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

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Dear Editor

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

For Peer Review

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 This paper is well organized and concise, but the literature review is insufficient and some references are outdated.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 As a result, we have replaced the outdated references (Lines 47, 51, 54, 60, 66, 74, 77, 80, 82, 83 and line 86).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 theses 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.

For Peer Review

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 µm). The megapores (r > 600 µm) 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).

For Peer Review

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

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

Running title : TCFLURGPR

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

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Abstract

Urban soils are a crucial component of urban ecosystems, especially in public green spaces, because of the ecosystem services they provide (*e.g.* public recreation, urban cooling or water infiltration). In this study we describe 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 was done in order to identify how these soils have been affected by urbanization. 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. Many of the properties of urban forest soils differed from those of other sites (*e.g.* texture, organic carbon content, total nitrogen and carbonate contents), possibly because the urban forests are much older than the lawns and because of the legacy of the historical management of soils in this region (Haussmann period). Urban lawn soils were more compacted than urban forests, probably due to higher foot traffic. The effects of urbanization were, at times, confounded with other processes (*e.g.* sandier texture of urban forests), which suggests that surface soil characteristics were influenced by past urban planning. Finally, this study constitutes a baseline analysis for the monitoring of soil quality in the region.

1- Introduction

Cities and towns exert significant pressures on both urban and surrounding environments (Kaushal et al., 2014; Chambers et al., 2016). Urban soils are particularly impacted, in that they are heavily managed, with whole soil profiles often being anthropogenic. For example, fertile agricultural soils from rural areas are often imported for use in constructing urban green spaces (Bullock and Gregory, 1991). Furthermore, they are subjected to the addition of waste materials, pollutants from numerous point and diffuse sources, atmospheric deposition of carbon and nitrogen, or heat island effects. Town planning 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 materiel
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 (Kozlowski, 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

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

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

2- Materials and methods

2.1- Study area

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

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

2.2- Determination of Urban-Rural Gradient of the Paris region

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

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

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

2.3- Sampling design and protocol

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

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

Soil characteristics were described from one composite soil sample per sampling site. Each composite sample was made of 3 sub-samples collected within a 1 m² square from the top 10 cm of the organo-mineral layer (after having removed any vegetal or anthropogenic debris and the humus layer). Each composite sample was homogenized to constitute a representative sample according to the NF X31-100 standard. Samples were collected with an 8 cm-diameter stainless steel hand auger, immediately placed in polyethylene bags and subsequently air-dried in the laboratory. In order to measure the water retention curve of the soils, a single undisturbed sample was also taken from the 0-5 cm surface layer, at the centre of each 1 m² square using the cylinder method (Blake and Hartge, 1986). Roots and rocks were removed by hand from the base and the top of the cylinder. The undisturbed samples (100 cm^3) were stored in sealed bags at a temperature of 4-5°C to reduce biological activity and preserve the sample structure.

2.4- Chemical, physical and hydrostructural soil analysis

International (ISO) or French (NF) standardized methods were used to measure the chemical and physical soil characteristics: clay, coarse and fine silt (CSi and FSi), coarse and fine sand (CSa and FSa), organic carbon (OC), total nitrogen (tot N), pH-H_2O (pH), carbonates ($CaCO_3$), total phosphorus (tot P) and cation exchange capacity (CEC) (Table A.1). Particle-size distribution was assessed by the dispersion of mineral particles after destruction of the organic matter using hydrogen peroxide and separation of the particles into different classes by sedimentation. Soil pH was measured in water in a 1:5 soil-to-solution ratio at 25°C after shaking the suspension for 1 hour. Total N was measured by dry

155 combustion, after burning samples at 1000°C in the presence of O_2 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 $OCS_{(n)}=0.1xBD_{(n)}xOC_{(n)}$, where 0.1 is the sampling depth in meters, and BD the bulk density.
160 The soil carbonate concentration was determined by measuring the volume of CO_2 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

mm) were calculated following equations given in 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.

2.5- Statistical analysis

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

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

3- Results

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

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

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

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

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

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

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

3- Discussion

3.1- Impact of urban-rural gradient on forest topsoil characteristics

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

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

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

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

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

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

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

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

The phosphorus fertilization of lawns (*e.g.* monoammonium and diammonium phosphate) was until recently common practice in the Paris region (DEVE, pers. comm.), which can cause P accumulation in soils when applied in excess (Carpenter et al., 1998). This 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 megaporosity 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

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

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

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

4- Conclusion

Taken together, our results show that studying the soils of Paris region could be 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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Topsoil characteristics of forests and lawns along an urban-rural gradient in the Paris region (France)

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Abstract

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

1- Introduction

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

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

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

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

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

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

2- Materials and methods

2.1- Study area

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

2.2- Determination of Urban-Rural Gradient of the Paris region

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

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

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

2.3- Sampling design and protocol

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

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

Soil characteristics were described from one composite soil sample per sampling site. Each composite sample was made of 3 sub-samples collected within a 1 m² square from the top 10 cm of the organo-mineral layer (after having removed any vegetal or anthropogenic debris and the humus layer). Each composite sample was homogenized to constitute a representative sample according to the NF X31-100 standard. Samples were collected with an 8 cm-diameter stainless steel hand auger, immediately placed in polyethylene bags and subsequently air-dried in the laboratory. In order to measure the water retention curve of the soils, a single undisturbed sample was also taken from the 0-5 cm surface layer, at the centre of each 1 m² square using the cylinder method (Blake and Hartge, 1986). Roots and rocks were removed by hand from the base and the top of the cylinder. The undisturbed samples (100 cm^3) were stored in sealed bags at a temperature of 4-5°C to reduce biological activity and preserve the sample structure.

2.4- Chemical, physical and hydrostructural soil analysis

International (ISO) or French (NF) standardized methods were used to measure the chemical and physical soil characteristics: clay, coarse and fine silt (CSi and FSi), coarse and fine sand (CSa and FSa), organic carbon (OC), total nitrogen (tot N), pH-H_2O (pH), carbonates ($CaCO_3$), total phosphorus (tot P) and cation exchange capacity (CEC) (Table A.1). Particle-size distribution was assessed by the dispersion of mineral particles after destruction of the organic matter using hydrogen peroxide and separation of the particles into different classes by sedimentation. Soil pH was measured in water in a 1:5 soil-to-solution ratio at 25°C after shaking the suspension for 1 hour. Total N was measured by dry combustion, after burning samples at 1000°C in the presence of O_2 using a CHN auto-analyzer (CHN 1500, Carlo Erba). Organic carbon was quantified by sulfochromic oxidation using an auto-analyzer (Technicon III, Brian and Luebbe, Axflow). The soil organic carbon stocks (OCS in kg m^{-2}) in the first 10 cm were estimated using the equation: $OCS_{(n)}=0.1 x BD_{(n)} x OC_{(n)}$, where 0.1 is the sampling depth in meters, and BD the bulk density. The soil carbonate concentration was determined by measuring the volume of CO_2 released by reaction with HCl, using a Bernard calcimeter. Total phosphorus was measured by the molybdenum blue method, and quantified using an auto-analyzer (Technicon III, Brian and Luebbe, Axflow). CEC was determined after percolation of 1.0M ammonium acetate solution at pH 7.

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 ($r < 0.2$ µm). The megapores ($r > 600$ µm) 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.

2.5- Statistical analysis

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

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

3- Results

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

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

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

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

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

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

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

4- Discussion

4.1- Impact of urban-rural gradient on forest topsoil characteristics

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

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

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

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

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

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

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

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

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

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

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

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

4.3- Synthesis of underlying factors and study limits

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

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

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

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

5- Conclusion

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

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

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

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

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Abstract

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

1- Introduction

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

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

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

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

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

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

2- Materials and methods

2.1- Study area

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

2.2- Determination of Urban-Rural Gradient of the Paris region

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

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

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

2.3- Sampling design and protocol

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

129 factors: the Urban-Rural Gradient (URG, 3 levels) and the Land-use Type (LT, 2 levels). The
130 URG contained three concentric classes that broadly corresponded to an urban-rural gradient:
131 a rural class, a suburban class and an urban class. The classes were distinguished based on
132 population density, built-up area and estimated heat island effects. For a complete description
133 of the method used to identify the gradient (Foti et al., 2017). The two-targeted land-uses
134 were forests and lawns that, respectively, represent 21% (2525 km^2) and 22.2% (2670 km^2) 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 x 2 LT x 30 replicates =
139 180 sites) (Fig. 1).

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

International (ISO) or French (NF) standardized methods were used to measure the chemical and physical soil characteristics: clay, coarse and fine silt (CSi and FSi), coarse and fine sand (CSa and FSa), organic carbon (OC), total nitrogen (tot N), pH-H_2O (pH), carbonates ($CaCO_3$), total phosphorus (tot P) and cation exchange capacity (CEC) (Table A.1). Particle-size distribution was assessed by the dispersion of mineral particles after destruction of the organic matter using hydrogen peroxide and separation of the particles into different classes by sedimentation. Soil pH was measured in water in a 1:5 soil-to-solution ratio at 25°C after shaking the suspension for 1 hour. Total N was measured by dry combustion, after burning samples at 1000°C in the presence of O_2 using a CHN auto-analyzer (CHN 1500, Carlo Erba). Organic carbon was quantified by sulfochromic oxidation using an auto-analyzer (Technicon III, Brian and Luebbe, Axflow). The soil organic carbon stocks (OCS in kg m^{-2}) in the first 10 cm were estimated using the equation: $OCS_{(n)}=0.1 x BD_{(n)} x OC_{(n)}$, where 0.1 is the sampling depth in meters, and BD the bulk density. The soil carbonate concentration was determined by measuring the volume of CO_2 released by reaction with HCl, using a Bernard calcimeter. Total phosphorus was measured by the molybdenum blue method, and quantified using an auto-analyzer (Technicon III, Brian and Luebbe, Axflow). CEC was determined after percolation of 1.0M ammonium acetate solution at pH 7.

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 ($r < 0.2$ µm). The megapores ($r > 600$ µm) 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.

2.5- Statistical analysis

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

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

3- Results

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

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

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

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

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

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

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

4- Discussion

4.1- Impact of urban-rural gradient on forest topsoil characteristics

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

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

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

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

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

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

4.3- Synthesis of underlying factors and study limits

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

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

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

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

5- Conclusion

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

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

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

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Table 1- Effect of the Urban-Rural Gradient (URG), Land-use Types (LT), and their interactions (URGxLT) on the chemical, physical and hydrostructural soil characteristics of the Paris region (OCS: *soil organic carbon stock*, OC: *organic carbon*, tot N: *total nitrogen*, tot P: *total phosphorus*, pH: *pH–H_2O*, CEC: *Cation Exchange Capacity,* C/N ratio*,* $CaCO_3$: *carbonates*, Clay, CSi and FSi: *coarse and fine silt*, CSa and FSa: *coarse and fine sand*, BD: *bulk density*, θ0.7: *saturation point,* θ2.5: *field capacity,* Meg: *megaporosity*, Mac: *macroporosity*, Mes: *mesoporosity,* AWS: *available water storage capacity*, θ4.2=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, θ0.7, θ2.5 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
$CaCO_3$	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				
θ0.7	0.54	0.01	2.30	0.004
θ2.5	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
θ4.2=Mic	9.80***	11.19**	2.64	0.15

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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

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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				
θ0.7	0.54	0.01	2.30	0.004
θ2.5	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
θ4.2=Mic	9.80***	11.19**	2.64	0.15

Results of linear models (degrees of freedom (df) (total residual df=174), F values) (*p-value<0.05, **p-value<0.01, ***p-value<0.001). All chemical, physical and hydrostructural soil variables were log-transformed, except Meg (square root) and pH (exponential). BD, θ0.7, θ2.5 and AWS were not transformed.

(**OCS:** soil organic carbon stock, **OC:** organic carbon, tot N: total nitrogen, **tot P:** total phosphorus, **pH:** pH–H_2O, **CEC:** Cation Exchange Capacity, **C/N ratio**, **$CaCO_3$:** carbonates, **Clay, CSi and FSi:** coarse and fine silt, **CSa and FSa:** coarse and fine sand, **BD:** bulk density, **θ0.7:** saturation point, **θ2.5:** field capacity, **Meg:** megaporosity, **Mac:** macroporosity, **Mes:** mesoporosity, **AWS:** available water storage capacity, **θ4.2=Mic:** permanent wilting point=microporosity)

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

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

Fig. 3- Between-group analysis on the chemical, physical and hydrostructural soil characteristics of the Paris region with the composite factor URGxLT as explanatory variable. (a) Correlation circle plot with the soil characteristic vectors (OC: *organic carbon*, tot N: *total nitrogen*, tot P: *total phosphorus*, pH: *pH–H_2O*, CEC: *cation exchange capacity,* $CaCO_3$: *carbonates*, Clay, CSa and FSa: *coarse and fine sand*, FSi: *fine silt*, BD: *bulk density*, Meg: *megaporosity*, Mac: *macroporosity*, Mes: *mesoporosity,* Mic: *microporosity*). (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).

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

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carbon, tot N: *total nitrogen*, tot P: *total phosphorus*, pH: *pH–H_2O*, CEC: *cation exchange capacity,* C/N ratio*,* $CaCO_3$: *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.

Fig. 5- Mean values of the hydrostructural soil characteristics of forest and lawn soils in rural, suburban and urban areas of the Paris region. (megaporosity, macroporosity, mesoporosity, and microporosity). 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.

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Fig. 1

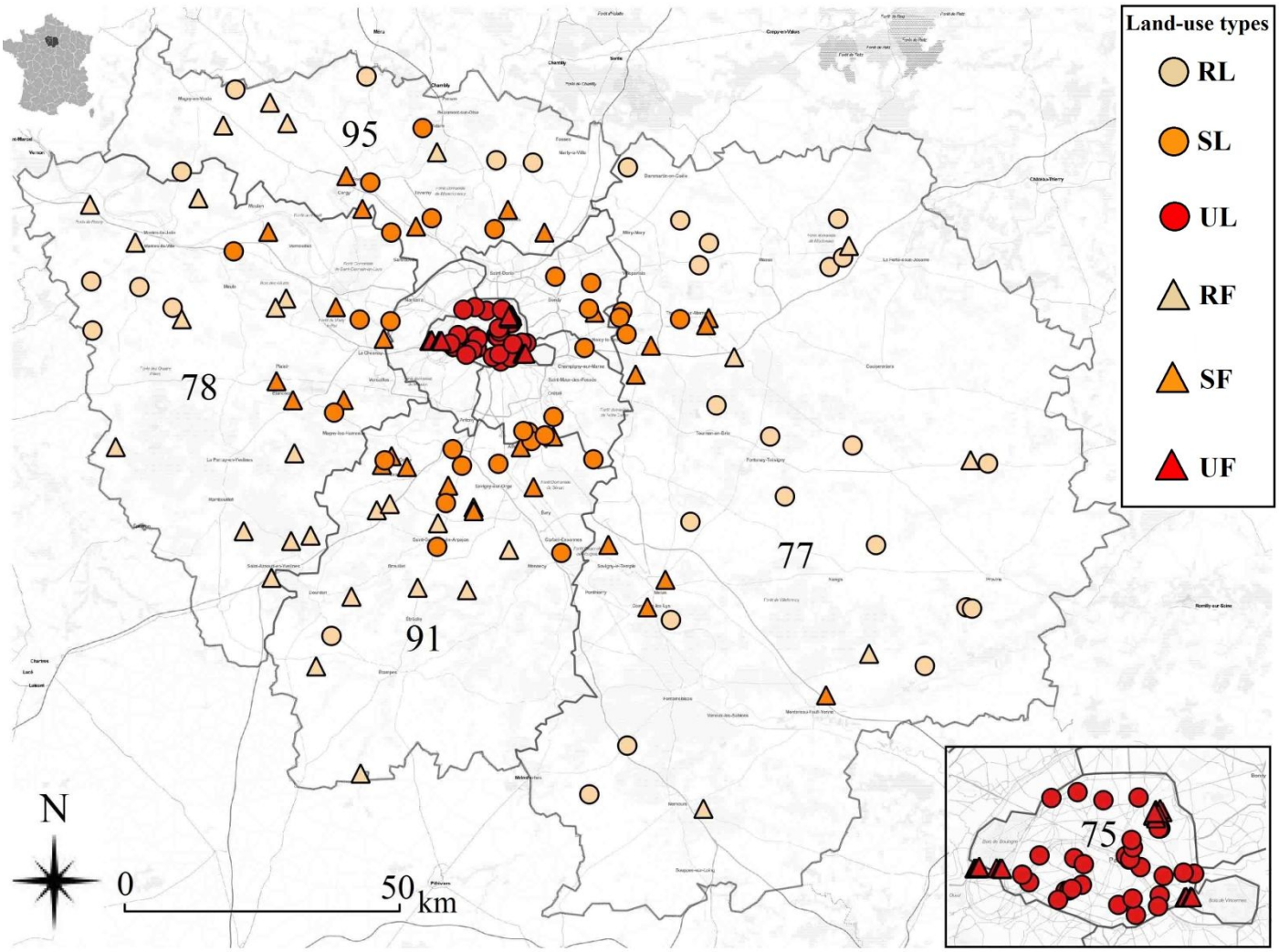

Fig. 2

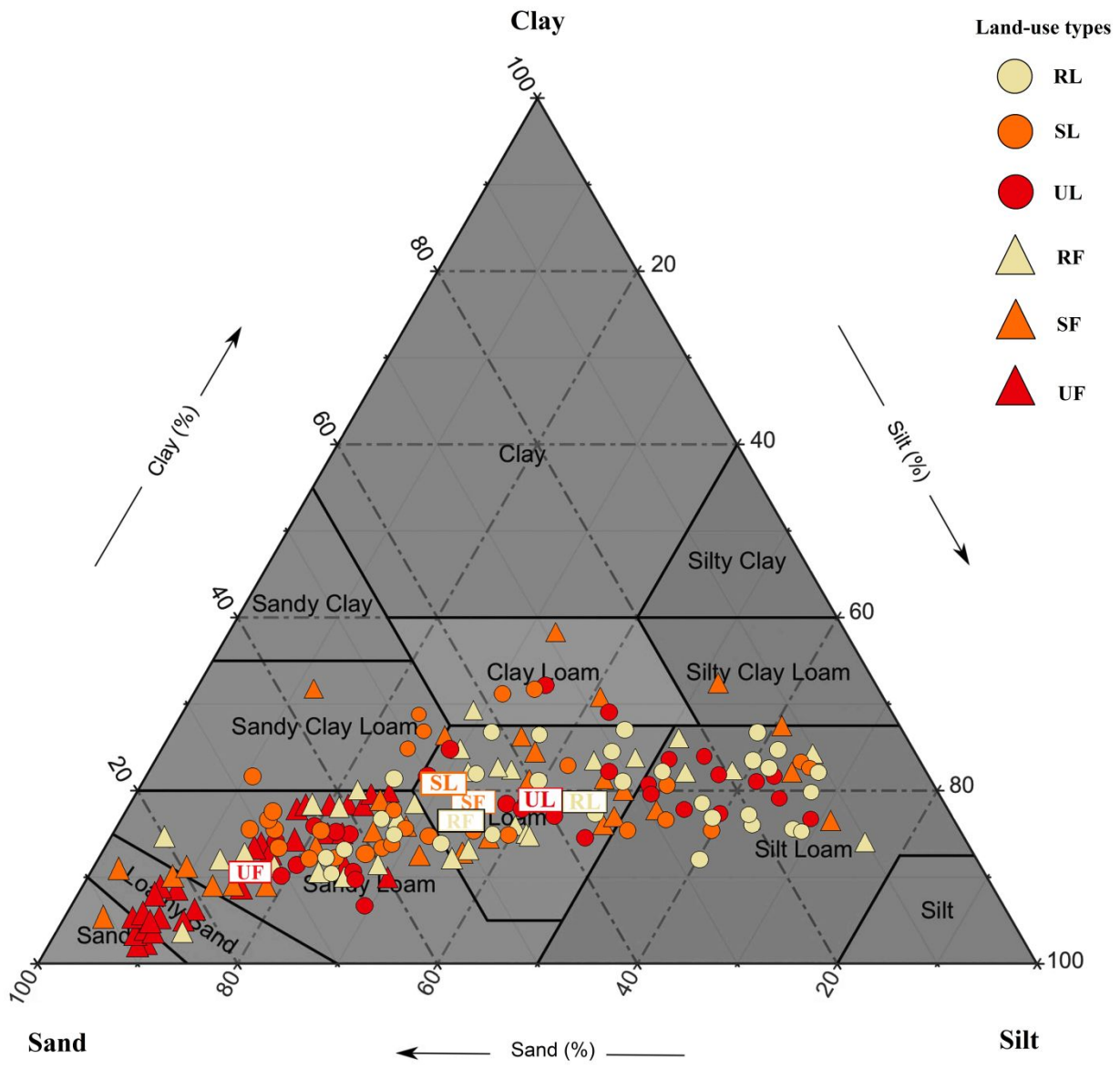
Clay
Land-use types
RL
SL
UL
RF
SF
UF
Clay (%)
Silt (%)
Clay
Silty Clay
Sandy Clay
Clay Loam
Silty Clay Loam
Sandy Clay Loam
Loam
Silt Loam
Sandy Loam
Loamy Sand
Sand
Silt
Sand
Silt
Sand (%)
100
80
60
40
20

Fig. 3

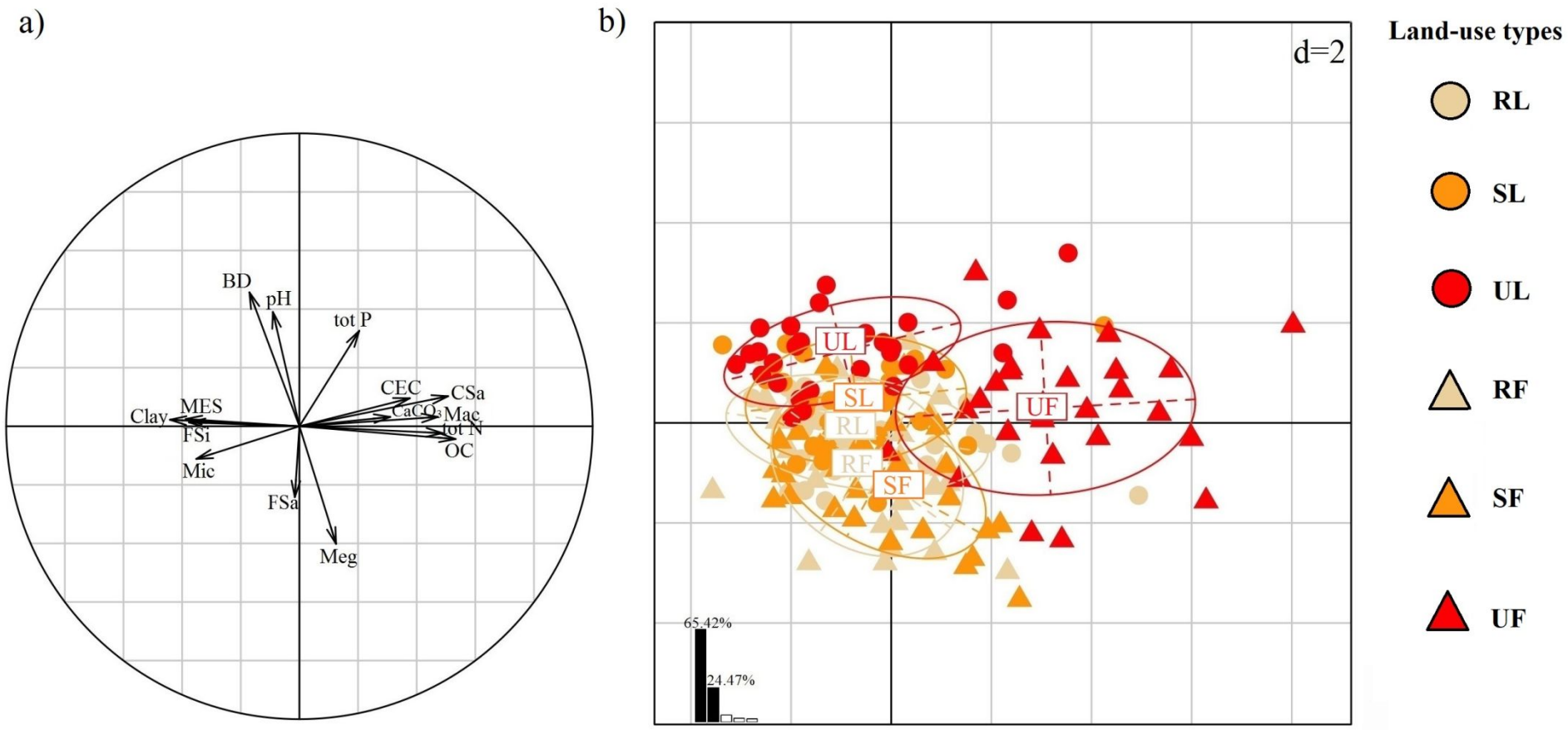
a)
BD
pH
tot P
CEC
CSa
Clay
MES
FSi
CaCO3
Mac
tot N
OC
Mic
FSa
Meg
b)
d=2
UL
SL
RL
RF
SF
UF
65.42%
24.47%
Land-use types
RL
SL
UL
RF
SF
UF

Fig. 4

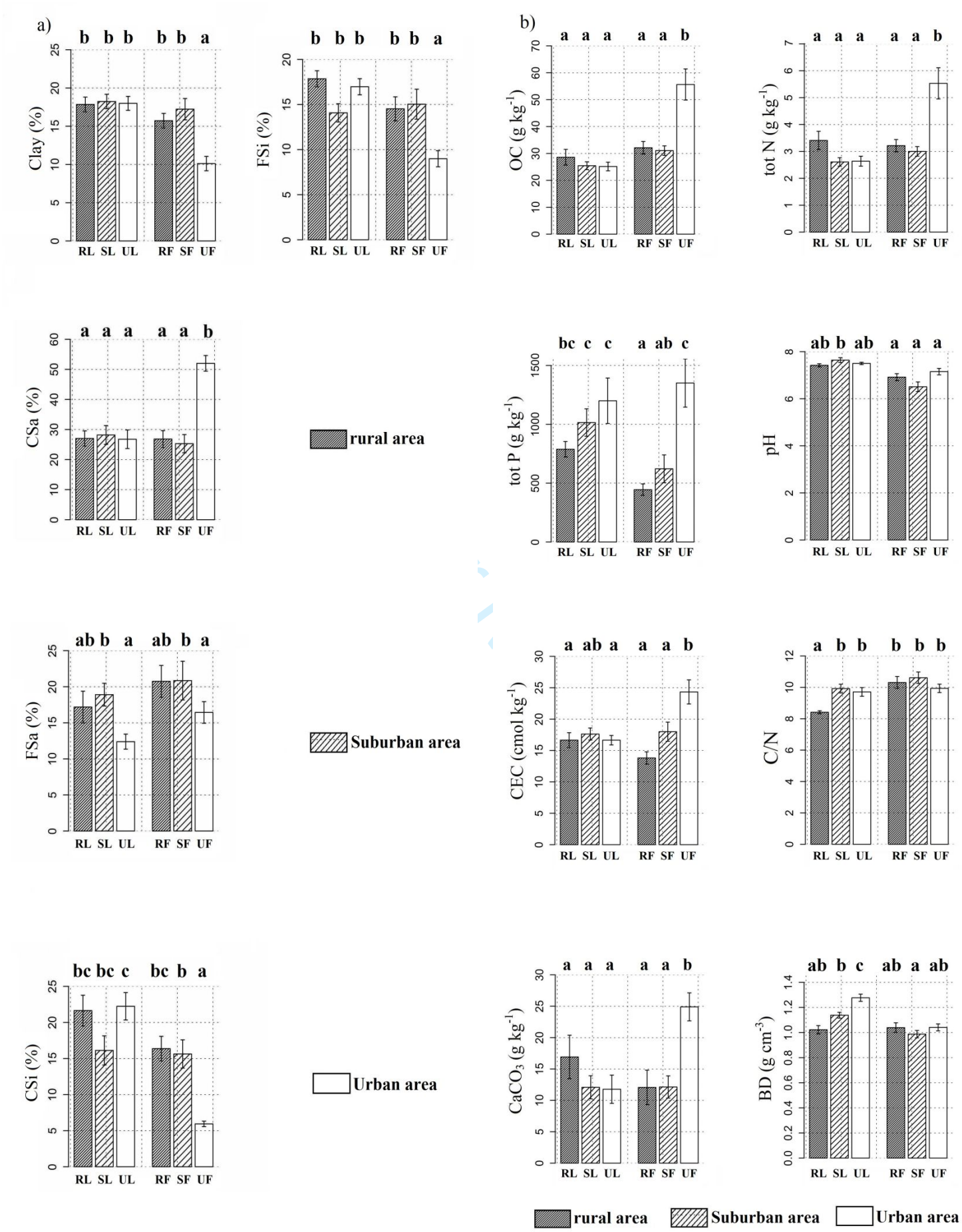
a)
b)
Clay (%)
FSi (%)
OC (g kg-1)
tot N (g kg-1)
CSa (%)
tot P (g kg-1)
pH
FSa (%)
CEC (cmol kg-1)
C/N
CSi (%)
CaCO3 (g kg-1)
BD (g cm-3)
RL SL UL RF SF UF
rural area
Suburban area
Urban area

Fig. 5

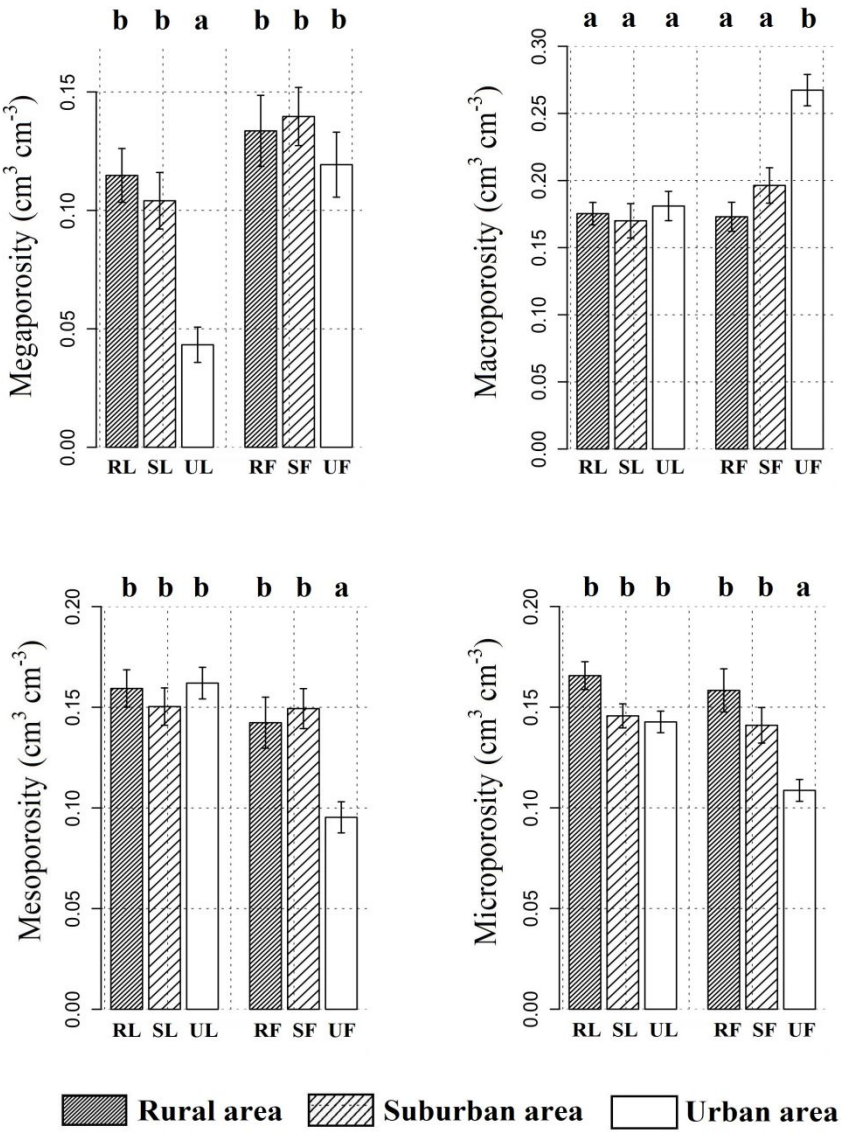
b b a b b b
Megaporosity (cm3 cm-3)
0.00 0.05 0.10 0.15
RL SL UL RF SF UF
a a a a a b
Macroporosity (cm3 cm-3)
0.00 0.05 0.10 0.15 0.20 0.25 0.30
RL SL UL RF SF UF
b b b b b a
Mesoporosity (cm3 cm-3)
0.00 0.05 0.10 0.15 0.20
RL SL UL RF SF UF
b b b b b a
Microporosity (cm3 cm-3)
0.00 0.05 0.10 0.15 0.20
RL SL UL RF SF UF
Rural area
Suburban area
Urban area

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

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

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

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

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

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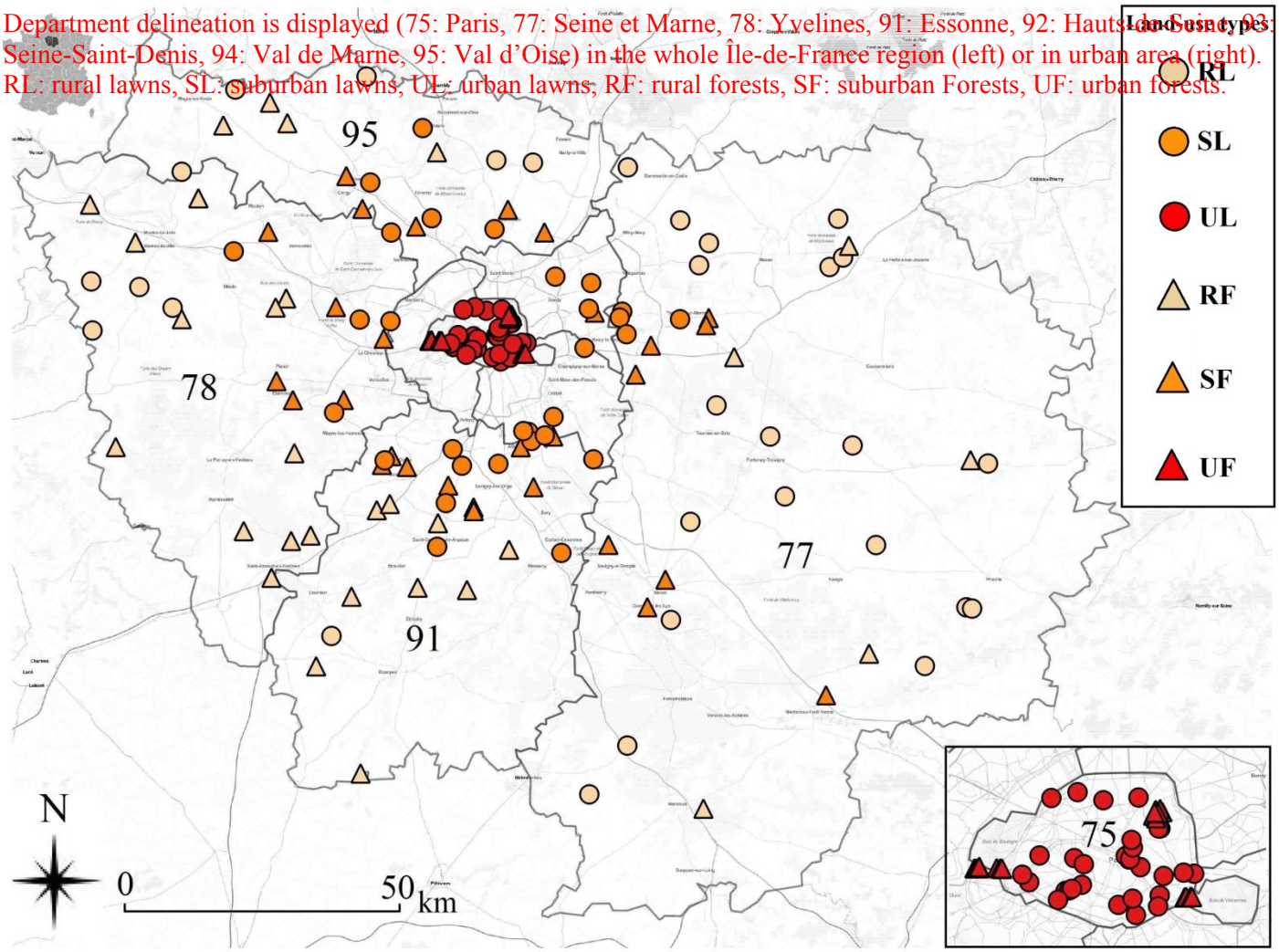
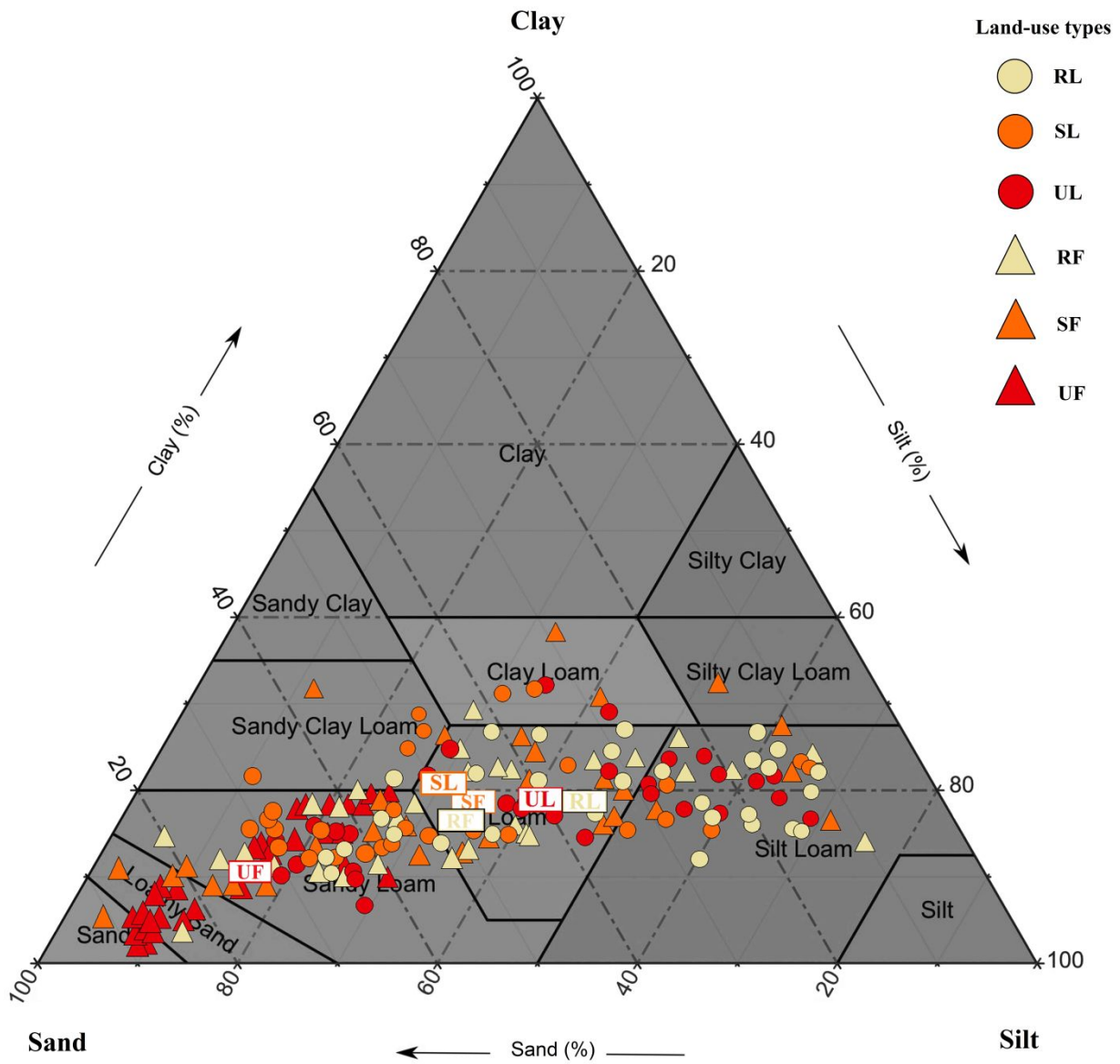
Fig. 1



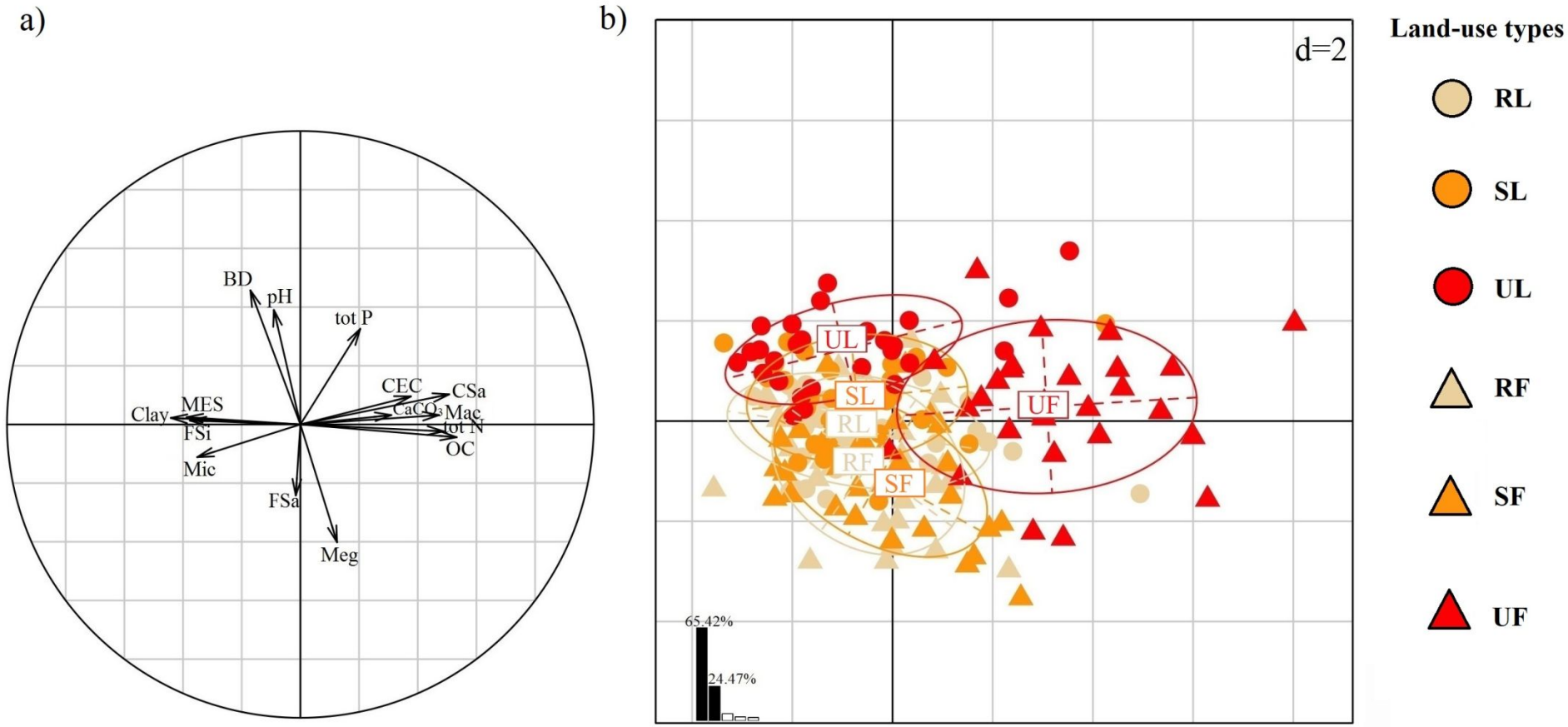
Department delineation is displayed (75: Paris, 77: Seine et Marne, 78: Yvelines, 91: Essonne, 92: Hauts-de-Seine, 93: Seine-Saint-Denis, 94: Val de Marne, 95: Val d'Oise) in the whole Île-de-France region (left) or in urban area (right). RL: rural lawns, SL: suburban lawns, UL: urban lawns, RF: rural forests, SF: suburban Forests, UF: urban forests.

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).

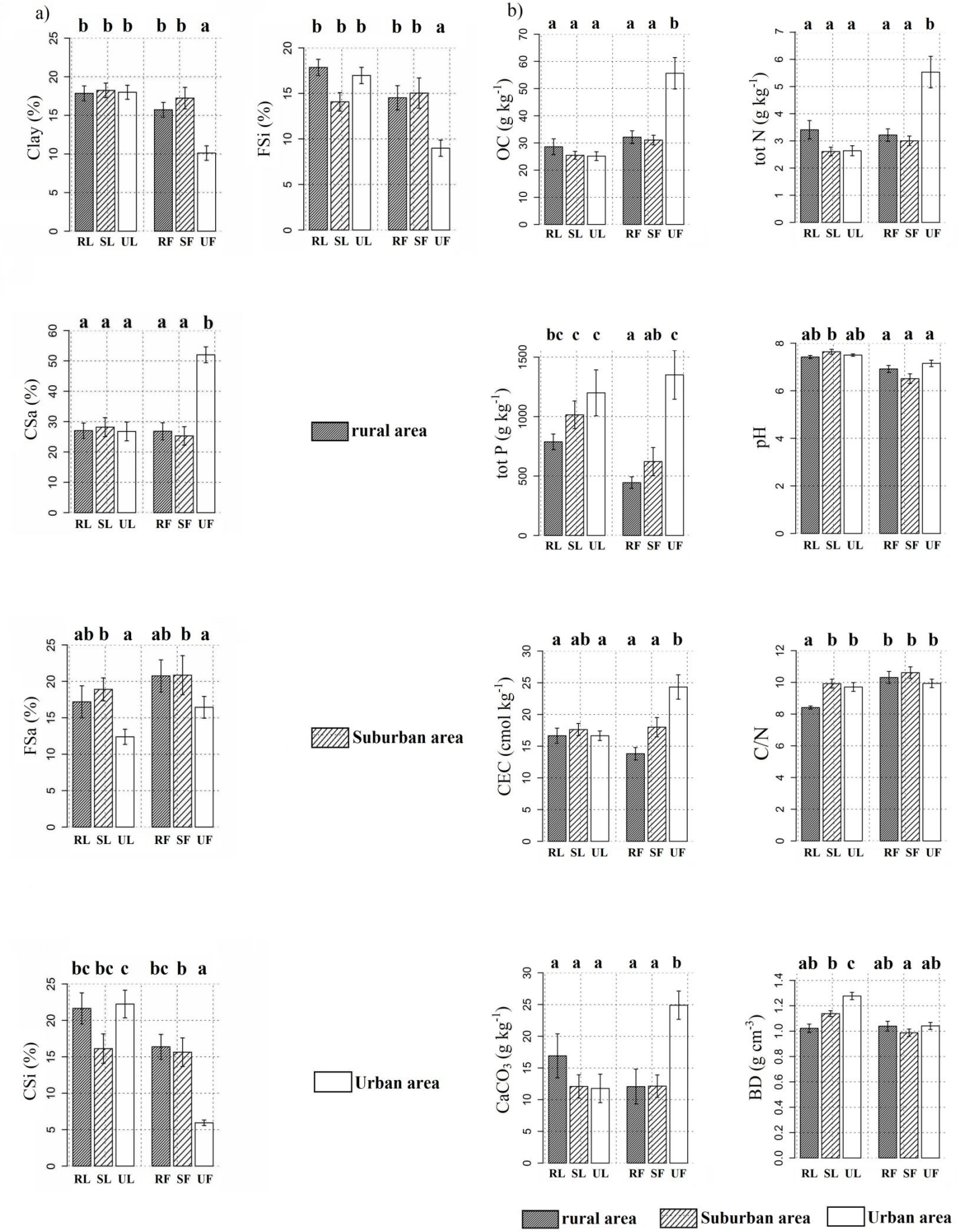
Fig. 3



(a) Correlation circle plot with the soil characteristic vectors (**OC:** *organic carbon*, **tot N:** *total nitrogen*, **tot P:** *total phosphorus*, **pH:** *pH–H_2O*, **CEC:** *cation exchange capacity,* **$CaCO_3$:** *carbonates*, **Clay, CSa and FSa:** *coarse and fine sand*, **FSi:** *fine silt*, **BD:** *bulk density*, **Meg:** *megaporosity*, **Mac:** *macroporosity*, **Mes:** *mesoporosity,* **Mic:** *microporosity*).

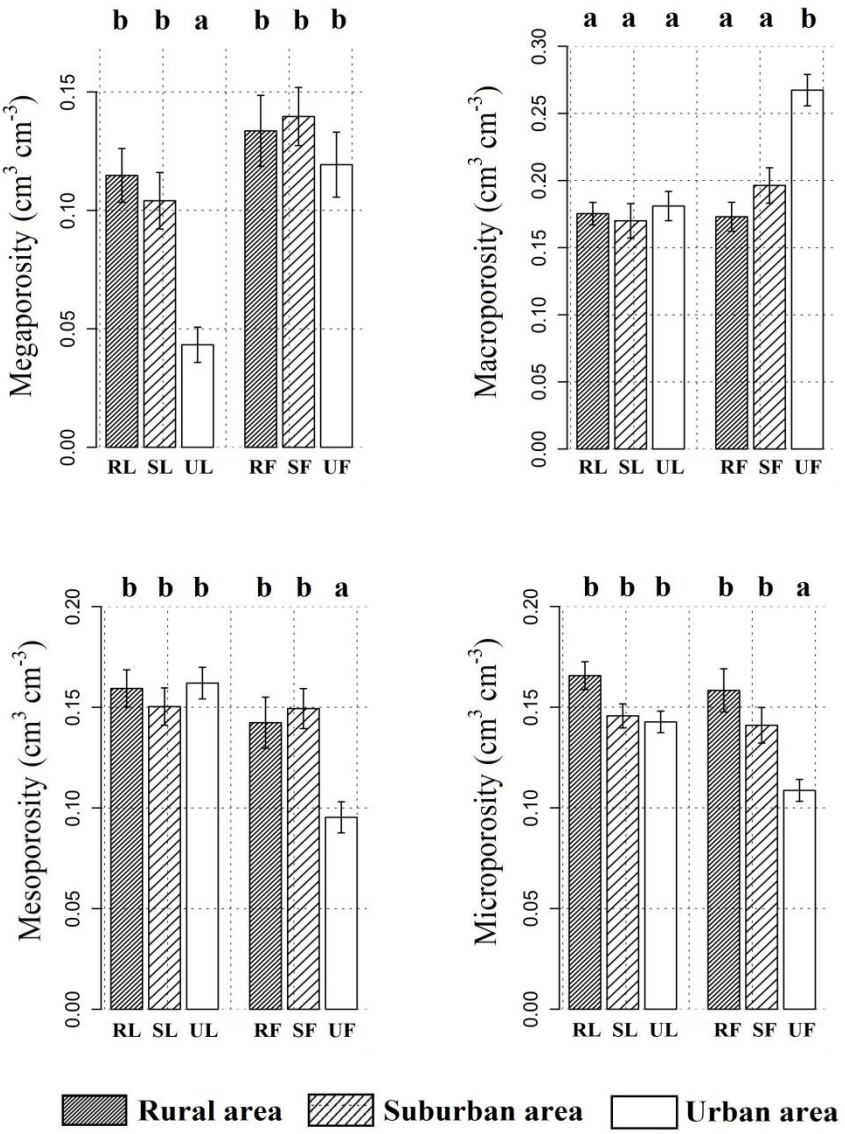
(b) Projection of the sampled soils on the factorial map of the first two discriminating axes according to the combination of URG (Urban-Rural Gradient) and LT (Land-use Type). Labels of the gravity centers: rural lawns (RL), suburban lawns (SL), urban lawns (UL), rural forests (RF), suburban forests (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).

Fig. 4



OC: *organic carbon*, tot N: *total nitrogen*, tot P: *total phosphorus*, pH: *pH–H_2O*, CEC: *cation exchange capacity,* C/N ratio, $CaCO_3$: *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.

Fig. 5



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_2O	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	[a]$BD_{(n)} = M_{t(n)}/V_{t(n)}$	g cm^{-3}	
Hydrostructural soil characteristics	Saturation point	θ0.7	[b]$\theta0.7_{(n)} = W0.7_{(n)}xBD_{(n)}$		
	Field capacity	θ2.5	$\theta2.5_{(n)} = W2.5_{(n)} x BD_{(n)}$		
	Total Porosity	TP	[c]$TP_{(n)} = 1 - BD_{(n)}/2.65$		
	Megaporosity	Meg	$MEG_{(n)} = TP_{(n)}-\theta0.7_{(n)}$	cm^3 cm^{-3}	
	Macroporosity	Mac	$MAC_{(n)} = \theta0.7_{(n)}-\theta2.5_{(n)}$		
	Mesoporosity	Mes	$MES_{(n)} = \theta2.5_{(n)}-\theta4.2_{(n)}$		
	Permanent wilting point= microporosity	θ4.2= Mic	$\theta4.2_{(n)} = W4.2_{(n)}xBD_{(n)}$		
	soil Organic Carbon Sock	OCS	[d]$OCS_{(n)} = 0.1xBD_{(n)}xOC_{(n)}$	kg m^{-2}	
	Available Water Storage	AWS	[d]$AWS_{(n)} = (W2.5_{(n)} - W4.2_{(n)})xBD_{(n)}x10$	mm	

[a]M_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,
[b]W is the gravimetric water soil content,
[c]2.65 g cm^{-3} is the constant particle density,
[d]For the top10 cm of the organo-mineral soil layer.

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Table A.2- Chemical, physical and hydrostructural soil characteristics (mean values, standard deviations and range) of the topsoil of forests and lawns in urban, suburban and rural areas of the Paris region. (OCS: *soil organic carbon stock*, OC: *organic carbon*, tot N: *total nitrogen*, tot P: *total phosphorus*, pH: *pH–H_2O*, CEC: *cation exchange capacity,* C/N ratio, $CaCO_3$: *carbonates*, Clay, CSi and FSi: *coarse and fine silt*, CSa and FSa: *coarse and fine sand,* BD: *bulk density*, θ0.7: *saturation point,* θ2.5: *field capacity*, Meg: *megaporosity*, Mac: *macroporosity*, Mes: *mesoporosity,* AWS: *available water storage capacity*, θ4.2=Mic: *permanent witlting point=microporosity*).

	Chemical, physical, and hydrostructural soil characteristics	Rural area		Suburban area		Urban area	
		Lawns	**Forests**	**Lawns**	**Forests**	**Lawns**	**Forests**
Chemical and physical soil characteristics	**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)
	$CaCO_3$ (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	**θ0.7** (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)
	θ2.5 (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)

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Fig. A.1- Water soil retention mean curves on both land-uses types (lawns and forests) from the urban-rural gradient of the Paris region. θ0.7: *Saturation point,* θ2.5: *Field capacity*, θ4.2: *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.

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

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Fig. A.3- Bubble map of (a) the soil organic carbon stock (OCS in kg m^{-2}), (b) the available water storage capacity (AWS in mm), and associated mean values (c and d) in lawn and forest soils along the rural, suburban and urban areas of the Paris region. 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.

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

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

Fig. A.1

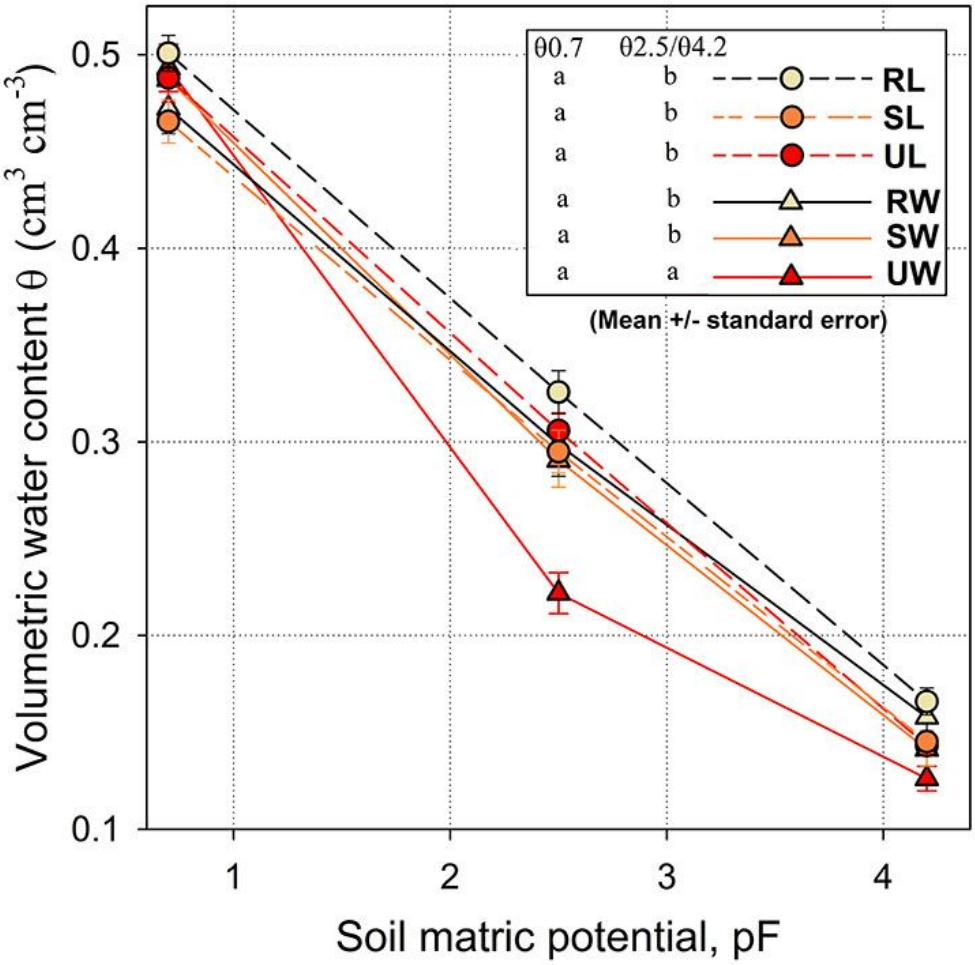

θ0.7 θ2.5/θ4.2
a b RL
a b SL
a b UL
a b RW
a b SW
a a UW
(Mean +/- standard error)
Volumetric water content θ (cm3 cm-3)
0.5
0.4
0.3
0.2
0.1
1
2
3
4
Soil matric potential, pF

Fig. A.2

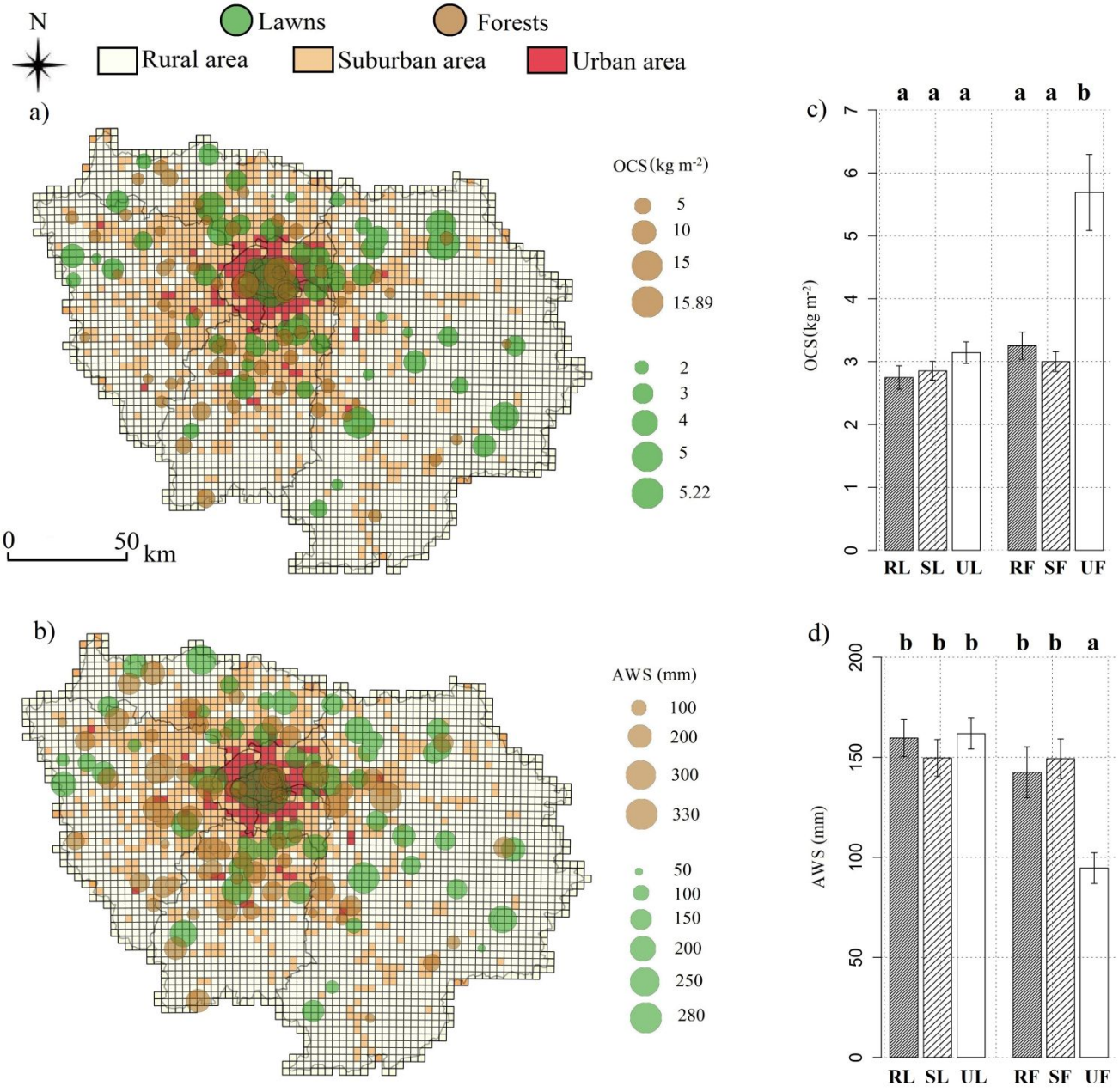
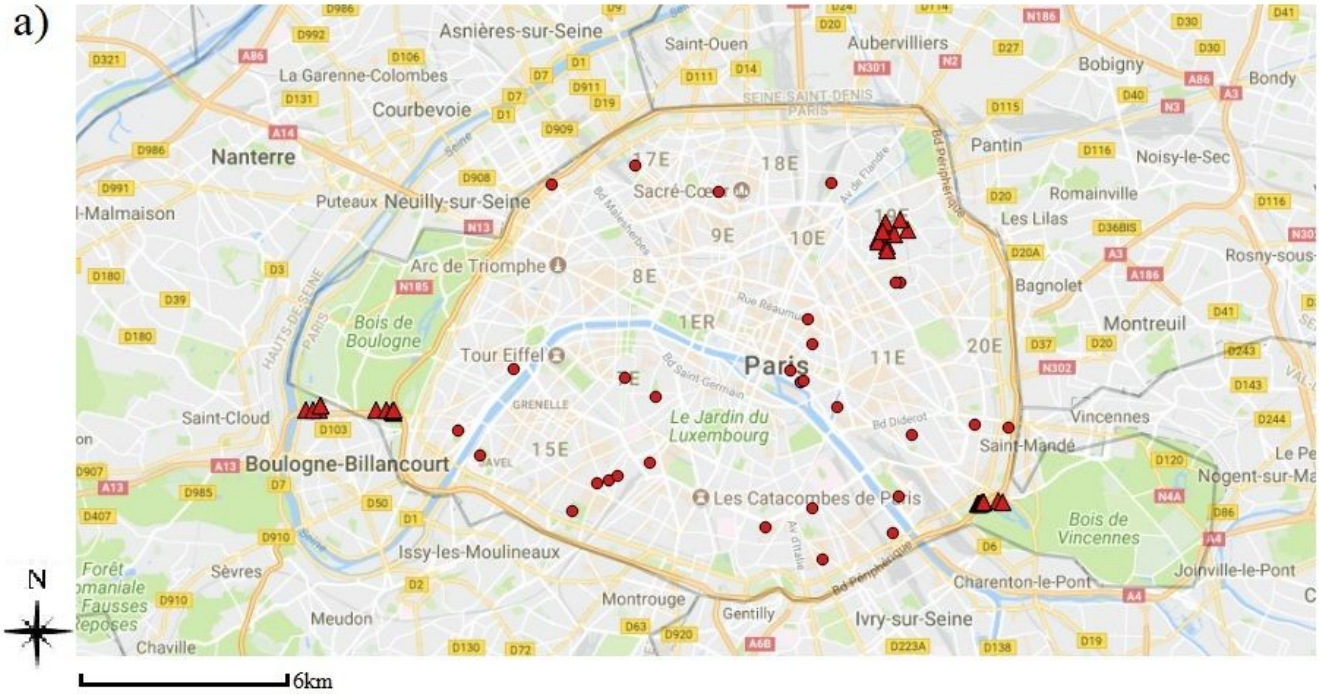

N
Lawns
Forests
Rural area
Suburban area
Urban area
a)
OCS(kg m-2)
5
10
15
15.89
2
3
4
5
5.22
0
50 km
b)
AWS (mm)
100
200
300
330
50
100
150
200
250
280
c)
a a a a a b
OCS(kg m-2)
0 1 2 3 4 5 6 7
RL SL UL RF SF UF
d)
b b b b b a
AWS (mm)
0 50 100 150 200
RL SL UL RF SF UF

Fig. A.3

a)


Asnières-sur-Seine
Saint-Ouen
Aubervilliers
Bobigny
Bondy
La Garenne-Colombes
Courbevoie
Nanterre
Puteaux
Neuilly-sur-Seine
Pantin
Noisy-le-Sec
Romainville
Les Lilas
Rosny-sous-
Bagnolet
Montreuil
Vincennes
Saint-Mandé
Nogent-sur-Ma
Bois de Vincennes
Joinville-le-Pont
Charenton-le-Pont
Ivry-sur-Seine
Gentilly
Montrouge
Meudon
Chaville
Sèvres
Issy-les-Moulineaux
Boulogne-Billancourt
Saint-Cloud
Bois de Boulogne
Arc de Triomphe
Tour Eiffel
Paris
Sacré-Cœur
Le Jardin du Luxembourg
Les Catacombes de Paris
17E
18E
9E
10E
8E
1ER
11E
20E
15E
N
6km

b)

Fig. A.4

Typology:

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

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_2O	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	[a]$BD_{(n)} = M_{t(n)}/V_{t(n)}$	g cm^{-3}	
Hydrostructural soil characteristics	Saturation point	θ0.7	[b]$\theta0.7_{(n)} = W0.7_{(n)}xBD_{(n)}$		
	Field capacity	θ2.5	$\theta2.5_{(n)} = W2.5_{(n)} x BD_{(n)}$		
	Total Porosity	TP	[c]$TP_{(n)} = 1 - BD_{(n)}/2.65$		
	Megaporosity	Meg	$MEG_{(n)} = TP_{(n)}-\theta0.7_{(n)}$	cm^3 cm^{-3}	
	Macroporosity	Mac	$MAC_{(n)} = \theta0.7_{(n)}-\theta2.5_{(n)}$		
	Mesoporosity	Mes	$MES_{(n)} = \theta2.5_{(n)}-\theta4.2_{(n)}$		
	Permanent wilting point= microporosity	θ4.2= Mic	$\theta4.2_{(n)} = W4.2_{(n)}xBD_{(n)}$		
	soil Organic Carbon Sock	OCS	[d]$OCS_{(n)} = 0.1xBD_{(n)}xOC_{(n)}$	kg m^{-2}	
	Available Water Storage	AWS	[d]$AWS_{(n)} = (W2.5_{(n)} - W4.2_{(n)})xBD_{(n)}x10$	mm	

[a]M_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,
[b]W is the gravimetric water soil content,
[c]2.65 g cm^{-3} is the constant particle density,
[d]For the top10 cm of the organo-mineral soil layer.

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Table A.2- Chemical, physical and hydrostructural soil characteristics (mean values, standard deviations and range) of the topsoil of forests and lawns in urban, suburban and rural areas of the Paris region.

	Chemical, physical, and hydrostructural soil characteristics	Rural area		Suburban area		Urban area	
		Lawns	**Forests**	**Lawns**	**Forests**	**Lawns**	**Forests**
Chemical and physical soil characteristics	**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)
	$CaCO_3$ (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	**θ0.7** (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)
	θ2.5 (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–H_2O, CEC: cation exchange capacity, C/N ratio, $CaCO_3$: carbonates, Clay, CSi and FSi: coarse and fine silt, CSa and FSa: coarse and fine sand, BD: bulk density, θ0.7: saturation point, θ2.5: field capacity, Meg: megaporosity, Mac: macroporosity, Mes: mesoporosity, AWS: available water storage capacity, θ4.2=Mic: permanent witlting point=microporosity.

For Peer Review

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

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

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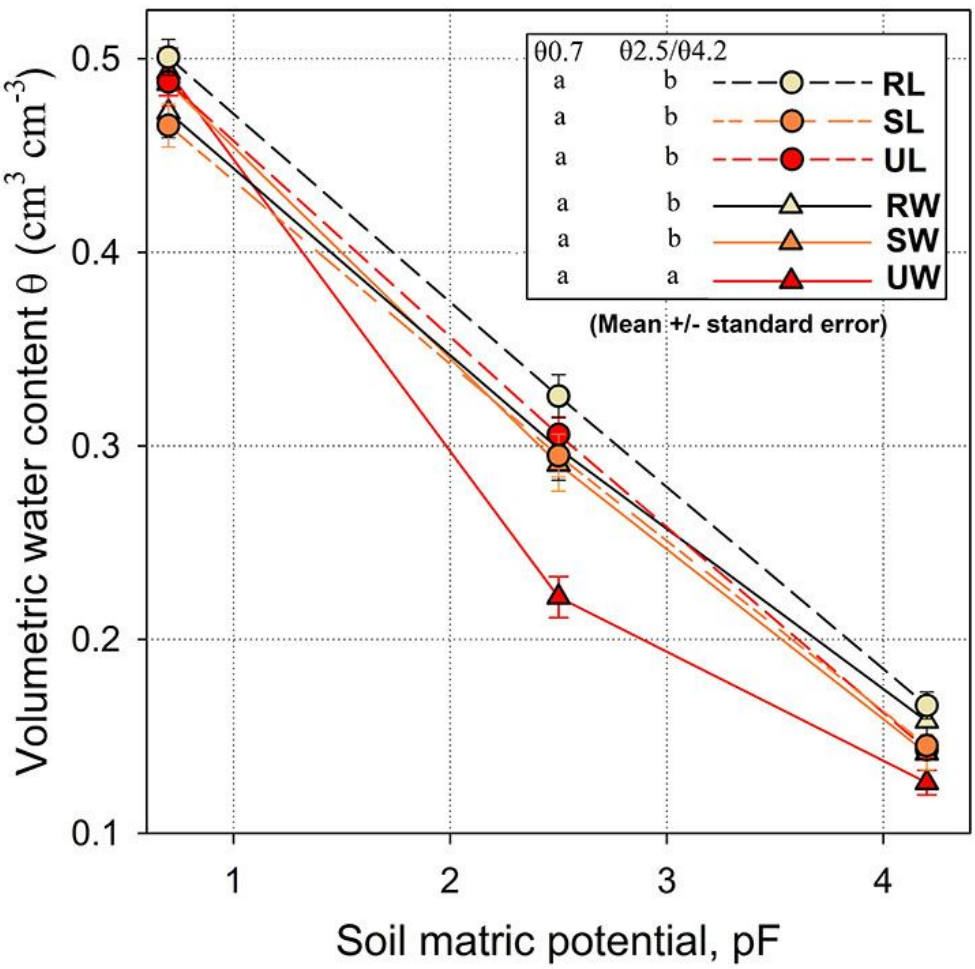
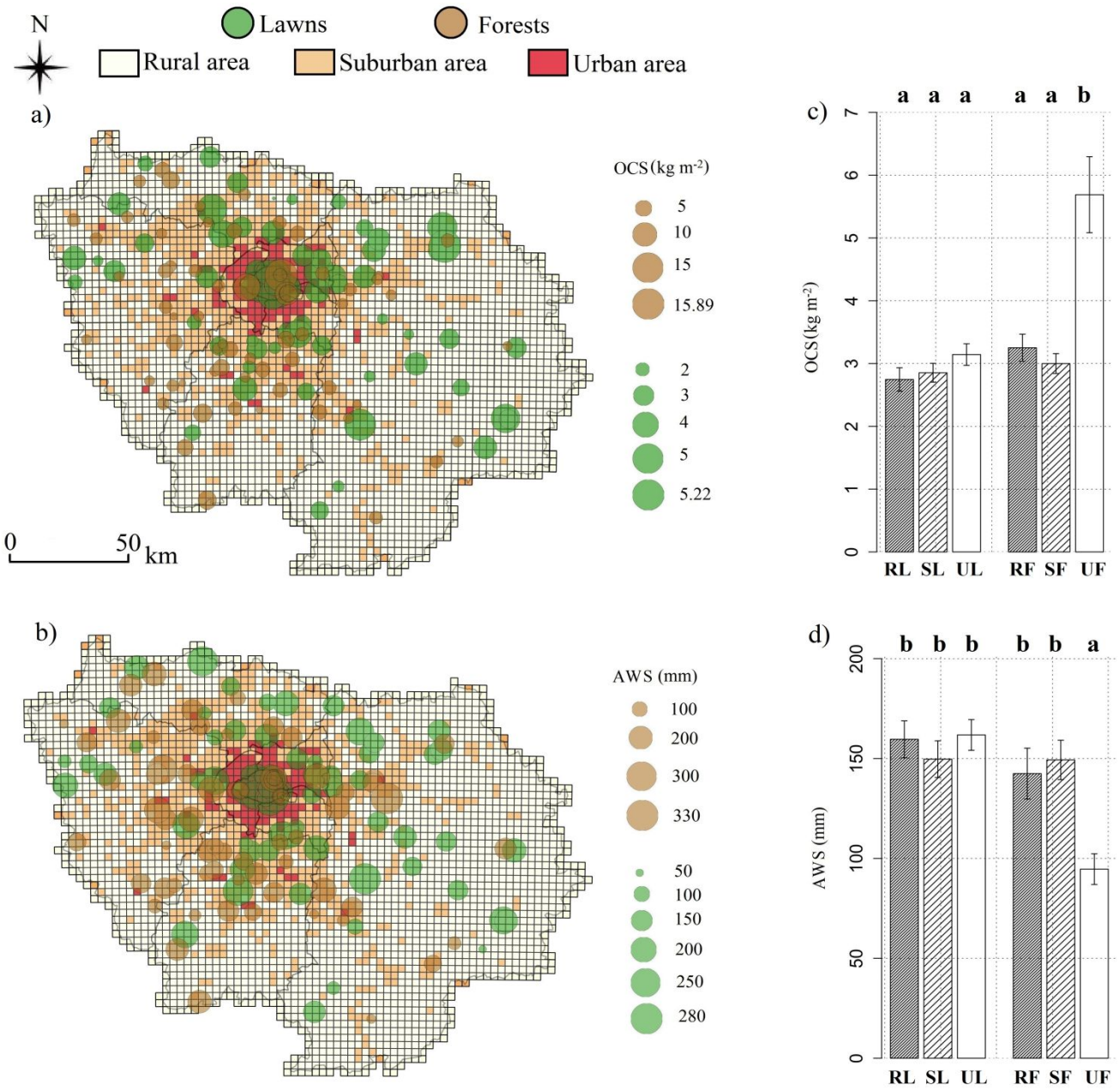
For Peer Review

Fig. A.1



θ0.7: *Saturation point,* θ2.5: *Field capacity*, θ4.2: *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.

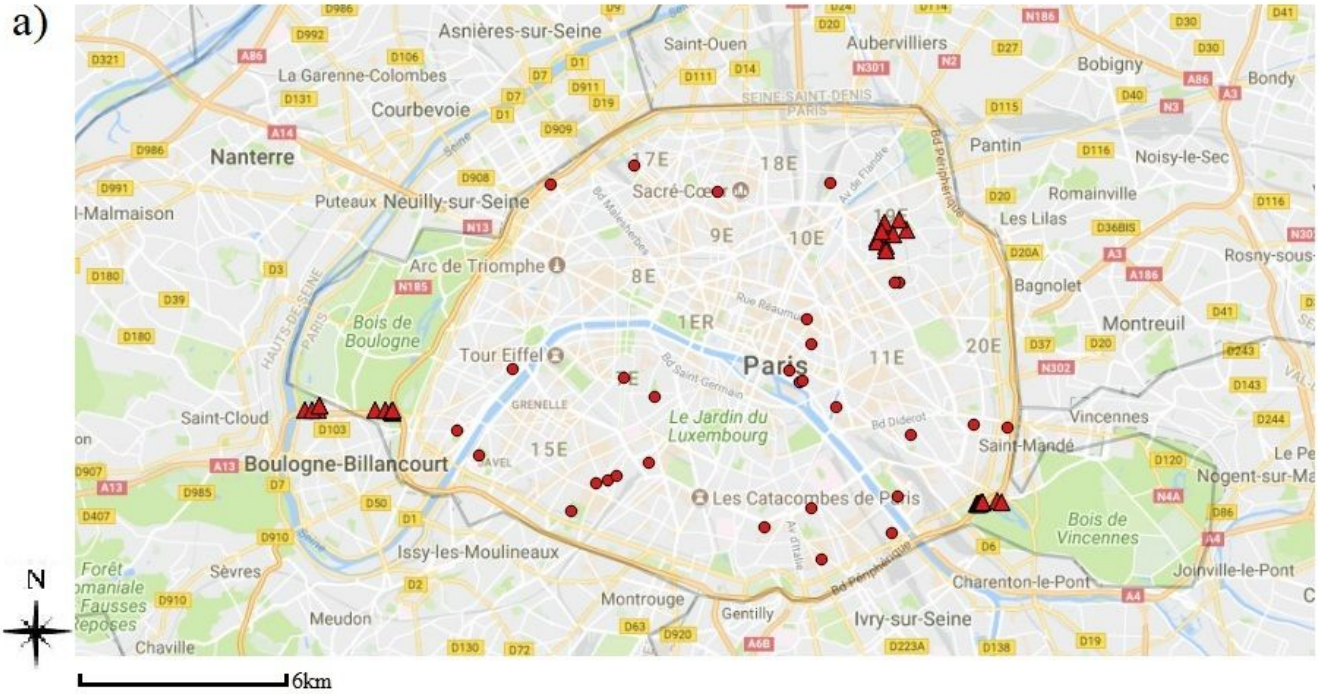
Fig. A.2



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.

Fig. A.3

a)


Asnières-sur-Seine
Saint-Ouen
Aubervilliers
Bobigny
Bondy
La Garenne-Colombes
Courbevoie
Nanterre
Puteaux
Neuilly-sur-Seine
Pantin
Noisy-le-Sec
Romainville
Les Lilas
Rosny-sous-
Bagnolet
Montreuil
Vincennes
Saint-Mandé
Nogent-sur-Ma
Le Pe
Sacré-Cœur
17E
18E
9E
10E
8E
1ER
11E
20E
15E
Arc de Triomphe
Bois de Boulogne
Tour Eiffel
Paris
Le Jardin du Luxembourg
Les Catacombes de Paris
Bois de Vincennes
Saint-Cloud
Boulogne-Billancourt
Issy-les-Moulineaux
Sèvres
Meudon
Chaville
Montrouge
Gentilly
Ivry-sur-Seine
Charenton-le-Pont
Joinville-le-Pont
N
6km

b)

Fig. A.4

Typology:

- Embankment without substrate indication
- Embankment on modern alluvium
- Embankment on old alluvium
- Embankment on Fx
- Embankment on e5c
- Embankment on e5d
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- Embankment on e7b
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- Scree on e7a
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