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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.

KEYWORDS

anthrosols, chemical urban soil characteristics, forests, hydrostructural urban soil characteristics, lawns, physical urban soil characteristics, urban–rural gradient

1 | INTRODUCTION

Cities and towns exert significant pressures on both urban and surrounding environments (Chambers et al., 2016; Kaushal, McDowell, & Wollheim, 2014). 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 & Zhang, 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, *for example* capacity to store carbon or water (Wang, Adhikari, Zhuang, Gu, & Jin, 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 & Pouyat, 1997; Vialle & Giampieri, 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 & 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 & Zhang, 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, Chenu, & Lorenz, 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 (Cheon, Ham, Lee, Park, & Lee, 2014; Huong & Pathirana, 2013; Yang & Zhang, 2011). 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, Bourrie, & Trolard, 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, Stoorvogel, Leemans, Valentini, & Hajiaghayeva, 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 America (Burghardt, Morel, & Zhang, 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, Delbecque, Verdoodt, & Seuntjens, 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 (Economic & Social Council, 2019; Kumar & Hundal, 2016; Vegter, 2007), 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 (Chiesura, 2004; Morel et al., 2015; Stroganova, Myagkova, & Prokof'eva, 1997; Vasenev et al., 2018). It is therefore critical to understand how urbanization affects their properties.

In France, monitoring programmes such as the French soil quality-monitoring network (RMQS) have been carried out to describe and monitor French agricultural, forest and grassland soils (Arrouays, Deslais, & Badeau, 2001; Saby, Brus, & Arrouays, 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 has 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, Eriksson, Eriksson, Berg, & Hedblom, 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 metres 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 & 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 × 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 21% (2,525 km^2) and 22.2% (2,670 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 × 2 LT × 30 replicates = 180 sites) (Figure 1).

Soil characteristics were described from one composite soil sample per sampling site. Each composite sample was made of three sub-samples collected within a 1 m^2 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 m^2 square using the cylinder method (Blake & 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 S1). 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 hr. Total N was measured by dry combustion, after burning samples at 1,000°C in the presence of O_2 using a CHN auto-analyser (CHN 1500, Carlo Erba). Organic carbon

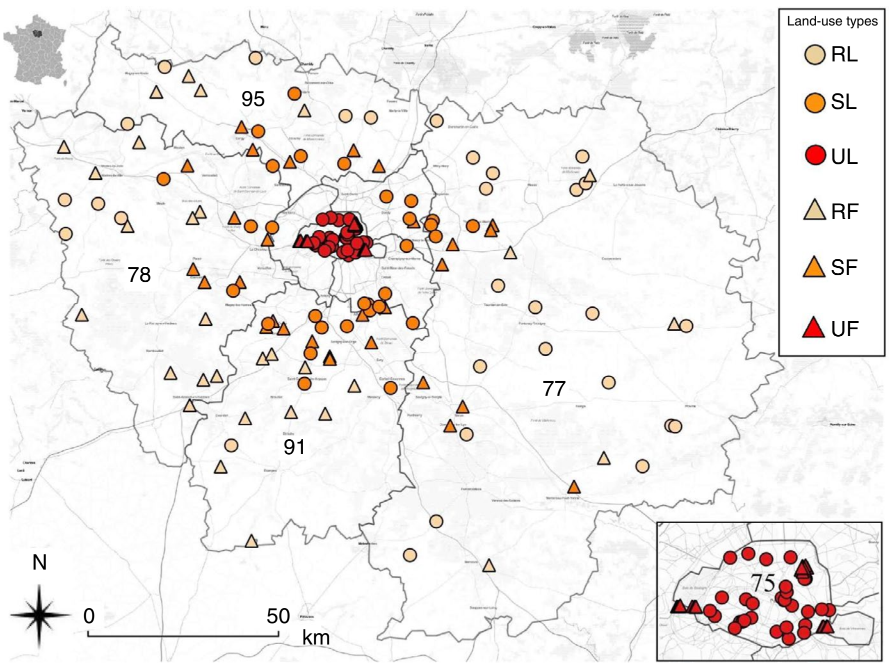

FIGURE 1 Map of the sampled sites (n = 180) located between 48°07′N, 1°35′E and 49°07′N, 3°26′E in the Île-de-France region around Paris City. Department delineation is displayed (75: Paris, 77: Seine et Marne, 78: Yvelines, 91: Essonne, 92: Hauts-de-Seine, 93: Seine-Saint-Denis, 94: Val de Marne, 95: 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

was quantified by sulfochromic oxidation using an auto-analyser (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: $OCS_{(n)} = 0.1 \times BD_{(n)} \times OC_{(n)}$, where 0.1 is the sampling depth in metres 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-analyser (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 & 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 −1,500 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 S1). 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 (−1,500 kPa), which were determined in accordance with Jurin's law. They delimited the macropores (600–9 μm), mesopores (9–0.2 μm) and micropores ($r < .2$ μm). The megapores ($r > 600$ μm) represent the quasi-permanent air-filled soil porosity (see Table S1). 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 Eijerkamp.

2.5 | Statistical analysis

All statistical analyses were performed using the R 3.4 (R Core Team, 2016). First, a between-group multivariate analysis (Baty, Facompré, Wiegand, Schwager, & Brutsche, 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 (1,000 permutations).

The effects of URG, LT and their interaction (URGxLT) on each chemical, physical and hydrological soil characteristics were then analysed using ANOVA. Variables that were not normally distributed were log-transformed prior

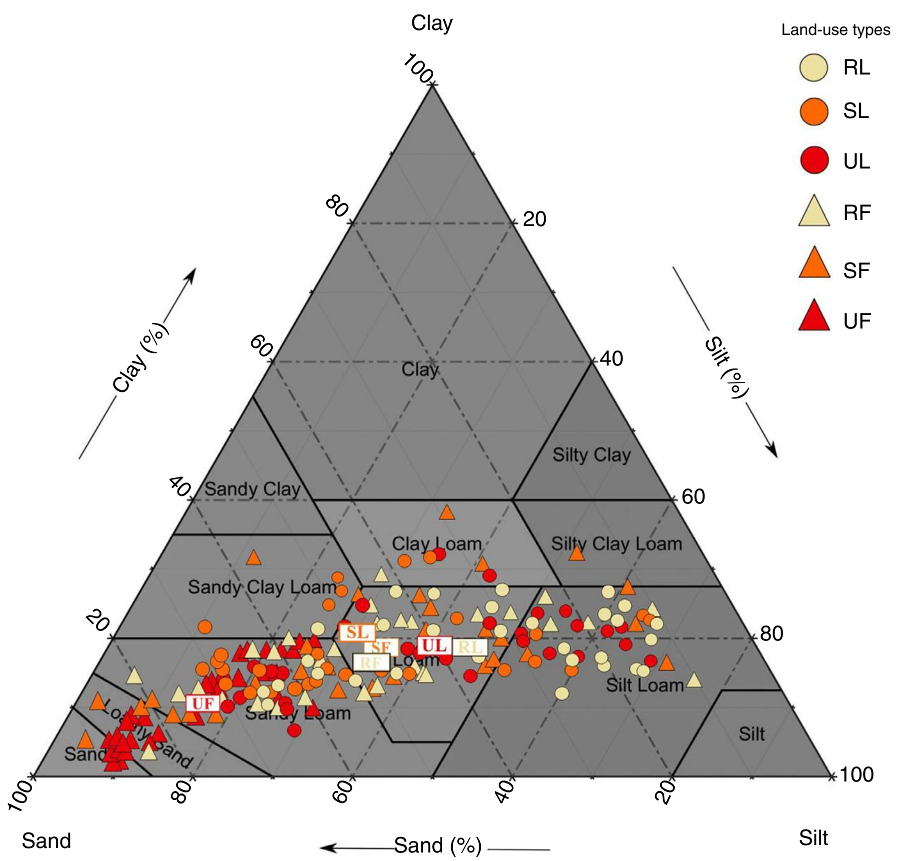

FIGURE 2 Ternary textural diagram (Davis and Bennett, 1927) of the lawn and forest soils in rural, suburban and urban areas of the Paris region. Labels of the gravity centers correspond to rural lawns (RL), suburban lawns (SL), urban lawns (UL), rural forests (RF), suburban forests (SF) and urban forests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

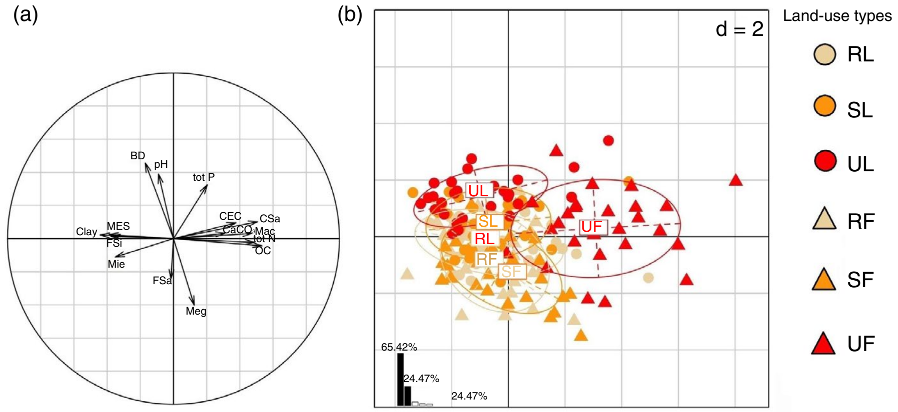

FIGURE 3 Between-group analysis on the chemical, physical and hydrostructural soil characteristics of the Paris region with the composite factor URGxLT as explanatory variable. (a) Correlation circle plot with the soil characteristic vectors (OC, organic carbon; tot N, total nitrogen; tot P, total phosphorus; 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)

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, Bretz, & Westfall, 2008). The residuals were checked for spatial autocorrelation using Moran's I correlogram (spdep package; Bivand et al., 2012). Since the Moran's I values (permutation test, $n = 1{,}000$) 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 analysed: soil texture ranged from sand to silt loam (Figure 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, while the other sites were loamy soils (Figure 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 (Figure 3). A Monte-Carlo permutation test showed that the URG and LT significantly affected the chemical, physical and hydrostructural soil characteristics (p = .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

TABLE 1 Effect of the urban–rural gradient (URG), land-use types (LT) and their interactions (URGxLT) on the chemical, physical and hydrostructural soil characteristics of the Paris region

	URG	LT	URGxLT	R^2
df	2	1	2	adjusted
Chemical and physical soil characteristics				
OCS	12.57***	15.71***	4.54**	.20
OC	4.68*	29.52***	6.81**	.21
Tot *N*	5.64**	15.64***	10.09***	.19
Tot P	14.74***	21.23***	4.66*	.23
Ph	0.81	17.54***	3.88*	.11
CEC	8.86***	0.23	7.00**	.13
C/N	5.49**	15.15***	4.29*	.14
$CaCO_3$	3.53*	5.23*	10.43***	.14
Clay	7.12**	19.38***	8.21***	.20
CSi	6.48**	31.21***	14.42***	.27
FSi	5.17**	25.33***	7.56***	.20
CSa	7.98***	6.00*	9.30***	.17
FSa	3.48*	2.42	0.97	.03
BD	9.64***	24.66***	8.93**	.24
Hydrostructural soil characteristics				
θ0.7	0.54	0.01	2.30	.004
θ2.5	8.70***	15.23***	5.84**	.18
Meg	11.21***	18.76***	3.83*	.20
Mac	10.13***	13.08***	7.84***	.20
Mes	3.33*	18.16***	7.45***	.16
AWS	3.17*	14.14***	6.34**	.14
θ4.2 = Mic	9.80***	11.19**	2.64	.15

Note: Results of linear models (degrees of freedom (*df*) (total residual *df* = 174), *F* values) (**p*-value < .05, ***p*-value < .01, ****p*-value < .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.

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

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 Figures 4 and 5, Table S2, Figures S1 and S2).

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 & Gupta, 1989). It is widely recognized that forest soils accumulate more organic matter than the other temperate terrestrial ecosystems, especially in topsoil (Guo & Gifford, 2002; Innangi, Danise, d'Alessandro, Curcio, & Fioretto, 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 Figure S3). 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, *for example* 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 (Chen, Liu, Liu, Jia, & He, 2014; Kandeler et al., 2008; Moynahan, Zabinski, & Gannon, 2002). 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 & 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

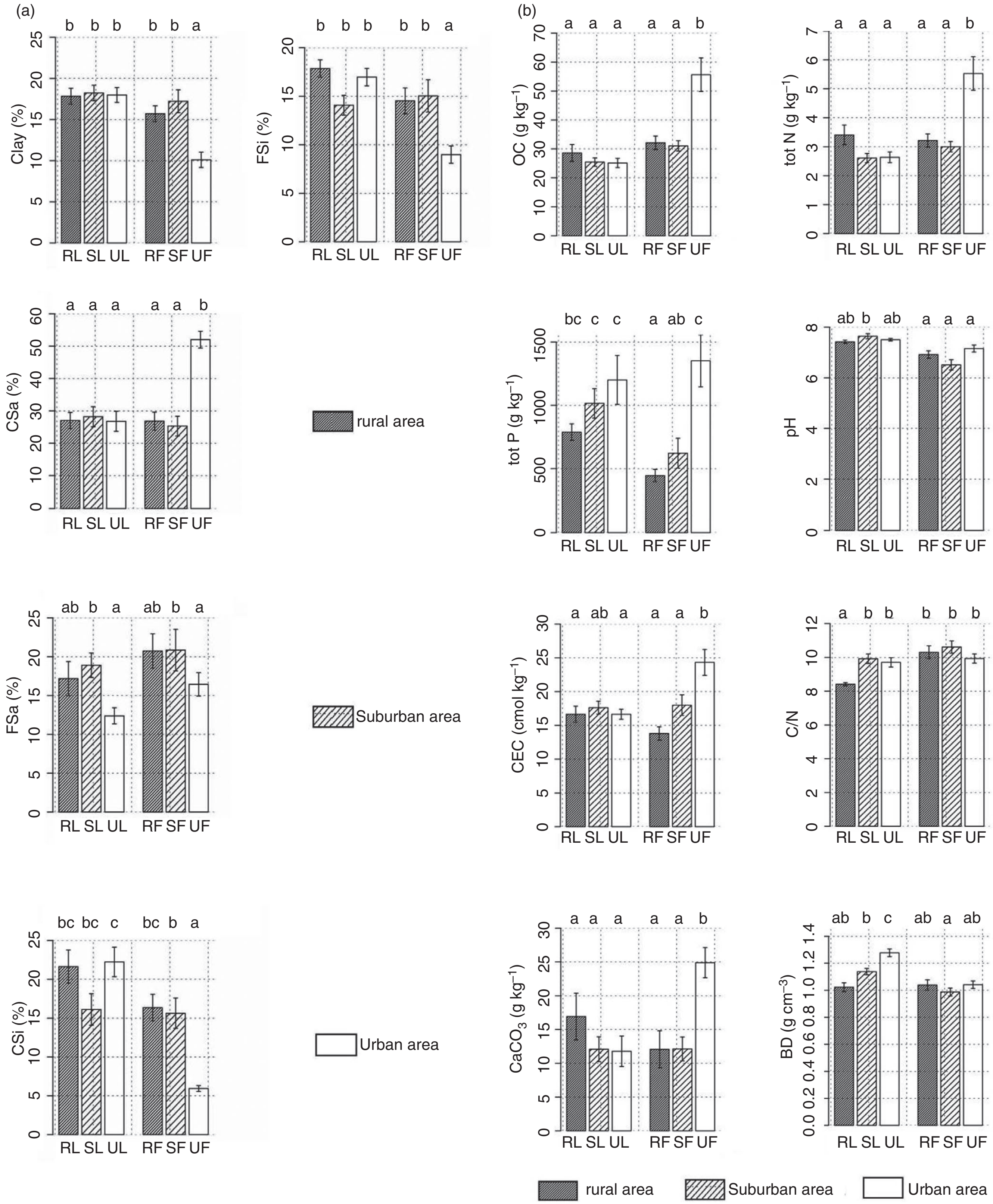

FIGURE 4 Mean values of the (a) textural and (b) chemical and physical soil characteristics of lawn and forest soils in rural, suburban and urban areas of the Paris region. OC, organic carbon; tot N, total nitrogen; tot P, total phosphorus; pH, pH–H_2O; CEC, cation exchange capacity; C/N ratio, $CaCO_3$, 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

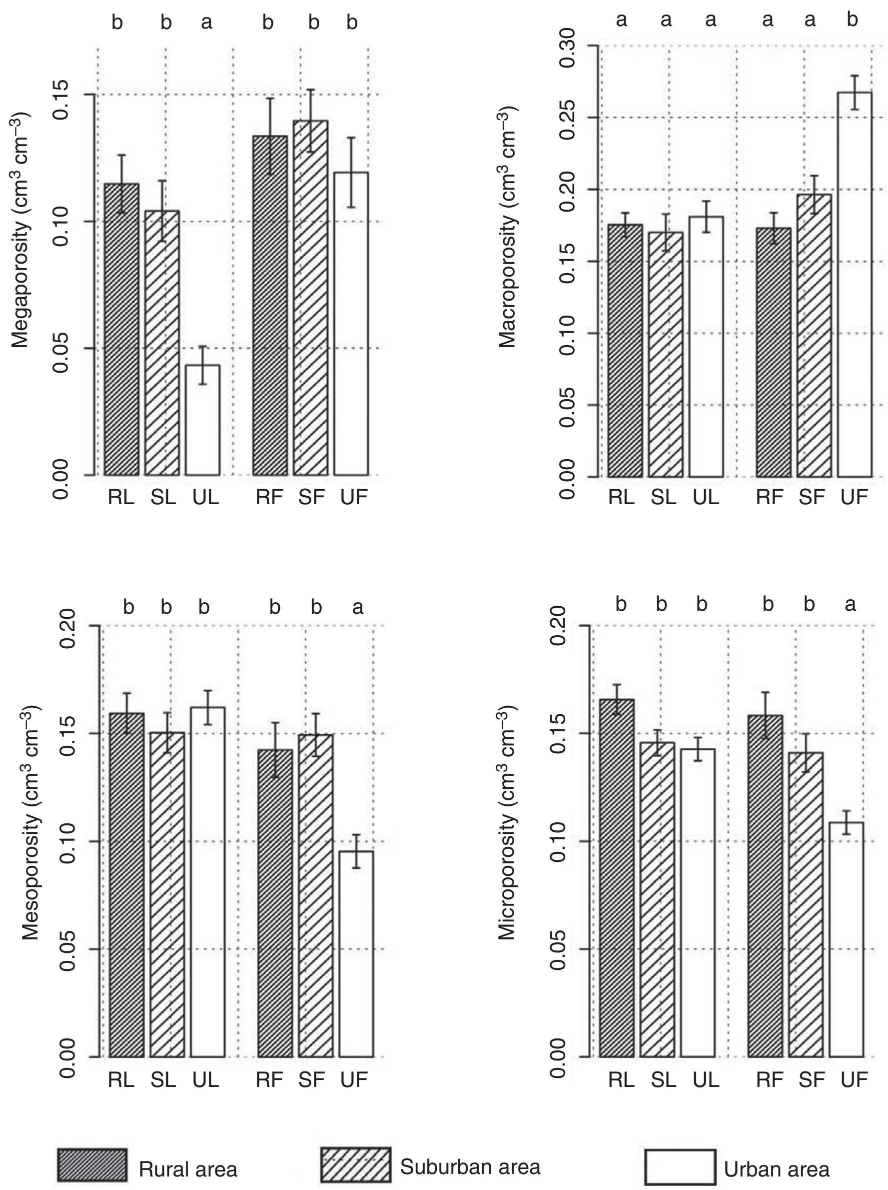

FIGURE 5 Mean values of the hydrostructural soil characteristics of forest and lawn soils in rural, suburban and urban areas of the Paris region. RL, rural lawns; SL, suburban lawns; UL, urban lawns; RF, rural forests; SF, suburban forests; UF, urban forests. Error bars represent standard errors. Letters indicate significant differences between means

subject, in particular because SOM pools with different recalcitrance have diverse sensitivities to temperature (Billings & 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, Renforth, & Manning, 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, Kolosz, Sohi, Lopez-Capel, & Manning, 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 (Figure S4). Thus, the high coarse sand and the low clay concentrations of urban forest soils likely 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, Jones, & Jacobsen, 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 (Forrest & Konijnendijk, 2005; Gandy, 1999). 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 (Barles, 1999; Moreau & Daverne, 1846). 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 (Schmidt et al., 2011; Skjemstad, Reicosky, Wilts, & McGowan, 2002), and wastewater irrigation can lead to the long-term organic matter accumulation in soils (Friedel, Langer, Siebe, & Stahr, 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 (Glaser, Lehmann, & Zech, 2002; Haynes & Naidu, 1998).

4.2 | 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 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, etc.). 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, *that is* 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 was until recently common practice in the Paris region (e.g. monoammonium and diammonium phosphate DEVE, pers. comm.), which can cause phosphorus accumulation in soils when applied in excess (Carpenter et al., 1998). This likely explains the high phosphorus concentrations observed in the urban and suburban lawn soils when compared to the rural and suburban forests, and the similar concentrations 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, Meyerhoff, Rehdanz, & Wüstemann, 2017). In a city with a high population density such as Paris (21 067 inhabitant km^{-2}; INSEE, 2013), 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, Bajla, & Szombathová, 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 centres, 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, Borelli, Conigliaro, & Yujuan, 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 & 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

While 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 centres, 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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DATA AVAILABILITY STATEMENT

Data openly available in a public repository that issues datasets with DOIs

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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