbonates (CaCO₃), 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 O₂ 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⁻²) 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 CO₂ 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 μm (-0.5
182 kPa), 9 μm (-33 kPa), and 0.2 μm (-1500 kPa), which were determined in accordance with
183 Jurin's law. They delimited the macropores (600-9 μm), mesopores (9-0.2 μm), 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⁻²; 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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1 **Topsoil characteristics of forests and lawns along an urban-rural gradient in the Paris**
2 **region (France)**

3

4 Ludovic Foti^{ab1}, Sébastien Barot^a, Jacques Gignoux^a, Michel Grimaldi^a, Jean-Christophe
5 Lata^{ac}, Thomas Lerch Z^a, François Nold^d, Naoise Nunan^a, Xavier Raynaud^a, Luc Abbadie^a,
6 Florence Dubs^a

7

8 ^aSorbonne Université, Université de Paris, UPEC, CNRS, IRD, INRA, UMR 7618, Institute
9 of Ecology and Environmental Sciences - Paris, iEES Paris, 4 place Jussieu, 75005 Paris,
10 France

11

12 ^bRegional Agency for Biodiversity Île-de-France, 15 rue Falguière, 75015 Paris, France

13

14 ^cDepartment of Geocology and Geochemistry, Institute of Natural Resources, Tomsk
15 Polytechnic University, 30, Lenin Street, Tomsk 634050, Russia

16

17 ^dLaboratory of agronomy of the Paris city, Paris Green Space and Environmental Division
18 (DEVE), Parc Floral - Pavillon 5 - Rond Point de la Pyramide, 75012 Paris, France

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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1 Corresponding author: ludovic.foti@gmail.com

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 km² 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 km²) and 22.2% (2670 km²) 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 m² 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 m² 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 cm³) 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-H₂O (pH),
157 carbonates (CaCO₃), 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 O₂ 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⁻²) 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 CO₂ 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 μm (-0.5
182 kPa), 9 μm (-33 kPa), and 0.2 μm (-1500 kPa), which were determined in accordance with
183 Jurin's law. They delimited the macropores (600-9 μm), mesopores (9-0.2 μm), 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⁻²; 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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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-H₂O*, CEC: *Cation Exchange Capacity*, C/N ratio, CaCO₃: *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 ² adjusted
df	2	1	2	
Chemical and physical soil characteristics				
OCS	12.57***	15.71***	4.54**	0.20
OC	4.68*	29.52***	6.81**	0.21
tot N	5.64**	15.64***	10.09***	0.19
tot P	14.74***	21.23***	4.66*	0.23
pH	0.81	17.54***	3.88*	0.11
CEC	8.86***	0.23	7.00**	0.13
C/N	5.49**	15.15***	4.29*	0.14
CaCO₃	3.53*	5.23*	10.43***	0.14
Clay	7.12**	19.38***	8.21***	0.20
CSi	6.48**	31.21***	14.42***	0.27
FSi	5.17**	25.33***	7.56***	0.20
CSa	7.98***	6.00*	9.30***	0.17
FSa	3.48*	2.42	0.97	0.03
BD	9.64***	24.66***	8.93**	0.24
Hydrostructural soil characteristics				
$\theta_{0.7}$	0.54	0.01	2.30	0.004
$\theta_{2.5}$	8.70***	15.23***	5.84**	0.18
Meg	11.21***	18.76***	3.83*	0.20
Mac	10.13***	13.08***	7.84***	0.20
Mes	3.33*	18.16***	7.45***	0.16
AWS	3.17*	14.14***	6.34**	0.14
$\theta_{4.2}=\text{Mic}$	9.80***	11.19**	2.64	0.15

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(**OCS**: soil organic carbon stock, **OC**: organic carbon, **tot N**: total nitrogen, **tot P**: total phosphorus, **pH**: pH-H₂O, **CEC**: Cation Exchange Capacity, **C/N ratio**, **CaCO₃**: carbonates, **Clay**, **CSi** and **FSi**: coarse and fine silt, **CSa** and **FSa**: coarse and fine sand, **BD**: bulk density, **θ_{0.7}**: saturation point, **θ_{2.5}**: field capacity, **Meg**: megaporosity, **Mac**: macroporosity, **Mes**: mesoporosity, **AWS**: available water storage capacity, **θ_{4.2}=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-H₂O*, CEC: *cation exchange capacity*, CaCO₃:
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),
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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-H₂O, CEC: cation exchange*
29 *capacity, C/N ratio, CaCO₃: 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.*

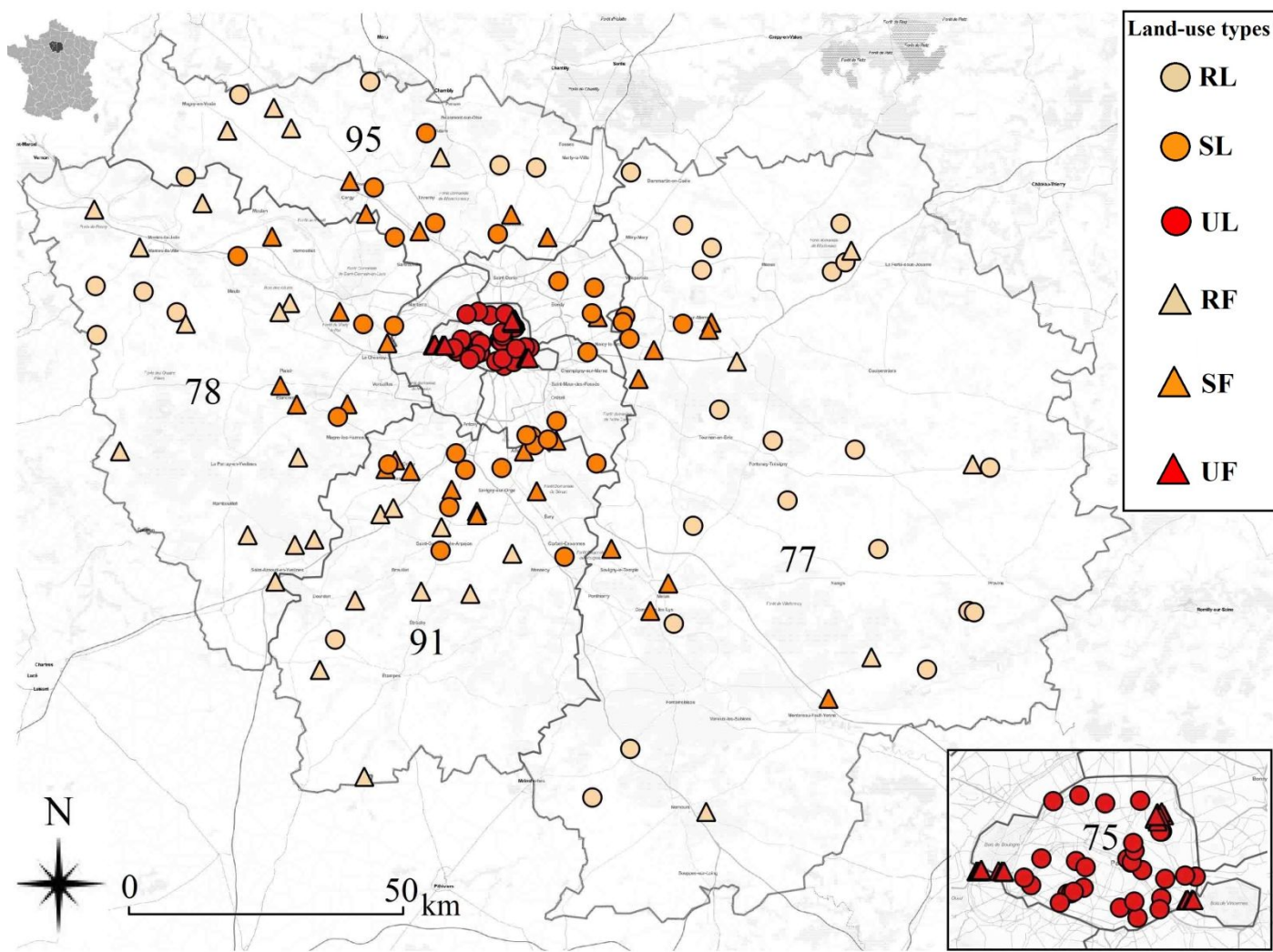
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34 Fig. 5- Mean values of the hydrostructural soil characteristics of forest and lawn soils in rural,
35 suburban and urban areas of the Paris region. (megaporosity, macroporosity, mesoporosity,
36 and microporosity). RL: rural lawns, SL: suburban 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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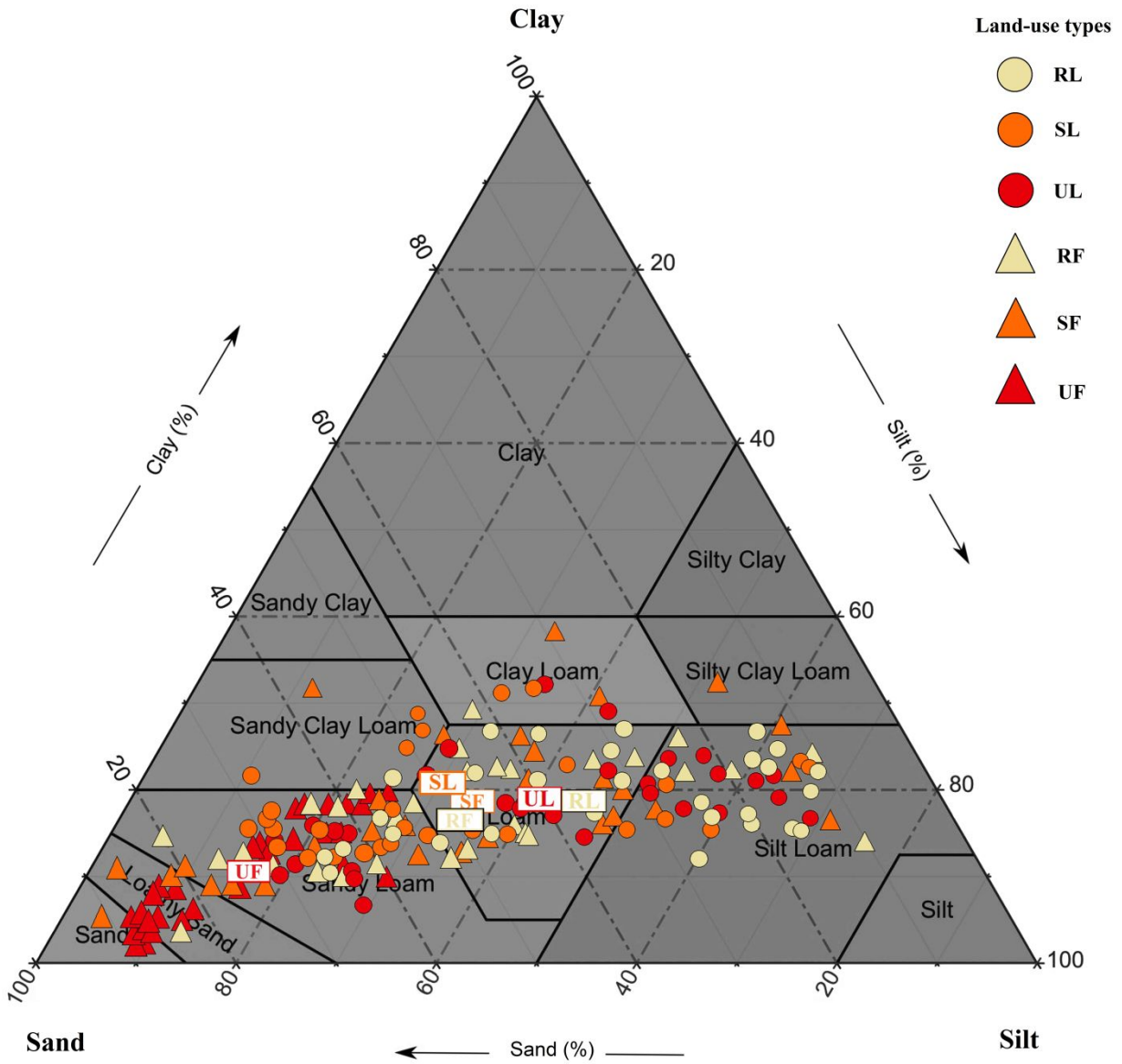
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Fig. 2



78 Fig. 3

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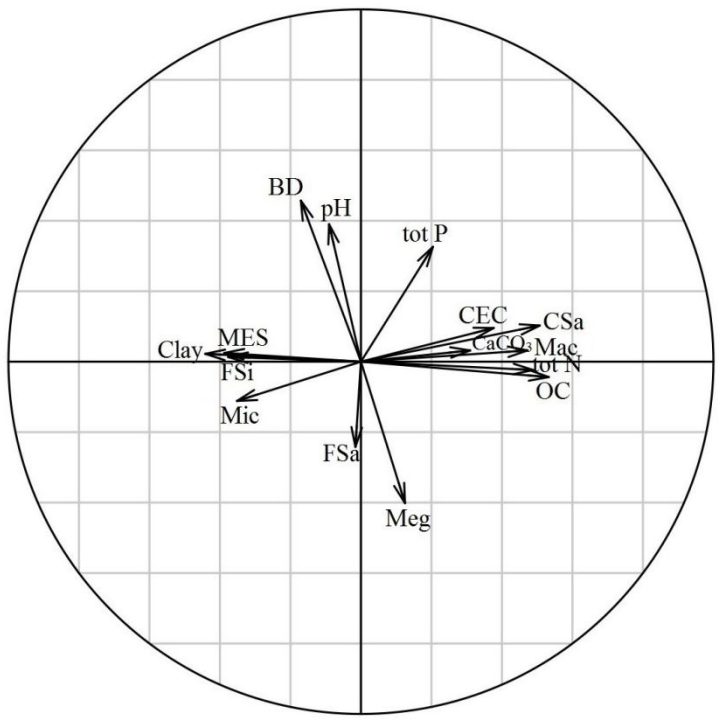
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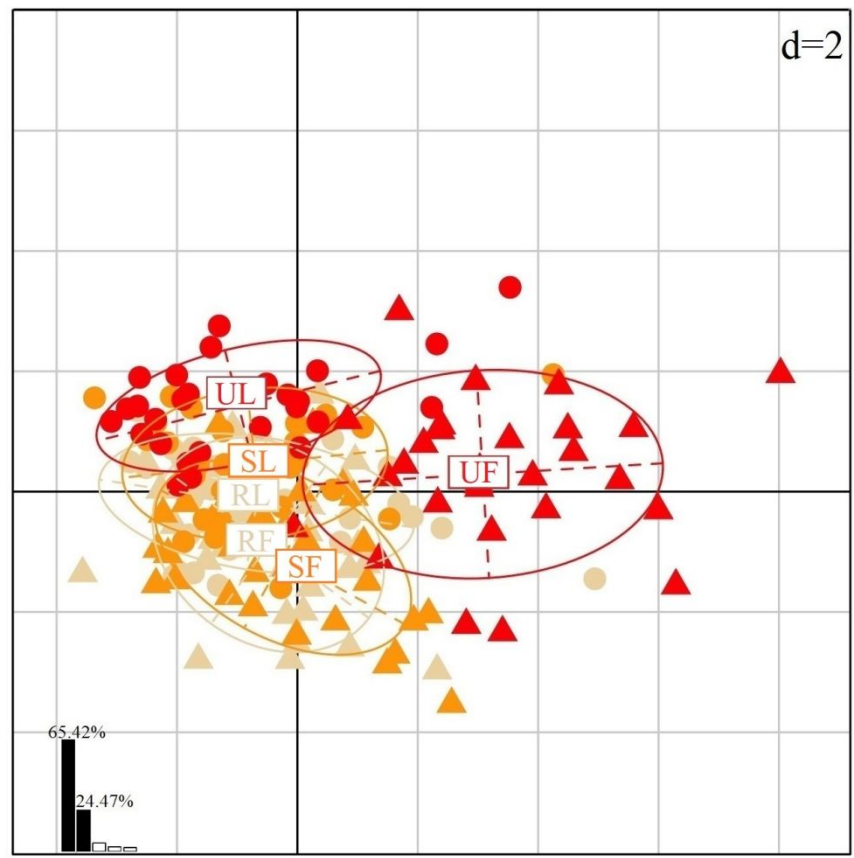
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a)



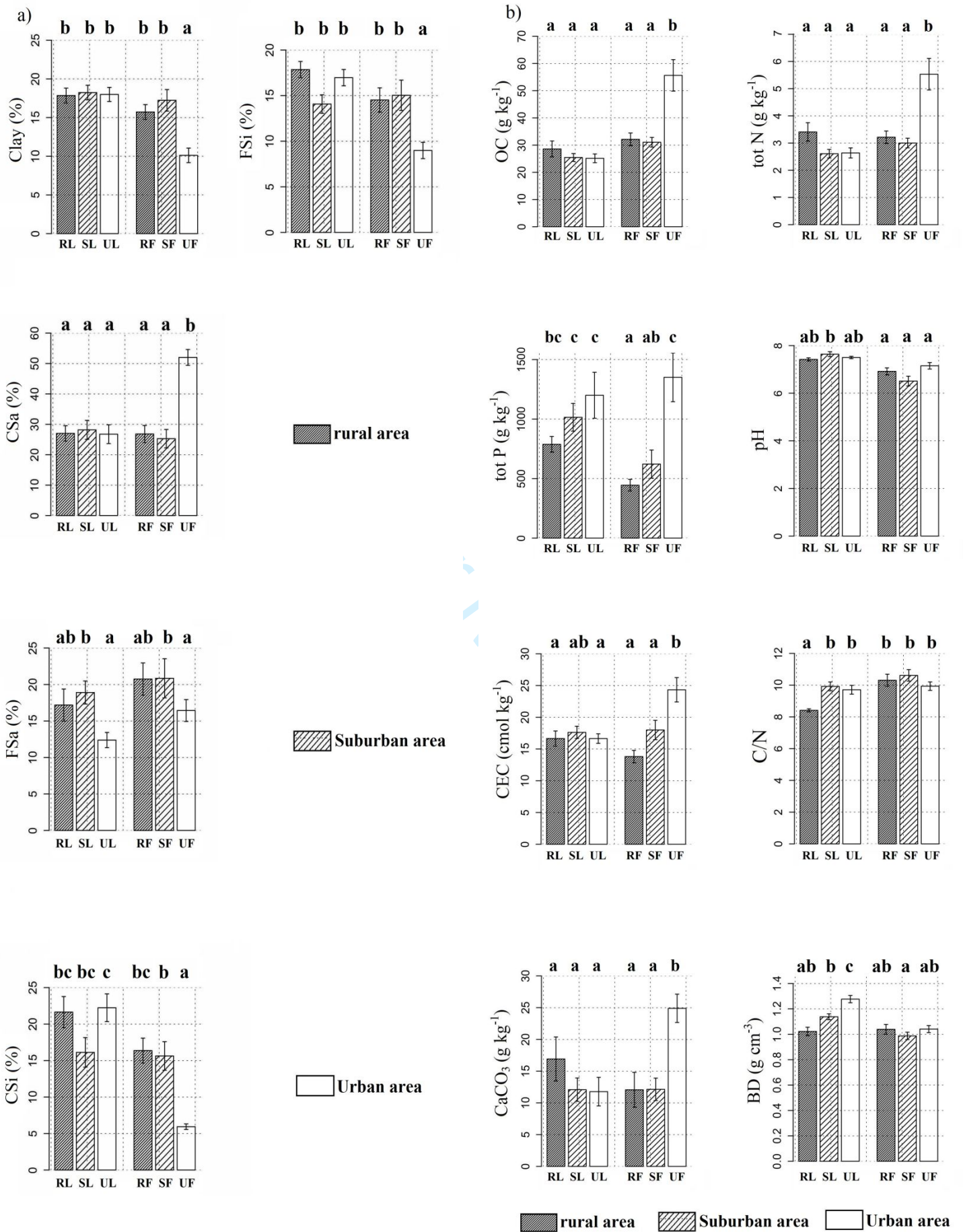
b)



Land-use types

- RL
- SL
- UL
- △ RF
- △ SF
- ▲ UF

Fig. 4



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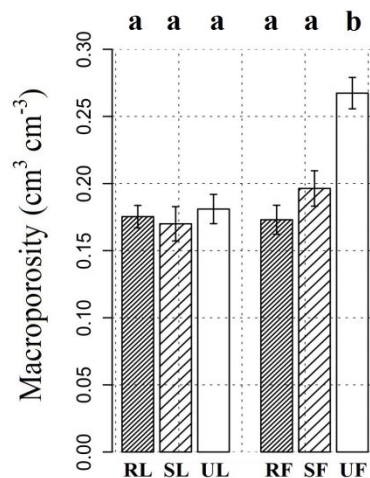
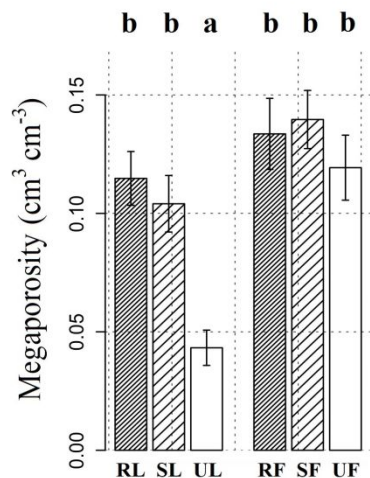
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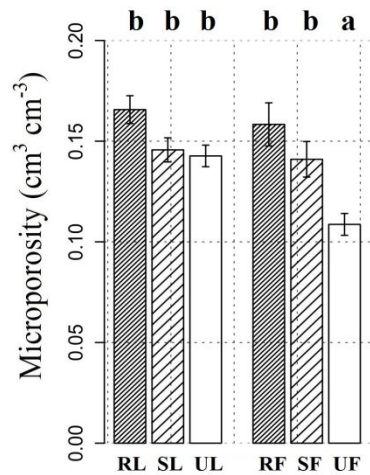
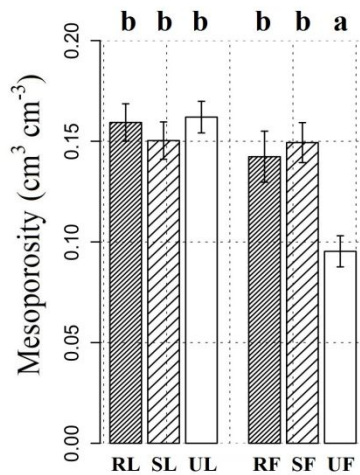
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137 Rural area Suburban area Urban area

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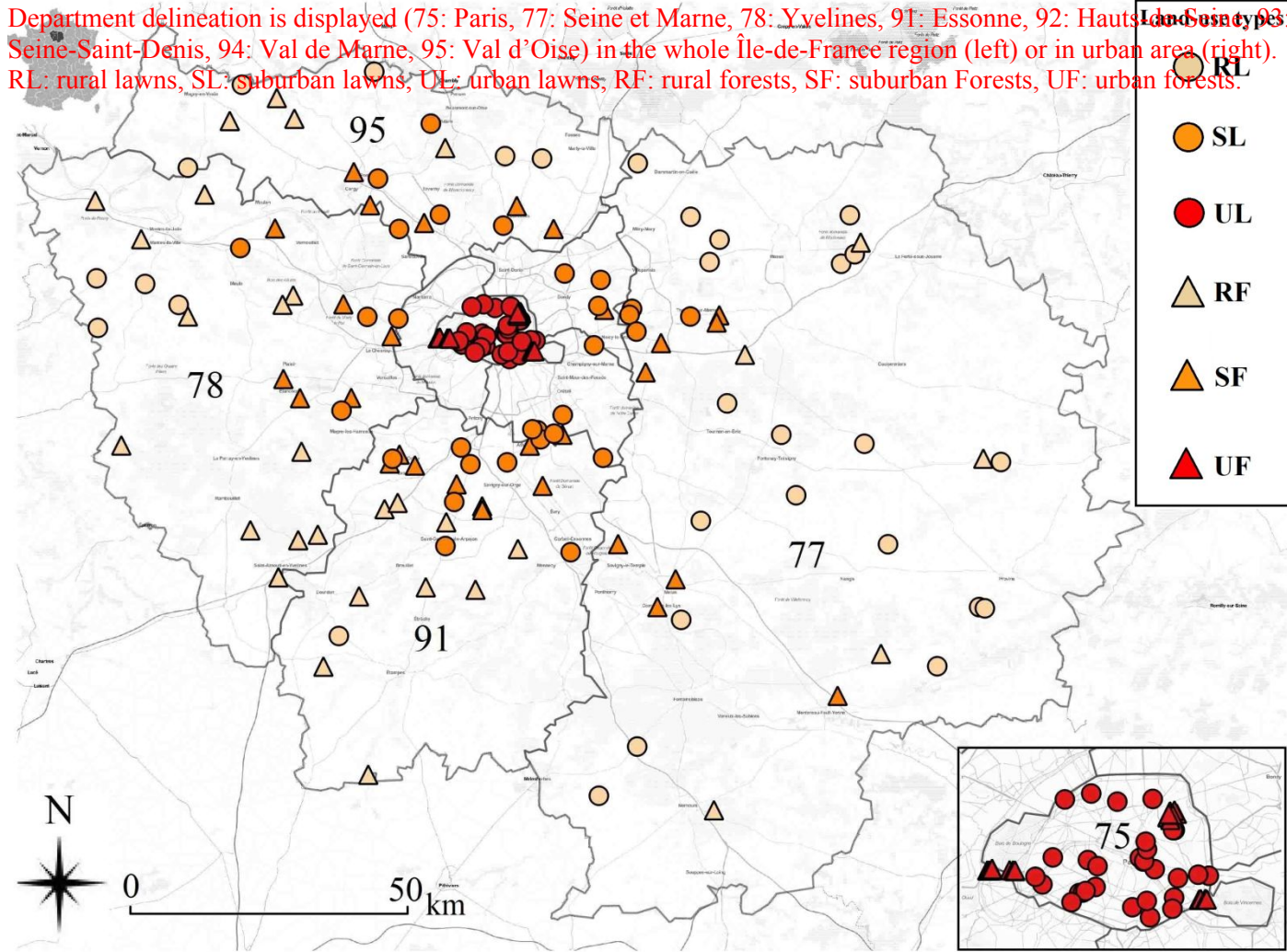
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15 Fig. 1

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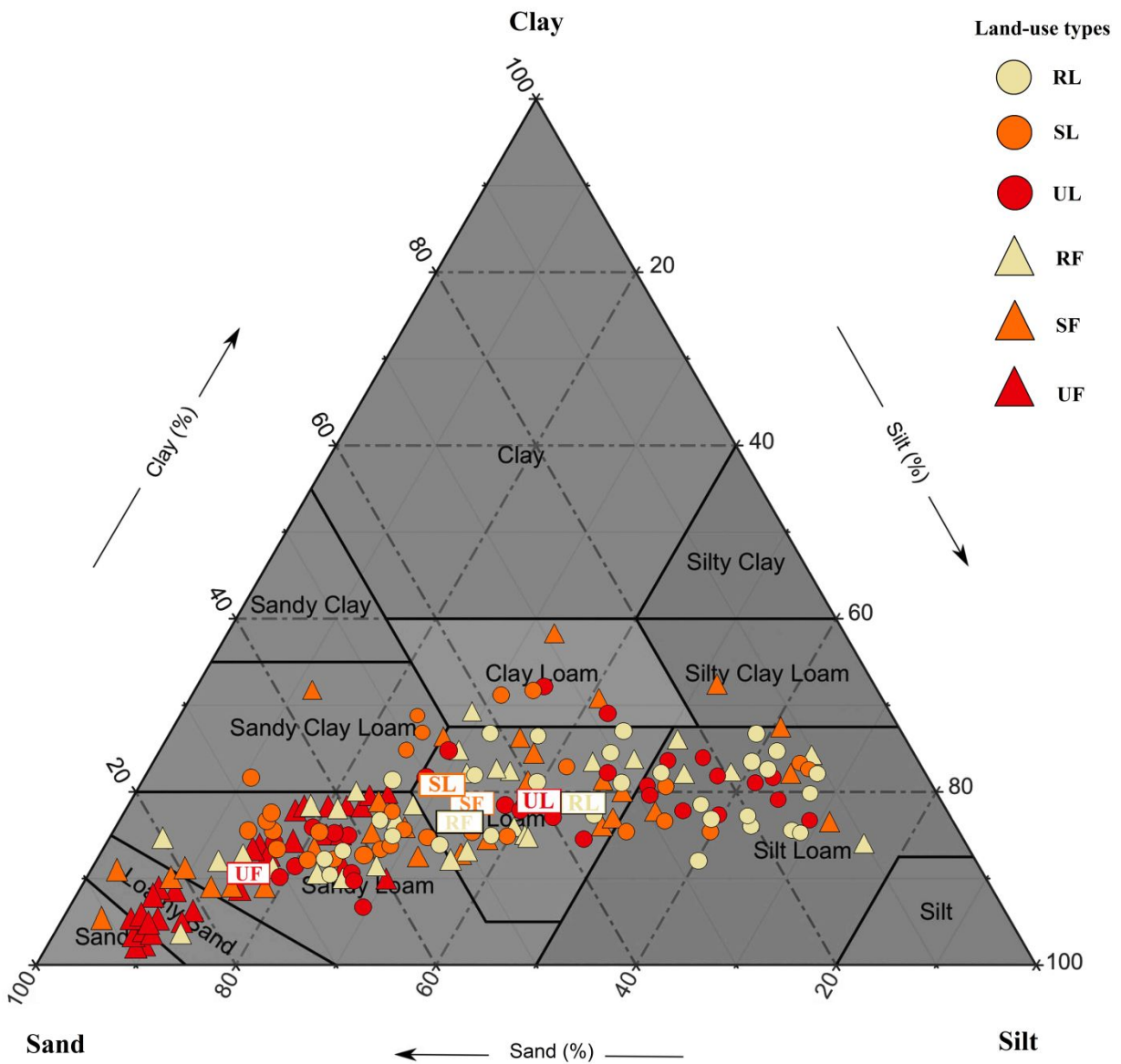
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Fig. 2



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).

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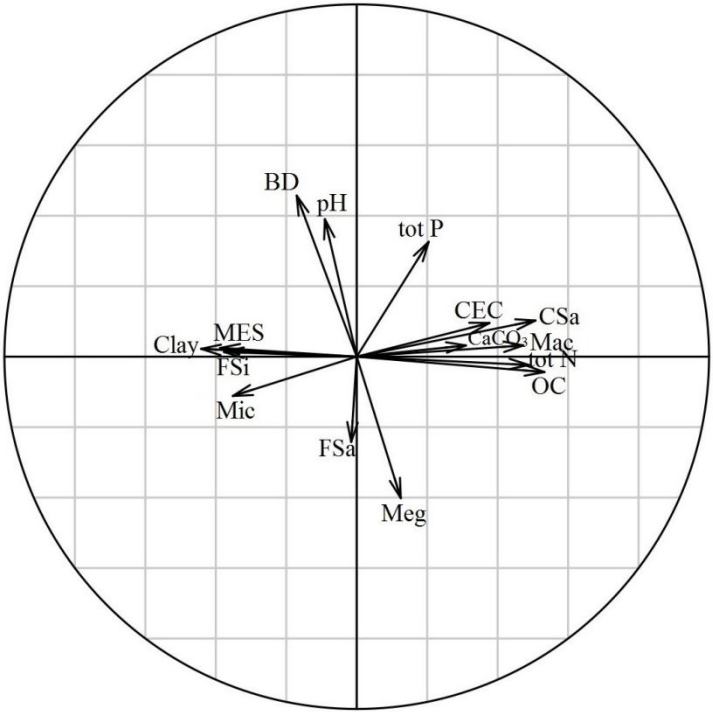
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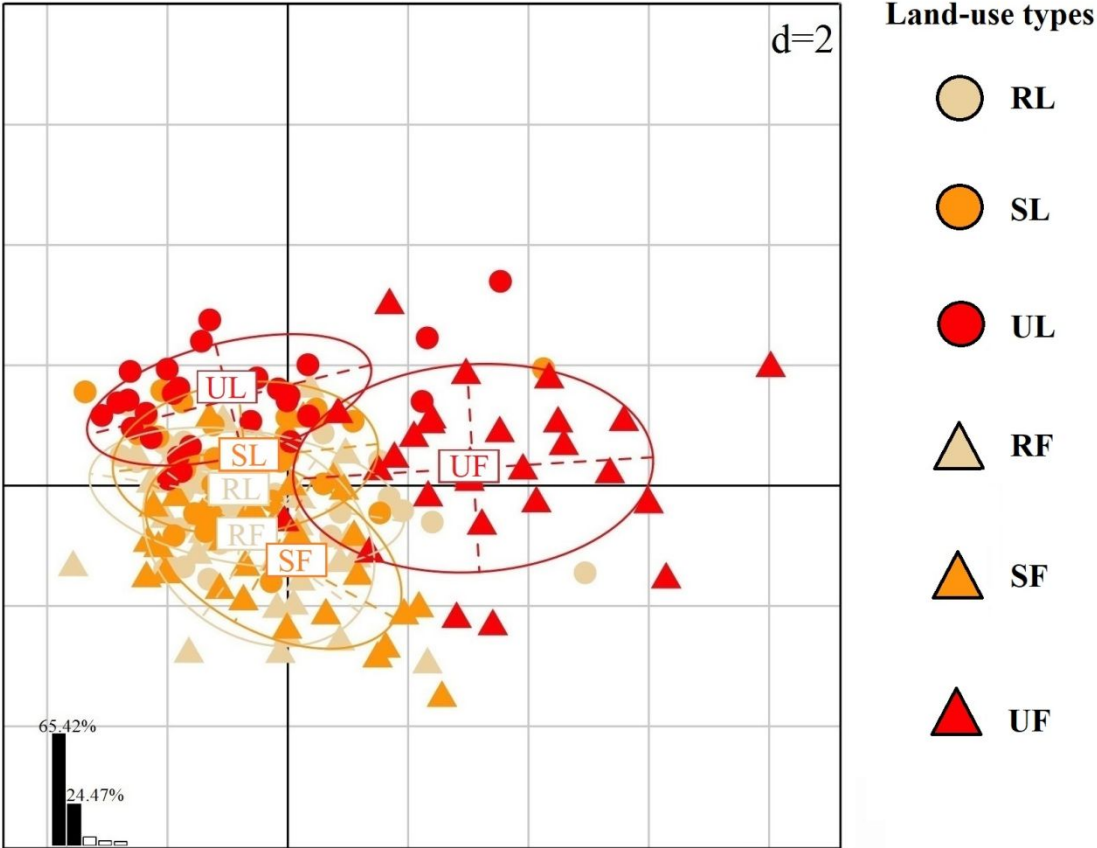
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a)



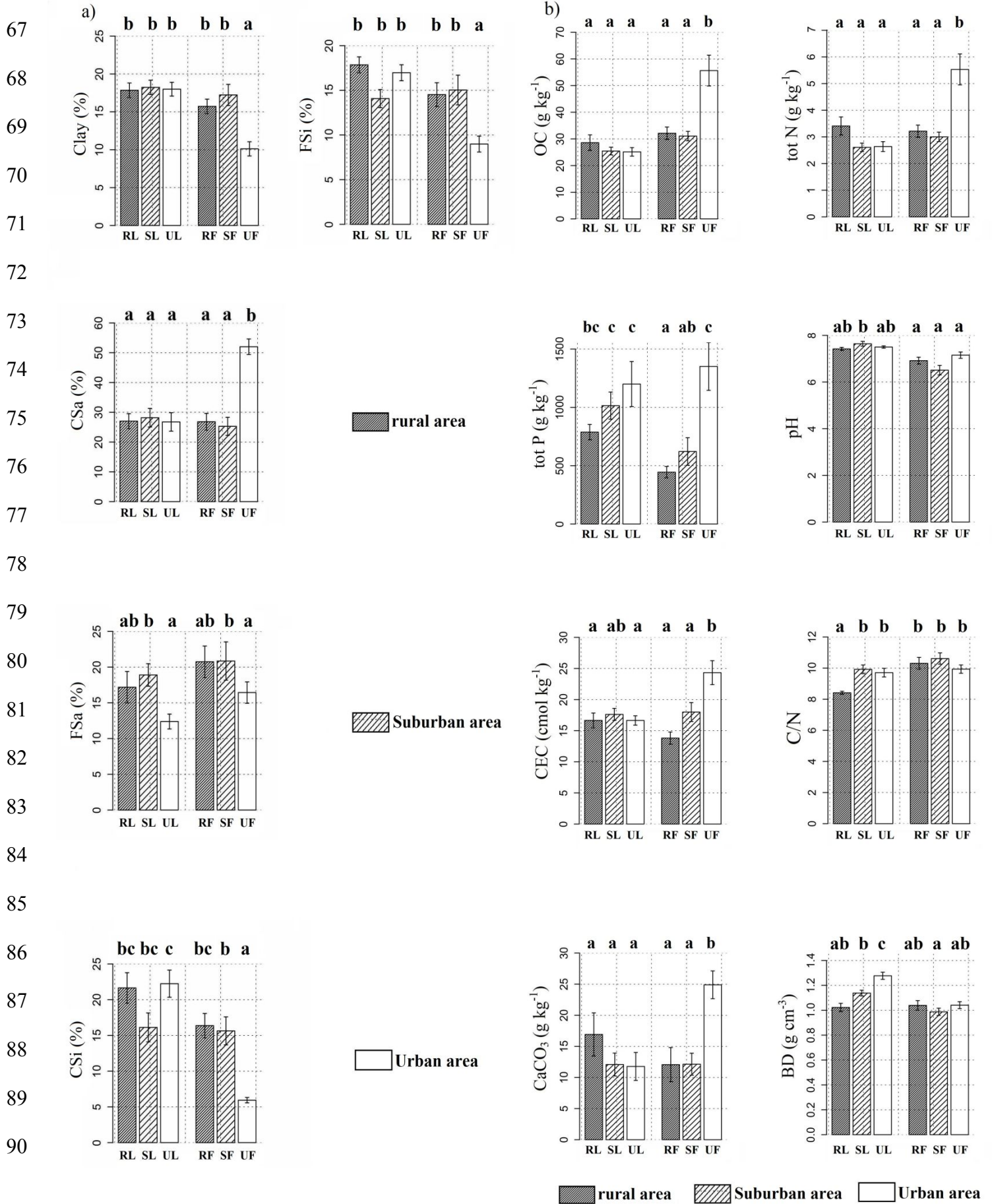
b)



64 (a) Correlation circle plot with the soil characteristic vectors (**OC**: organic carbon, **tot N**: total nitrogen, **tot P**: total phosphorus, **pH**: pH-H₂O, **CEC**: cation exchange capacity, **CaCO₃**: 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-H₂O, CEC: cation exchange capacity, C/N ratio, CaCO₃: 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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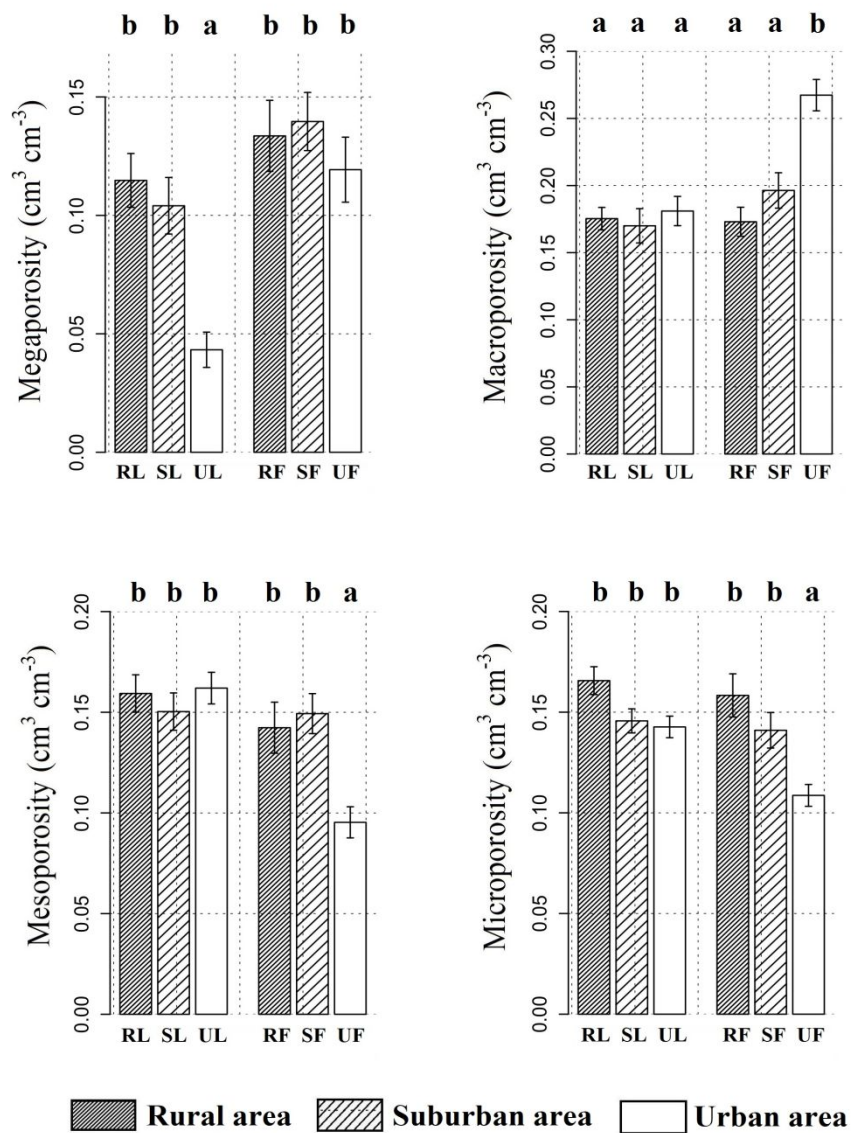
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RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural forests, SF: suburban forests, UF: urban forests. Error bars represent standard errors. Letters indicate significant differences between means.

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 ⁻¹	NF ISO 10694 standard
	Organic Carbon	OC			NF ISO 14235 standard
	Total Nitrogen	tot N	–	g kg ⁻¹	NF ISO 13878 standard
	pH–H ₂ O	pH			
	Cation Exchange Capacity	CEC	–	cmol kg ⁻¹	NF X 31-130 standard
C/N ratio	C/N	$C/N_{(n)} = OC_{(n)}/totN_{(n)}$	–	–	
Carbonates	CaCO ₃	–	g kg ⁻¹	NF ISO 10693 standard	
Bulk Density	BD	${}^aBD_{(n)} = M_{t(n)}/V_{t(n)}$	g cm ⁻³		
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 ³ cm ⁻³	
	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 ⁻²		
Available Water Storage	AWS	${}^dAWS_{(n)} = (W2.5_{(n)} - W4.2_{(n)}) \times BD_{(n)} \times 10$	mm		

^aM_t 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_t the total volume for each soil sample,

^bW is the gravimetric water soil content,

^c2.65 g cm⁻³ is the constant particle density,

^dFor 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-H₂O, CEC:
 11 cation exchange capacity, C/N ratio, CaCO₃: carbonates, Clay, CSi and FSi: coarse and fine silt, CSa and FSa:
 12 coarse and fine sand, BD: bulk density, $\theta_{0.7}$: saturation point, $\theta_{2.5}$: field capacity, Meg: megaporosity, Mac:
 13 macroporosity, Mes: mesoporosity, AWS: available water storage capacity, $\theta_{4.2}$ =Mic: permanent wilting
 14 point=microporosity).



Chemical, physical, and hydrostructural soil characteristics	Rural area		Suburban area		Urban area	
	Lawns	Forests	Lawns	Forests	Lawns	Forests
OCS (kg m ⁻²)	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)
OC (g kg ⁻¹)	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)
tot N (g kg ⁻¹)	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)
tot P (mg kg ⁻¹)	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)
pH	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)
CEC (cmol kg ⁻¹)	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)
C/N	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)
CaCO₃ (g kg ⁻¹)	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)
Clay (%)	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)
CSi (%)	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)
FSi (%)	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)
CSa (%)	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)
FSa (%)	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)
BD (g cm ⁻³)	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)
$\theta_{0.7}$ (cm ³ cm ⁻³)	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)
$\theta_{2.5}$ (cm ³ cm ⁻³)	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)
Meg (cm ³ cm ⁻³)	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)
Mac (cm ³ cm ⁻³)	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)
Mes (cm ³ cm ⁻³)	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)
AWS (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)
Mic (cm ³ cm ⁻³)	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.

21
 22 Fig. A.2- Bubble map of (a) the soil organic carbon stock (OCS in 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.

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 30 Fig. A.3- Bubble map of (a) the soil organic carbon stock (OCS in 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.

37
 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: .

41
 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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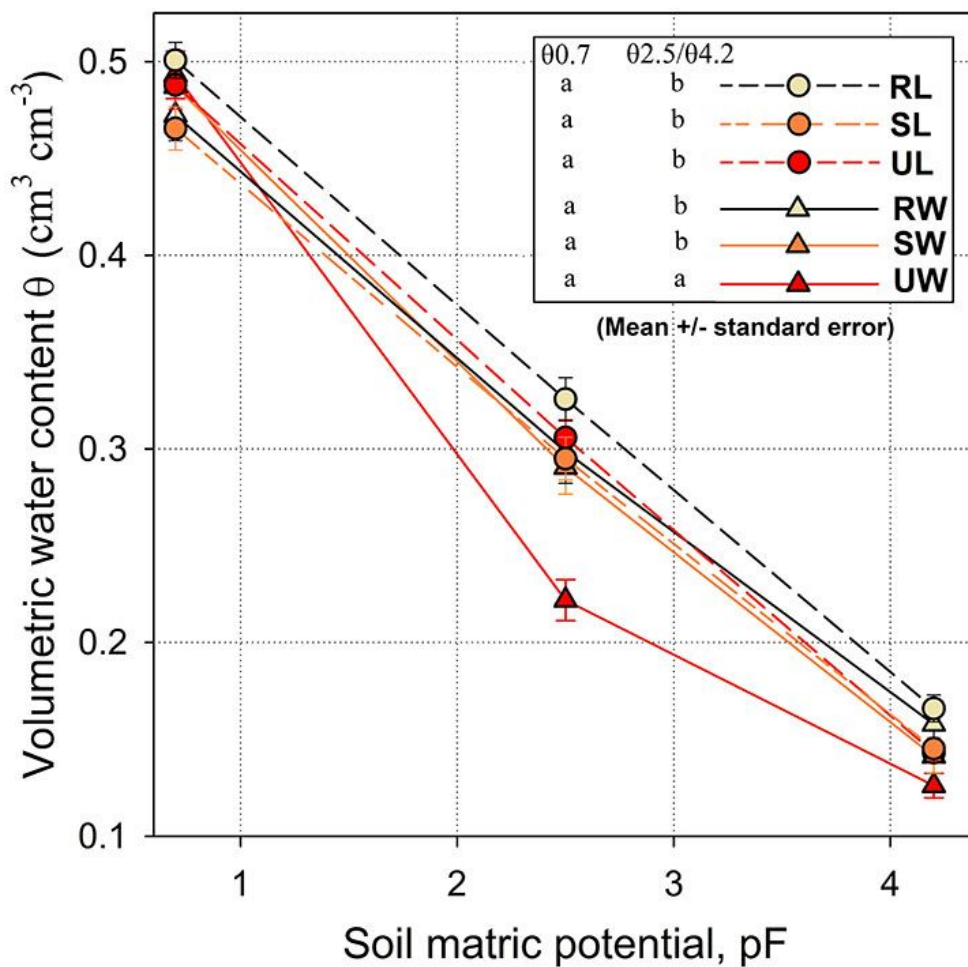
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67 Fig. A.2

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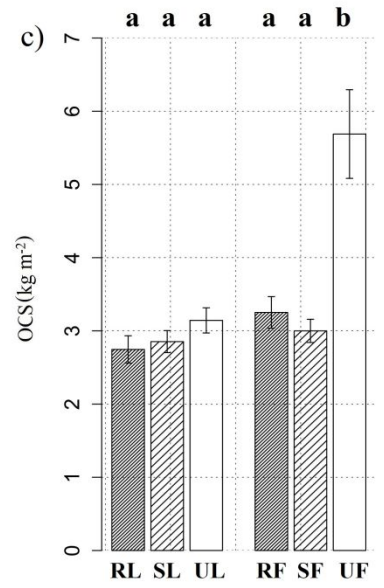
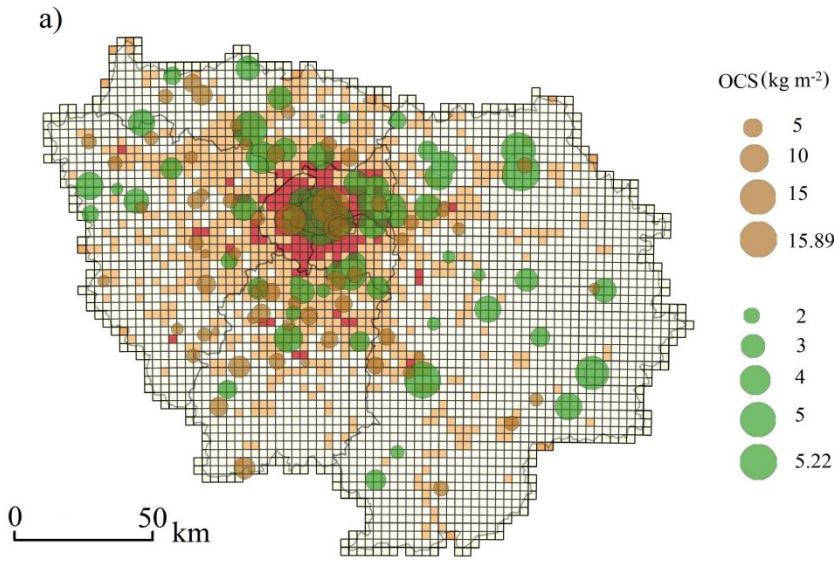
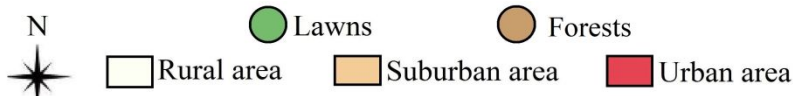
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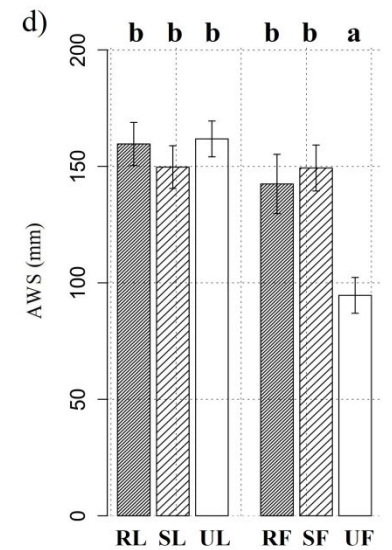
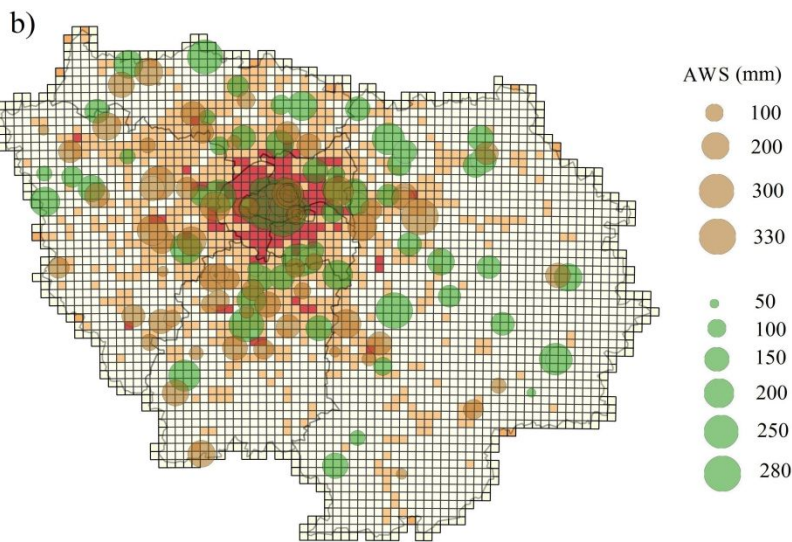
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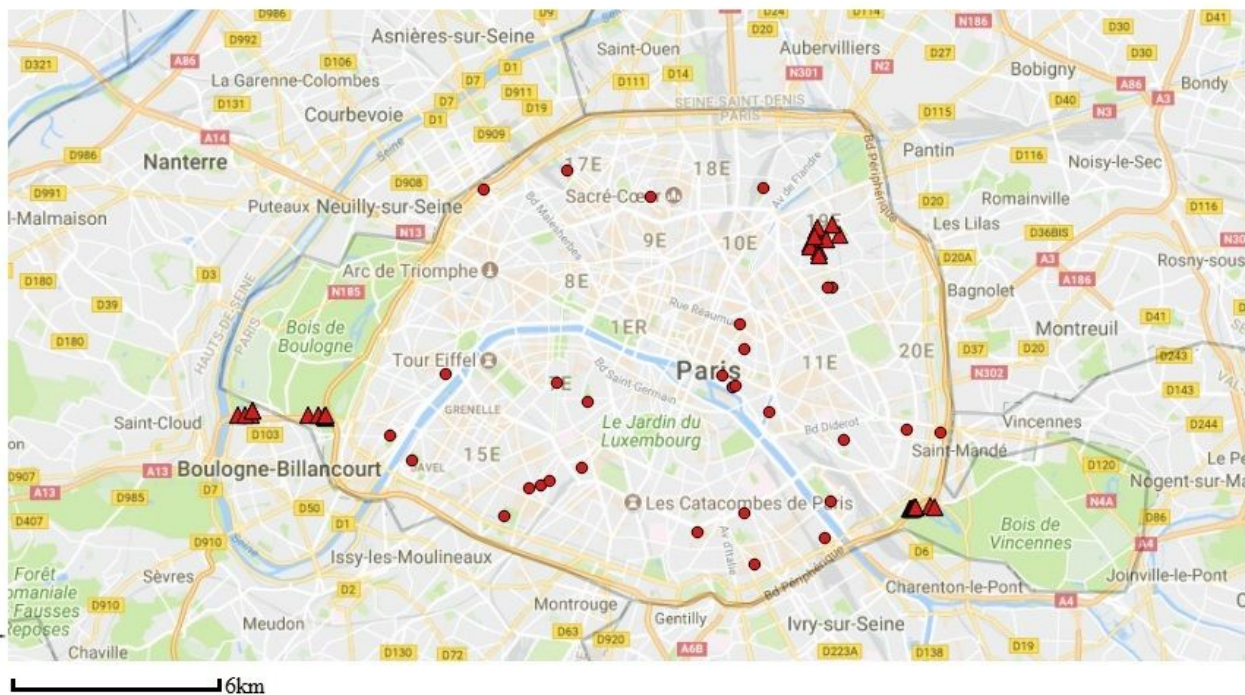
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94 Fig. A.3

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121 Fig. A.4

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Typology:



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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 ⁻¹	NF ISO 10694 standard
	Organic Carbon	OC			NF ISO 14235 standard
	Total Nitrogen	tot N	–	g kg ⁻¹	NF ISO 13878 standard
	pH–H ₂ O	pH			
	Cation Exchange Capacity	CEC	–	cmol kg ⁻¹	NF X 31-130 standard
C/N ratio	C/N	$C/N_{(n)} = OC_{(n)}/totN_{(n)}$	–	–	
Carbonates	CaCO ₃	–	g kg ⁻¹	NF ISO 10693 standard	
Bulk Density	BD	${}^aBD_{(n)} = M_{t(n)}/V_{t(n)}$	g cm ⁻³		
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 ³ cm ⁻³	
	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 ⁻²		
Available Water Storage	AWS	${}^dAWS_{(n)} = (W2.5_{(n)} - W4.2_{(n)}) \times BD_{(n)} \times 10$	mm		

2 ^aM_t 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_t the total volume for each soil sample,

4 ^bW is the gravimetric water soil content,

5 ^c2.65 g cm⁻³ is the constant particle density,

6 ^dFor 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	
OCS (kg m ⁻²)	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)	
OC (g kg ⁻¹)	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)	
tot N (g kg ⁻¹)	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)	
tot P (mg kg ⁻¹)	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)	
pH	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)	
CEC (cmol kg ⁻¹)	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)	
C/N	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)	
CaCO₃ (g kg ⁻¹)	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)	
Clay (%)	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)	
CSi (%)	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)	
FSi (%)	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)	
CSa (%)	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)	
FSa (%)	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)	
BD (g cm ⁻³)	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)	
Hydrostructural soil characteristics	θ_{0.7} (cm ³ cm ⁻³)	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)
	θ_{2.5} (cm ³ cm ⁻³)	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)
	Meg (cm ³ cm ⁻³)	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)
	Mac (cm ³ cm ⁻³)	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)
	Mes (cm ³ cm ⁻³)	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)
	AWS (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)
	Mic (cm ³ cm ⁻³)	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-H₂O, CEC: cation exchange capacity, C/N ratio, CaCO₃: carbonates, Clay, CSi and FSi: coarse and fine silt, CSa and FSa: coarse and fine sand, BD: bulk density, θ_{0.7}: saturation point, θ_{2.5}: field capacity, Meg: megaporosity, Mac: macroporosity, Mes: mesoporosity, AWS: available water storage capacity, θ_{4.2}=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.

17
18 Fig. A.2- Bubble map of (a) the soil organic carbon stock (OCS in 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.

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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:  .

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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: .

28 Fig. A.1

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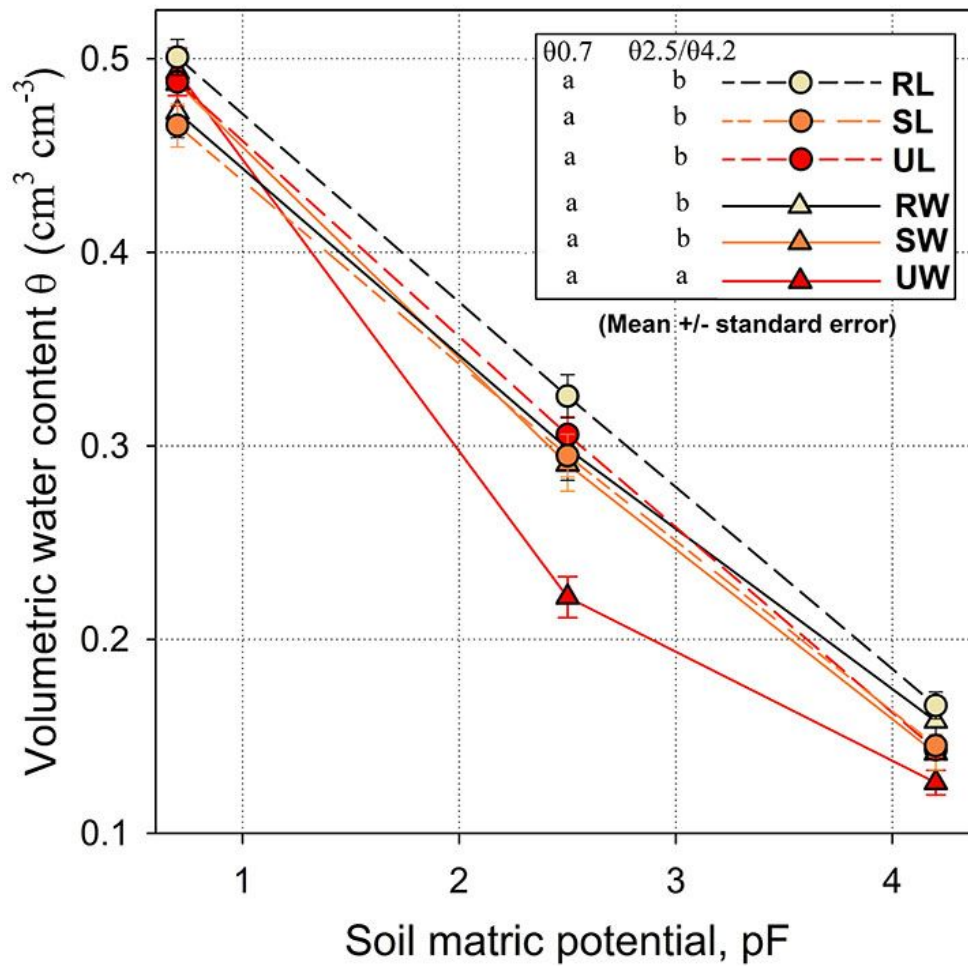
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47 00.7: Saturation point, 02.5: Field capacity, 04.2: Permanent wilting Point. RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural forests, SF: suburban forests, UF: urban forests. Error bars represent standard errors. Letters indicate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

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51 Fig. A.2

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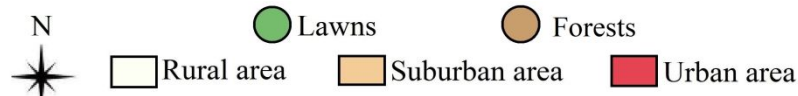
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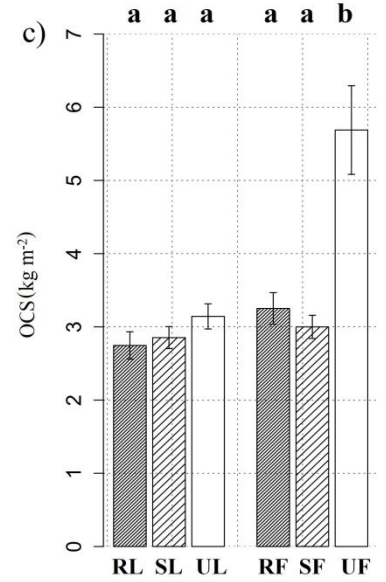
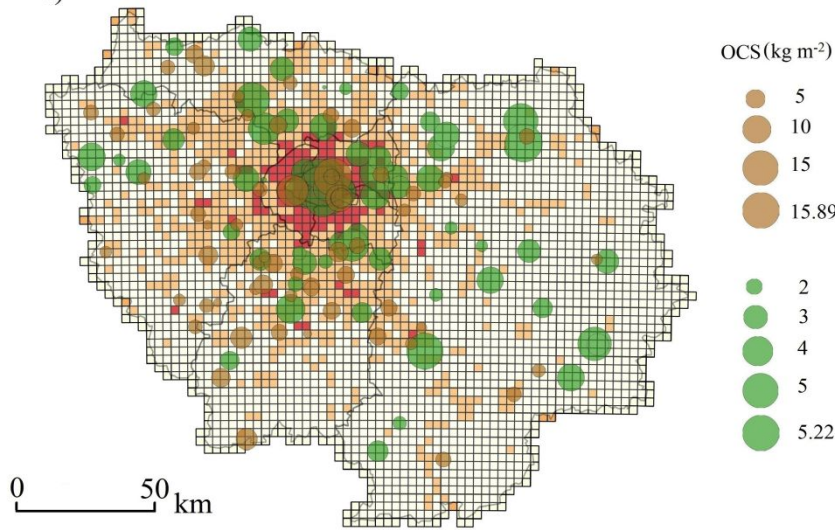
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a)



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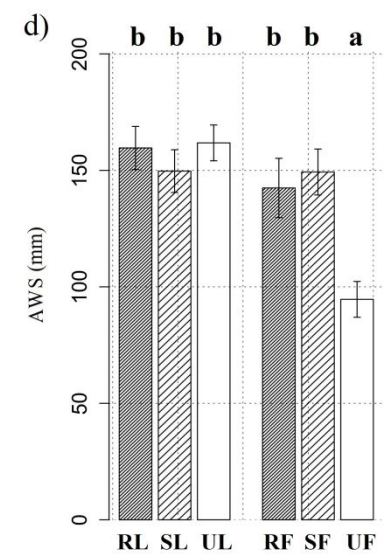
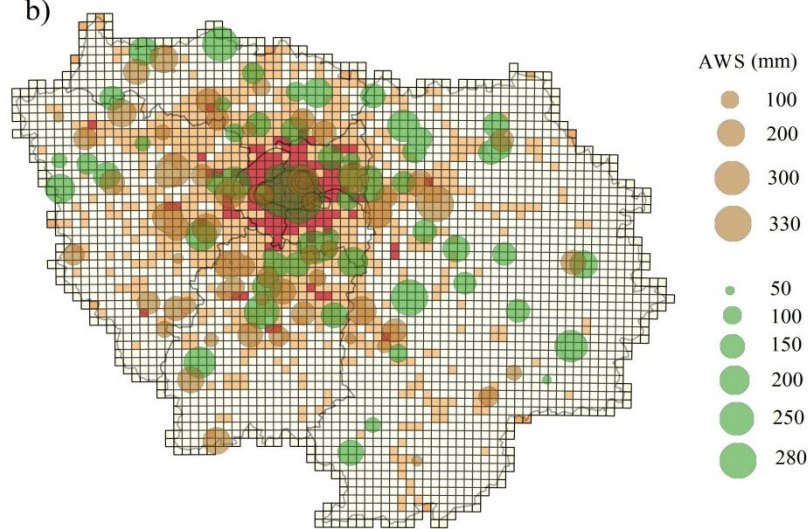
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b)



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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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80 a)

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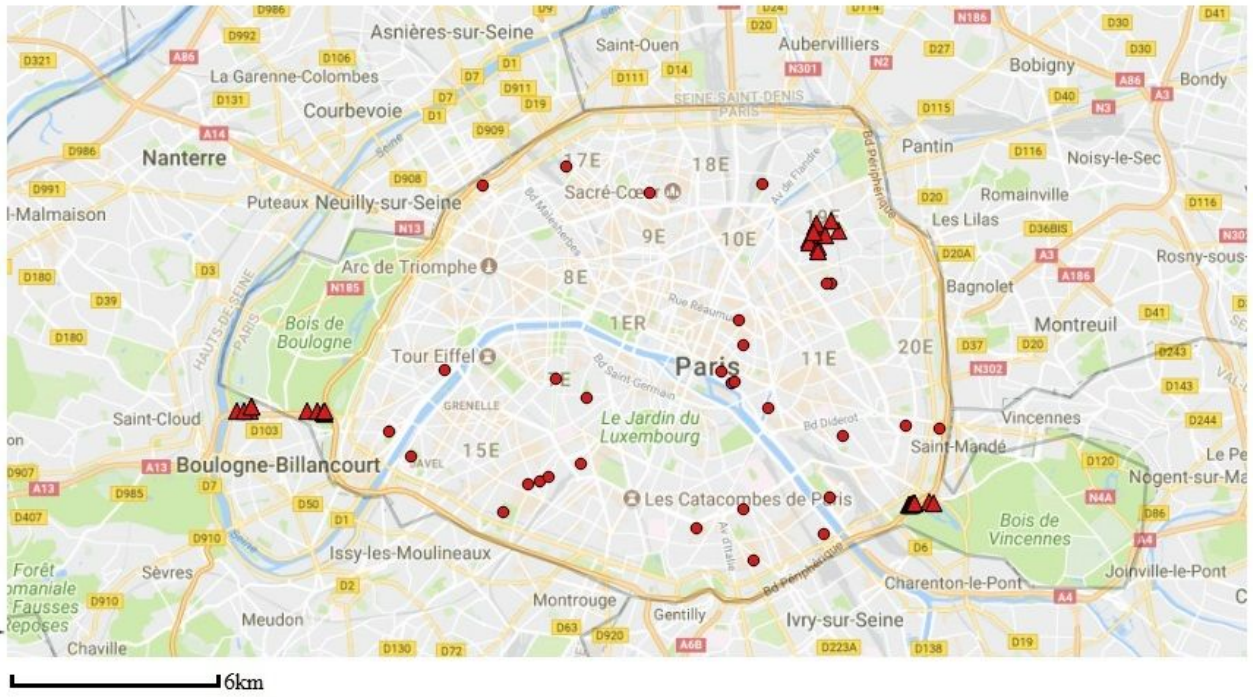
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90 b)

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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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