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Urban Green Space Soils: Not Critically Compacted but Shaped by a Human-Pressure Gradient—Evidence From Milan, Italy

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ABSTRACT

Urban soils play a crucial role in supporting ecosystem services, yet they are often overlooked or perceived as degraded. This study provides an assessment of physical and chemical properties of soils in public green spaces in Milan, Italy—a representative medium-sized European city—with particular attention to soil compaction. Sixty georeferenced plots were sampled across five categories of publicly accessible green areas differing in vegetation cover, management intensity, and human pressure. Measurements included bulk density (BD), penetration resistance (PR), pH, organic carbon (SOC), total nitrogen, available phosphorus (AvP) and texture. Milan's soils generally retained favourable ecological properties. BD was low (mean ± sd: $1.03 \pm 0.13\,g\,cm^{-3}$), below thresholds limiting root growth and soil biota, and PR profiles showed no critical compaction. However, BD and PR varied across categories: values were lowest in peri-urban forests and highest in central parks and urban green islands, reflecting vegetation, management, and recreational pressure differences. SOC was relatively high in the topsoil (mean ± sd: 3.23% ± 0.75%), supporting fertility and carbon storage, with no significant differences among categories. Conversely, pH and phosphorus varied: peri-urban sites had acidic to sub-acidic conditions and moderate AvP levels, while central parks and urban islands showed near-neutral to slightly alkaline pH and elevated AvP, indicating stronger anthropogenic influence. These findings challenge the widespread assumption that urban soils are uniformly compacted and degraded. Soils in Milan's green spaces preserve properties that sustain ecosystem services, with differences reflecting management intensity, recreational use and land-use history. The framework adopted here can be applied in other cities to guide soil protection and support sustainable urban planning.

1 | Introduction

Urban areas currently host 55% of the global population, and this proportion is expected to increase (United Nations, Department of Economic and Social Affairs, Population Division 2019). Urban expansion not only increases impervious surfaces but also contributes to land fragmentation through urban sprawl (Burghardt et al. 2015). The scattered unsealed areas that persist within urbanised territories remain the only ones capable of providing essential ecosystem services (ES) for the well-being of city inhabitants. In this context, urban soils play a crucial role in improving the environmental quality of cities. Despite anthropogenic disturbance, urban soils—like natural and semi-natural ones—provide numerous ecosystem services (Lehmann and Stahr 2007; Morel et al. 2015; Pouyat et al. 2020). These include flood prevention through water infiltration, microclimate regulation, heat island effect mitigation, carbon storage, food provision via urban agriculture, support for biodiversity and recreational benefits for city residents (O'Riordan et al. 2021).

Nevertheless, soils are often neglected in urban ecosystem management, being seen as a resource for intensive use rather than a natural heritage that must be preserved to maintain its ecological functionality (Morel et al. 2015; Pouyat et al. 2020). There is a persistent prejudice that all urban soils are highly altered and of poor quality (Morel et al. 2015; Pouyat et al. 2020). However, the situation is more complex than commonly assumed. Although all urban soils are affected by human activities, the extent of alteration and degradation can vary considerably within the same urban context, where highly altered soils can coexist with pseudo-natural soils (Pouyat et al. 2007; Chaurasia et al. 2024). Some soils are deeply transformed, with chemical and physical properties that differ drastically from non-urban soils (e.g., high compaction, alkaline pH and the presence of artefacts and residues from human activities) and hinder biological activity and plant growth. Contamination can also be a concern in some cases (Norra and Stuben 2003; Horváth et al. 2015). In contrast, some urban soils remain relatively undisturbed and exhibit properties more similar to those of natural soils, such as low bulk density, high organic matter content and rich biodiversity.

Urban soils are characterised by high spatial heterogeneity, even over short distances (i.e., within just a few tens of meters, Greinert 2015), making it difficult to define the characteristics of a 'typical' urban soil (Pouyat et al. 2007). This heterogeneity is driven by current differences in land use, vegetation cover and management practices, as well as land use legacies and historical processes that have shaped the different patches of soil throughout the city's history (Pickett and Cadenasso 2009; Ziter and Turner 2018; Paradelo et al. 2021; Chaurasia et al. 2024). Among these, the time since the actual land use has been established is a key factor that can sometimes be crucial in explaining differences in soil properties (Scharenbroch et al. 2005; Greinert 2015). In the heterogeneous mosaic of soil patches that compose urban landscapes, a general gradient of soil property alteration can sometimes be observed, following the urbanisation gradient from rural to urban areas (Foti et al. 2021; Whitehead et al. 2021).

Recently, urban soils have received increasing attention both within the scientific community and in European policy frameworks such as the EU Soil Strategy for 2030 (European Commission 2021). However, significant knowledge gaps remain, and current research does not yet provide a comprehensive overview of their status. While topics such as heavy metal contamination and soil organic carbon have been more extensively studied, others, such as soil compaction and biodiversity, remain underexplored (Binner et al. 2024).

Compaction can significantly contribute to soil degradation in urban environments (Lehmann and Stahr 2007; Morel et al. 2015), leading to alterations in soil structure that result in increased bulk density and reduced porosity. These changes limit air circulation, promote anaerobic conditions and enhance denitrification (Li et al. 2014). Reduced infiltration capacity contributes to increased surface runoff and a higher risk of flooding (Gregory et al. 2006; Johnston et al. 2016). Compaction also creates unsuitable habitat conditions for soil microorganisms and fauna, compromising soil biological activity (Beylich et al. 2010; Devigne et al. 2016). Moreover, increased soil resistance to penetration hinders root development and thus affects plant growth (Yang and Zhang 2015). Soil compaction in urban environments results from various factors, including high foot traffic in green spaces, vehicles used for greenery maintenance, heavy machinery used for construction and landscaping and intentional compaction for infrastructure development (Yang and Zhang 2015).

Urban soils have often been associated with high levels of compaction (Lehmann and Stahr 2007), but more recent studies suggest that this assumption is not universally valid. One reason for this perception is that many studies reporting high bulk density (BD) values have focused on specific, highly disturbed areas rather than providing a comprehensive view of urban soils (Edmondson et al. 2011). Large-scale investigations on urban areas, on the other hand, reveal a more complex and variable picture, showing that soil compaction is not always widespread and largely depends on land use, vegetation cover and the intensity of human activity. Several studies have reported that compaction tends to be confined to zones of high-intensity use, while bulk density values across the entire urban area generally remain low (Foti et al. 2021; Paradelo et al. 2025), sometimes even falling below those observed in the surrounding agricultural areas (Edmondson et al. 2011). Conversely, other authors (Scharenbroch et al. 2005; Chaurasia et al. 2024) have documented widespread soil compaction within the city, with bulk density values often reaching levels known to restrict root growth (United States Department of Agriculture, Natural Resources Conservation Service (USDA NRCS) 2023).

This study addresses the current knowledge gap on urban soils by providing an extensive assessment of their physical and chemical properties in public green spaces, with a particular focus on soil compaction, using the city of Milan as a representative case study of a medium-sized European city. We selected a set of green space categories to reflect the most characteristic situations across the city, trying to capture differences in vegetation type, management intensity, land-use history, levels of human use and position within the urban context. The aim was to investigate whether urban pressure has altered soil characteristics and whether such alterations, if present, may influence its ability to support ecological functions.

2 | Materials and Methods

2.1 | Study Area

The investigation was carried out in the city of Milan, located in northern Italy, in the central-western part of the Po Valley's alluvial plain. The landscape is predominantly flat, with an average elevation of about 100 m. The climate is classified as continental, with a mean annual temperature of 13.0°C and a mean annual precipitation of 920 mm. Monthly mean temperatures range from 2.3°C in January to 23.8°C in July (1991–2021). The predominant soil types in the lowland area where Milan is located are Luvisols (primarily Dystric and Gleyic) and Cambisols (mostly Skeletic and Gleyic) (ERSAL 1993, 1999).

Milan's urban structure reflects its long history of development, which has profoundly shaped the territory. The surrounding area has historically been an important agricultural region. The city evolved from a medieval core built over the former Roman settlement, with successive expansions radiating outward from the centre. The districts surrounding the old core were largely developed in the late 19th and early 20th centuries, when Milan had become a major industrial centre, a role it maintained until the onset of deindustrialisation in the 1970s. The outer belt expanded mainly after World War II through rapid urban sprawl, converting former rural and agricultural areas into densely built environments (Canedoli et al. 2017). As a result, the present-day city shows a clear gradient from the dense historical centre to more heterogeneous peripheral areas, where residential, industrial and semi-natural spaces coexist.

Today, Milan and its metropolitan area are among the largest and most densely populated urban regions in Italy. The city hosts 1,407,044 residents, resulting in a population density of 7741 people per square kilometre. Public green spaces cover approximately 25 km^2, accounting for nearly 14% of the city's total area (Municipality of Milan 2024).

2.2 | Selection of Green Area Categories

Five categories of public green areas were defined, based on the vegetation cover, the type of green space and the levels of public use most frequently observed across the city. In the absence of objective data, the intensity of green space use was evaluated qualitatively based on factors that can be indicative of varying levels of anthropogenic pressure across the city, including green area size, location (historic centre vs. peri-urban areas) and history of land use.

The selected categories include grasslands in urban parks inside and outside the historic centre (UPC and UP respectively); grasslands in urban green islands (UGI); grasslands in peri-urban parks (PP) and forests in peri-urban parks (PPf).

Central parks (UPC) are historic green areas that are intensively managed and subject to long-term recreational use, with high foot traffic. Urban parks outside the centre (UP) are more recent and are generally less frequented than historic parks, but are managed similarly. Urban green islands (UGI) are small, publicly accessible vegetated spaces—such as green spaces within urban squares and traffic islands—designed for both ornamental and recreational purposes. Due to their small size and proximity to roads and buildings, they are often exposed to high localised disturbance. Peri-urban parks (PP and PPf) are extensive areas with lower management intensity and reduced human pressure and often retain semi-natural features.

All green spaces considered in this study are publicly accessible and not subject to trampling restrictions. However, patterns of use differ: in forested sites, visitors generally remain on designated paths, whereas in grasslands, people tend to use the entire surface.

2.3 | Soil Sampling and Compaction Measurements

A total of 60 sampling locations were selected and distributed across the five green area categories throughout the city (Figure 1). The number of locations per category was as follows: PPf = 9, PP = 21, UGI = 10, UP = 10 and UPC = 10. At each location, a georeferenced experimental plot (4 × 4 m) was defined for soil sampling and soil compaction measurements. The plots were located on surfaces representative of the prevailing conditions within each green space, while avoiding localised features (e.g., footpaths, edges, or temporary alterations) that may not reflect the general characteristics of the area.

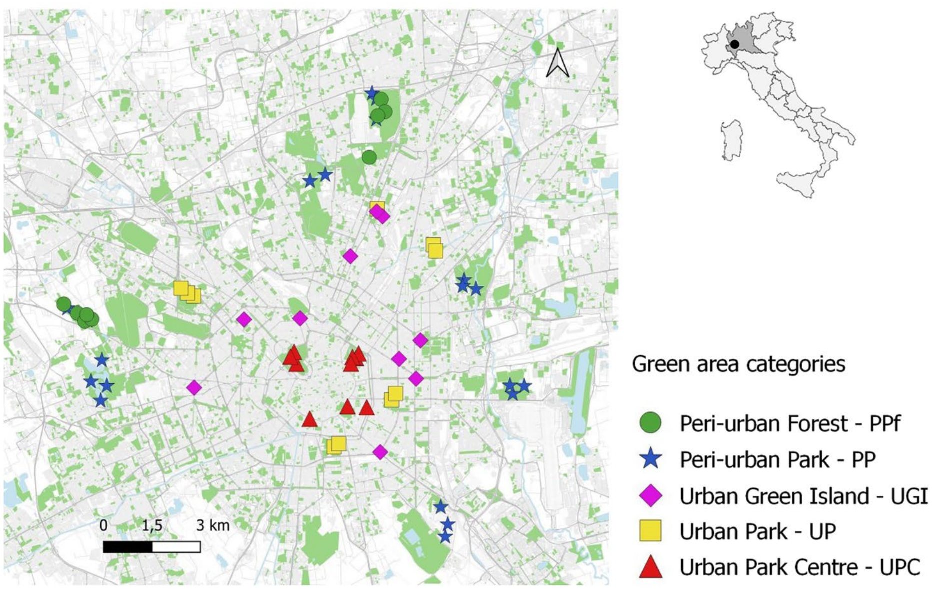

FIGURE 1 | Location of the 60 sampling plots across Milan.

Soil samples were collected at three depths: 0–10, 10–20 and 20–40 cm, using a 4-cm-diameter auger. For each depth, a composite sample was obtained by combining five subsamples, following the standard LUCAS (Land Use and Cover Area frame Survey) protocol: one central subsample (at the centre of the plot) and four subsamples placed along the axes, each 2 m from the centre.

Soil compaction status was assessed by measuring soil bulk density and soil resistance to penetration. Bulk density (BD) was measured in the top 5 cm by taking three subsamples of undisturbed soil with a cylindrical sampler (volume = 100 cm^3, total composite sample volume = 300 cm^3). Soil resistance to penetration (PR) was measured using a field penetrometer (*FieldScout SC 900 Soil Compaction Meter*, *Spectrum Technologies Inc*., Plainfield, IL), which records soil resistance at increasing depths (with 2.5 cm resolution), up to a maximum depth of 45 cm. Five repeated penetrometer measurements were taken within each experimental plot and averaged to obtain a single value. To account for the influence of soil moisture on PR, the soil water content was measured at 0–10 cm depth using a TDR sensor (*FieldScout TDR 150 Soil Moisture Meter, Spectrum Technologies Inc*., Plainfield, IL).

2.4 | Laboratory Analyses

A total of 178 soil samples were air-dried, sieved (2 mm mesh) and analysed to determine soil organic carbon (SOC, after carbonate removal) and total nitrogen content (*Flash EA 1112 NCSoil*, *Thermo Fisher Scientific elemental analyser*, Pittsburgh, PA, USA), pH in water (soil to water ratio of 1:2.5), particle-size distribution by sieving and sedimentation (Burt 2004) (coarse sand: 0.1–2 mm; fine sand: 0.05–0.1 mm; silt: 0.002–0.05; clay, < 0.002 mm), and available phosphorus (Olsen et al. 1954; determined in the 0–10 cm layer only). Bulk density of fine earth was calculated on the 60 composite samples, correcting for the volume of rock fragments by separating the coarse fraction, weighing it and measuring its volume.

2.5 | Data Processing and Statistical Analyses

To allow for direct comparison of soil PR measurements collected under varying soil moisture conditions, the data were corrected for differences in water content, since this parameter significantly impacts the values obtained (Busscher et al. 1997). The correction function was derived from a modified version of the procedure described by Duarte et al. (2022), using data from a non-compacted reference site, whose soil texture matched the predominant texture found in the sampling plots. At the reference site, both PR and water content were measured across a range of soil moisture conditions. This approach enabled us to isolate the effect of soil moisture on PR, independently of compaction. The correction function was then applied to all field data, adjusting PR values to a common reference water content corresponding to field capacity (FC = 24%).

Descriptive statistics (minimum, maximum, mean and standard deviation) were calculated for all measured soil properties in all the 60 plots. To ensure uniformity, PR values were averaged within the same three depth intervals as the other soil properties.

To test for differences among categories, linear mixed-effects models (LMMs) were fitted for each soil property (pH, SOC, N, P, BD and PR in three layers), with green area category as the only fixed effect and site (i.e., a specific park) as a random effect (Schabenberger and Gotway 2005). To further isolate the effect of green space category on soil compaction, a second set of LMMs was fitted for bulk density and penetration resistance. Unlike the previous models, these included not only green area category but also relevant soil parameters as fixed effects, with site included as a random effect. By accounting for key soil covariates, these models aimed to separate the anthropogenic effect from the influence of intrinsic soil characteristics. Covariates were selected using a stepwise model selection procedure based on Akaike's Information Criterion (AIC).

Model assumptions were checked by visual inspection of diagnostic plots and by applying the Shapiro–Wilk test for normality. When needed, variables that were not normally distributed were log-transformed prior to analysis. Residual spatial autocorrelation was tested using Moran's I across all fitted models. All confidence intervals were calculated at the 95% level. When significant effects were found, pairwise comparisons were performed between the different green area categories using Tukey's Honestly Significant Difference (HSD) test.

All statistical analyses were performed in R (version 4.5.0, R Core Team 2025) using the *stats, nlme*, *spdep* and *emmeans* packages.

3 | Results

The main physical and chemical properties of soils from all 60 sampling plots are summarised in Table 1. Soil organic carbon content decreased markedly with increasing depth. In the topsoil (0–10 cm), SOC values were generally high (mean ± SD: 3.23% ± 0.75%), with values ranging from 2.01% to 4.98%. In deeper layers, SOC generally remained at moderate levels, although some plots exhibited very low values (< 1%). Total nitrogen content followed a similar trend. The C:N ratio remained consistent across all green area categories, including both grasslands and forests. Average values were 11 in the surface layer and 10 at greater depths, with low variability between plots. However, some outliers were observed, including notably high values in one UGI plot. Regarding pH, mean values increased slightly with depth, from 6.2 ± 0.8 in the topsoil to 6.5 ± 1.2 in the deepest layer, consistently falling within the range typical of neutral to slightly acidic soils. However, across layers, there were also extremes that vary from very acidic (minimum = 4.5) to subalkaline conditions (maximum = 8.0). Bulk density averaged 1.03 ± 0.13 g cm^{-3}, with maximum values up to 1.27 g cm^{-3}. Soil penetration resistance increased with depth. Average values were relatively moderate, but PR ranged widely across plots and layers, from 0.47 to 3.85 MPa. Available phosphorus in the topsoil (0–10 cm) was highly variable, ranging from 9 to 127 mg kg^{-1} across plots.

TABLE 1 | Descriptive statistics of soil data (60 plots).

	Layer	Mean	SD	Min	Max
BD ($g\,cm^{-3}$)	0–5	1.03	0.13	0.73	1.27
PR (MPa)	0–10	1.63	0.56	0.47	2.89
	10–20	2.31	0.66	0.69	3.85
	20–40	2.40	0.64	0.82	3.82
pH	0–10	6.2	0.8	4.9	7.7
	10–20	6.3	1.0	4.5	7.9
	20–40	6.5	1.2	4.5	8.0
SOC (%)	0–10	3.23	0.75	2.01	4.98
	10–20	1.75	0.61	0.63	3.20
	20–40	1.20	0.42	0.30	2.20
tN (%)	0–10	0.30	0.07	0.11	0.46
	10–20	0.17	0.05	0.04	0.28
	20–40	0.12	0.05	0.04	0.28
C:N	0–10	11	1	9	18
	10–20	10	2	7	17
	20–40	10	2	5	18
AvP1 ($mg\,kg^{-1}$)	0–10	33	25	9	127

Note: Layer: Depth in cm.
Abbreviations: AvP = available phosphorus, D = bulk density, PR = penetration resistance, SOC = soil organic carbon, tN = total nitrogen.

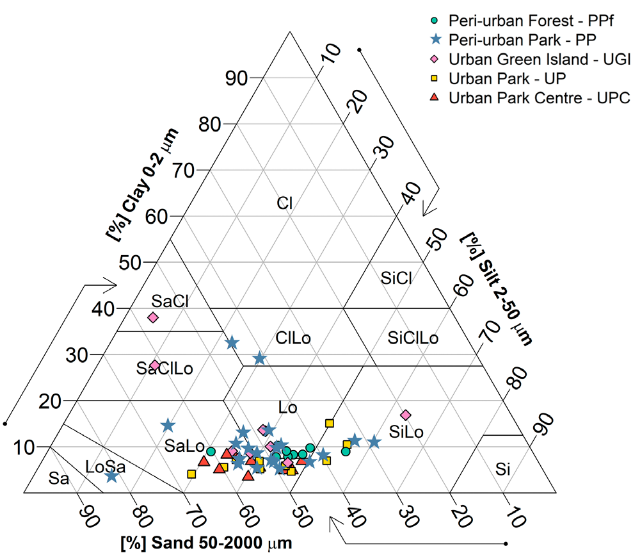

FIGURE 2 | Soil texture classes (USDA) of soil samples collected in the first layer (0–10 cm).

Soil texture classes in the topsoil (0–10 cm) are shown in the textural triangle (Figure 2). In this layer, all plots belonging to UP, UPC and PPf exhibited exclusively loam, sandy loam, or silty loam textures. In contrast, PP and UGI displayed somewhat greater variability. With increasing depth, soil texture generally remained similar to that of the top layer, except for UGI plots, where the higher variability observed in the surface horizons tended to decrease in the deeper layers.

Figure 3 displays the mean soil penetration resistance profiles by green area category, down to a depth of 45 cm. In all grassland categories (PP, UGI, UP and UPC), PR increased sharply from the soil surface to a depth of approximately 10–12.5 cm, after which it remained relatively stable until the deeper layers, where more pronounced variations were observed. These categories exhibited highly similar profiles throughout most of the soil depth, with mean PR values remaining always below 2.75 MPa. In contrast, the profile for PPf showed a more gradual and nearly linear increase in PR with depth, without the initial rapid rise observed in the grassland categories. PR values in PPf were consistently much lower, ranging from about 0.50 MPa at the surface to 1.75 MPa at 40 cm, clearly distinguishing this category from the others.

Complete outputs of the LMMs are reported in Supporting Information. Here we summarise the main results.

Linear mixed models revealed significant differences in pH between green area categories in all three investigated soil layers (Figure 4). In the upper two layers, a very similar pattern emerged: peri-urban plots (PP and PPf) exhibited the lowest mean pH values (0–10 cm: mean = 5.9, 95% CI [5.6–6.3] for PP; mean = 5.7, 95% CI [5.2–6.2] for PPf), which differed significantly from those of UPC and UGI, both characterised by the highest values (0–10 cm: mean = 6.9, 95% CI [6.4–7.5] for UPC; mean = 6.7, 95% CI [6.3–7.2] for UGI). UP plots had intermediate pH values (0–10 cm: mean = 6.4, 95% CI [5.9–6.9]). In the deepest layer (20–40 cm), the differences between the categories were even more pronounced. PPf exhibited significantly lower pH values than all the other categories (mean = 5.4, 95% CI [4.9–6.0]), including PP. In contrast, UPC had the highest pH values, reaching the sub-alkaline range (mean = 7.6, 95% CI [6.8–8.4]), and differed significantly from both peri-urban park categories.

A similar pattern of differences was observed for available phosphorus as for pH. The LMM showed significant differences among green area categories (Figure 4). PP and PPf exhibited the minimum values (mean = 20, 95% CI [16–26] mg kg^{-1} and mean = 18, 95% CI [12–26] mg kg^{-1}, respectively), which were significantly lower than those observed in UGI and UPC, which showed the highest values (mean = 47, 95% CI [32–68] mg kg^{-1} and mean = 43, 95% CI [30–62] mg kg^{-1}, respectively). No significant differences were found for UP.

The linear mixed-effects models detected no significant differences among green area categories for soil organic carbon, total nitrogen and C:N ratio; descriptive statistics for these variables (means and standard deviations by category) are reported in Table S1.

The best-fitting LMM for BD included green area category and soil organic carbon in the top layer (0–10 cm) as fixed effects (Figure 5). SOC had a significant negative effect on BD (estimate = −0.039, $p = 0.044$). BD was significantly lower in forests (mean = 0.90, 95% CI [0.83–0.98] g cm^{-3}) compared to all grassland categories. PP (mean = 0.98, 95% CI [0.93–1.03] g cm^{-3}) had lower values than UPC (mean = 1.15, 95% CI [1.08–1.22] g cm^{-3}) but did not differ significantly from UP (mean = 1.08, 95% CI [1.01–1.15] g cm^{-3}) or

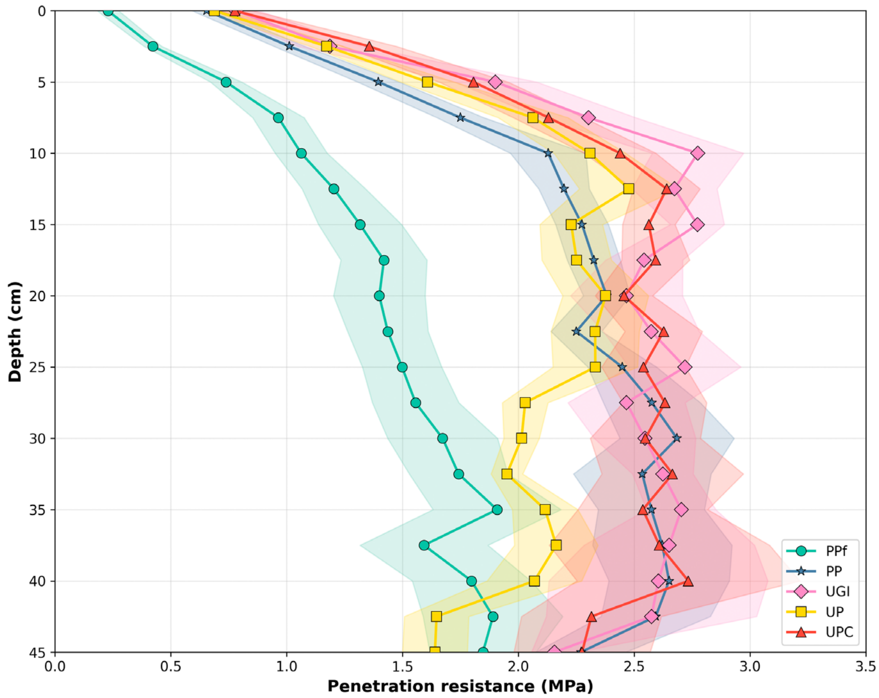

FIGURE 3 | Soil penetration resistance profiles by green area category. Mean values (solid lines) and standard error (shaded bands) are reported.

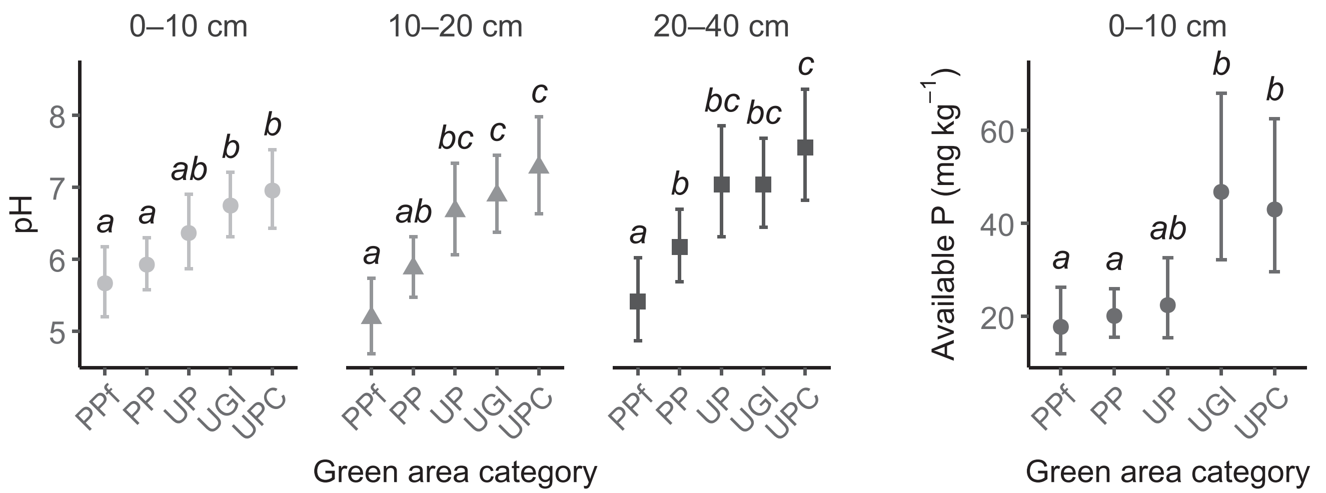

FIGURE 4 | Estimated marginal means (±95% CI) for pH and available P from LMMs including green area category as fixed effect. Letters in italic indicate significant pairwise differences among green area categories (Tukey post hoc test).

UGI (mean = 1.08, 95% CI [1.02–1.15] g cm^{-3}). UP and UGI also did not differ significantly from either PP or UPC.

For PR in the topsoil (0–10 cm), the best-fitting model included green area category as the only fixed effect. In the 10–20 cm layer, soil organic carbon, sand and clay were selected in addition to the green area category. For the deepest layer (20–40 cm), sand, clay and green area category were included.

In the second and third soil layers, sand content was positively associated with PR (PR 10–20 cm: estimate = 0.002, $p = 0.019$; PR 20–40 cm: estimate = 0.003, $p = 0.002$). In all three layers, green area category had a significant effect on PR. In the topsoil (0–10 cm), a clear pattern emerged among green area categories (Figure 5): PR was lowest in PPf (mean = 0.80, 95% CI [0.52–1.08] MPa), which was significantly lower than all other categories. PP (mean = 1.57, 95% CI [1.39–1.75] MPa) showed lower PR than UGI (mean = 2.04, 95% CI [1.78–2.31] MPa) but did not differ significantly from UP (mean = 1.79, 95% CI [1.53–2.05] MPa) or UPC (mean = 1.93, 95% CI [1.67–2.20] MPa). UP and UPC had intermediate values, not significantly different from either PP or UGI. The highest PR values were observed in UGI. In the second (10–20 cm) and third (20–40 cm) layers, the only significant difference that remained was between peri-urban forests and all other categories, with PR in PPf (mean = 1.32, 95% CI [1.01–1.63] MPa at 10–20 cm; mean = 1.68, 95% CI [1.35–2.01] MPa at 20–40 cm) being significantly lower than in any other group (Figure 5).

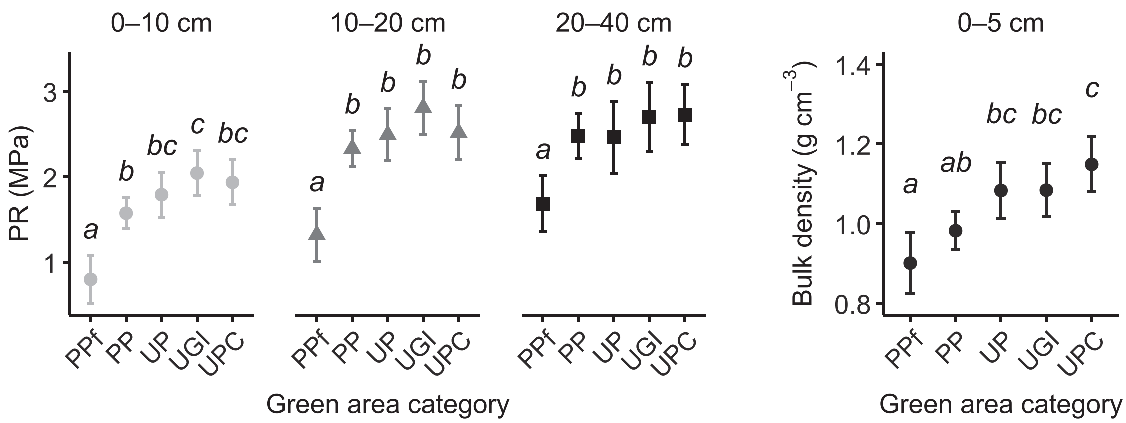

FIGURE 5 | Estimated marginal means (±95% CI) for PR and BD from LMMs including green area category and selected soil covariates as fixed effects. Letters in italic indicate significant pairwise differences among green area categories (Tukey post hoc test).

4 | Discussion

This study represents one of the first extensive investigations of the chemical and physical properties of soils in the city of Milan, aside from the work of Canedoli et al. (2020), which focused specifically on SOC stocks. Our aim was to provide an overview of the soils in Milan's public green spaces, by considering the combined influence of vegetation type, management practices, intensity of human use, land-use history and location within the urban context. More broadly, the goal was to assess the quality of urban soils in Milan and to evaluate whether their properties are consistent with the ecological functioning and the delivery of ecosystem services.

Our study focuses on a well-defined subset of urban soils: publicly accessible green spaces designed for recreational and ornamental purposes, including parks, neighbourhood greens and small vegetated areas such as traffic islands. Excluding heavily impaired or marginal urban land types has a direct influence on the results. Many urban soil studies which reported altered soil properties included highly disturbed sites such as barren land, construction areas, or roadside verges (Gregory et al. 2006; Park et al. 2010; Zandybay et al. 2024). Consequently, comparing findings across studies requires careful attention to the characteristics of the sampled sites and the context in which the research was conducted.

Soil texture across Milan's public green spaces appeared relatively uniform, with most samples falling into loam, sandy loam, or silty loam classes that are typical of the region's natural soils, suggesting limited soil disturbance. An exception was observed in UGI, where surface horizons showed greater heterogeneity in texture. Due to their ornamental nature and small size, these spaces are often subject to frequent redesigns, maintenance works and surface transformations. In most cases, textural variability decreased with depth, indicating that disturbances are primarily confined to the topsoil. As is commonly reported in urban soil studies (Morel et al. 2015), anthropogenic activities tend to affect only the upper horizons, while deeper layers generally retain their original texture.

Brick fragments were commonly observed in small quantities across sites. Other anthropogenic materials (such as glass, plastic, concrete, or metal) were sporadic and localised. Overall, the total amount of artefacts was low, suggesting limited signs of artificialisation despite the urban context. According to WRB classification criteria, no Technosols were identified. Our sampling depth (0–40 cm) prevented complete WRB classification; deeper sampling would likely reveal Cambisols and Luvisols typical of the Milan area. The sampled surface horizons could be described as those of 'pseudo-natural soils' (Morel et al. 2015).

As expected, SOC content decreased with depth. Surface soils (0–10 cm) showed relatively high concentrations. Low values were uncommon and were mostly found in deeper horizons. These findings are consistent with those of previous studies (Edmondson et al. 2012; Foti et al. 2021) and confirm that soils in Milan's green spaces have good levels of organic matter, supporting soil fertility and structural stability. In addition, they contribute significantly to carbon storage, as highlighted by Canedoli et al. (2020). Moreover, SOC concentrations are similar to those of permanent grasslands and exceeded those of agricultural soils in the areas surrounding the city—an outcome frequently highlighted in the literature (Vasenev et al. 2013; Paradelo et al. 2021).

No significant differences in SOC were detected across green area categories, consistent with findings from other cities (Pouyat et al. 2007; Paradelo et al. 2021). Even in more central and potentially disturbed contexts, such as UPC and UGI, SOC levels remain comparable to those in peri-urban categories. Interestingly, SOC content in forested areas was not higher than in grass-covered ones, probably due to a legacy effect. Although these forest patches were established nearly 50 years ago, SOC content still bears the imprint of the former agricultural land use. This supports the idea that SOC responds slowly to changes in vegetation cover, with soil transformations occurring over longer timescales than vegetation shifts (Poeplau et al. 2011). This is further supported by the C:N ratio, which showed similar values in both forested and grass-covered sites, suggesting that not only the quantity but also the quality of the soil organic matter remains similar across these green areas.

As expected, pH values increased with depth, indicating relatively undisturbed soil profiles. Lower pH values—acidic to sub-acidic—were found in peri-urban grasslands and especially in forested areas, consistent with their vegetation cover and limited anthropogenic disturbance. In contrast, higher values—near neutral or slightly alkaline—were observed in the more intensively managed and centrally located sites (UGI and UPC), likely reflecting the influence of calcareous fill materials, construction residues, or urban fertilisation practices (Yang and Zhang 2015). Intermediate values were recorded in UP sites, possibly due to greater internal variability across parks. Differences became more pronounced in deeper horizons, with PPf and UPC representing the two extremes. Similar trends have been reported in previous urban soil studies (Greinert 2015), which, as in our case, observed pH values within ecologically optimal ranges. This challenges the generalised assumption that urban soils are typically excessively alkaline (Yang and Zhang 2015).

Available phosphorus concentrations showed patterns consistent with those observed for pH, with higher values recorded in more intensively managed and centrally located green spaces (UGI and UPC). These areas are subject to frequent—historical or ongoing—fertilisation practices, which likely contribute to the elevated P levels. In contrast, lower concentrations were found in the less intensively managed peri-urban areas, where fertilisation is not expected. Even in these sites, however, phosphorus availability remained adequate to support plant growth. Previous studies, such as Foti et al. (2021), have similarly reported an increase in phosphorus levels from rural to urban areas, interpreting this as a legacy of lawn fertilisation practices in city parks.

Overall, no signs of problematic surface compaction were observed in the public green spaces sampled across Milan. Bulk density values in Milan's public green spaces were relatively low (0.73–1.27 $g\,cm^{-3}$, mean 1.03 $g\,cm^{-3}$), with even the highest recorded value falling within a range considered favourable for root growth (< 1.6 $g\,cm^{-3}$; United States Department of Agriculture, Natural Resources Conservation Service (USDA NRCS) 2023) and not detrimental to soil biota (< 1.7 $g\,cm^{-3}$; Beylich et al. 2010). These results are consistent with previous findings (Edmondson et al. 2011; Paradelo et al. 2025). In contrast, higher values have been reported in other studies. For example, in US cities, Scharenbroch et al. (2005) reported BD values of 1.4–1.7 $g\,cm^{-3}$ in residential areas, while Pouyat et al. (2007) found an overall range of 0.7–1.7 $g\,cm^{-3}$ across different urban uses. Similarly, Matziris et al. (2016) observed average values around 1.5 $g\,cm^{-3}$ in urban parks in Thessaloniki, Greece.

Bulk density values significantly differed across green area categories, even when accounting for the effect of SOC, which was negatively correlated with BD, as expected. PPf showed the lowest mean BD (0.90 $g\,cm^{-3}$), significantly different from all the other categories. A key factor could be the presence of organic surface horizons (mainly OL and OF), which typically characterise forest soils even in relatively young woodlands. These organic layers play a crucial protective role for the underlying soil structure acting as a physical buffer to reduce the direct impact of trampling and mechanical loads, thereby limiting compaction. In addition, site management is minimal and foot traffic tends to be largely confined to designated paths. Among grassland categories, PP showed relatively low BD values, likely due to lower pedestrian traffic and low maintenance—typically limited to mowing—making them similar to semi-natural grassland systems. In contrast, UPC recorded the highest mean BD (1.15 $g\,cm^{-3}$), which was significantly greater than in peri-urban areas. This likely reflects the effects of intense and prolonged pedestrian traffic, along with the more frequent use of maintenance machinery that characterise these areas.

Despite the observed differences, all values remained within acceptable limits, confirming that soil physical conditions are generally suitable and do not indicate critical compaction. This general absence of critical compaction may be explained by the relatively high organic matter content, which improves soil structural stability (Leroy et al. 2008).

Not surprisingly, soil resistance to penetration profiles differed markedly between forested and grass-covered areas. In peri-urban forests, PR values were consistently low and increased gradually and almost linearly with depth. In contrast, grass-covered areas showed higher overall resistance, with a sharp rise in the top 10–15 cm, followed by either stable or more variable values at greater depths. This near-surface peak likely reflects compaction from trampling and traffic from maintenance machinery, as commonly reported in urban soils (Gregory et al. 2006). These activities tend to compact the subsurface layers while leaving the uppermost centimetres less dense due to biological activity, root growth, or recent surface works.

Differences in PR among green area categories were most evident in the topsoil, where use, management and surface disturbance have the strongest impact. PR patterns were consistent with those observed for BD, highlighting the link between surface compaction and human activity. Below a depth of 10 cm, differences among categories became less pronounced. While a broad distinction between forested and grass-covered areas persisted, reflecting the influence of vegetation, deeper compaction appeared to reflect mainly site-specific disturbances rather than systematic differences across green area categories.

The ability of roots to overcome soil mechanical resistance varies across species and growth stages, but pressures up to approximately 2.5 MPa can be exerted by root tips in many crops (Gregory 1994). Similar mean values have been observed in topsoil of urban prairies with no visible signs of compaction stress (Johnston et al. 2016), suggesting that PR values around this threshold are not uncommon in healthy soils. For trees, Sinnett et al. (2008) reported that about 90% of roots develop in soil volumes where penetration resistance remains below 3 MPa.

In our data, mean PR values by category remained below 2.5 MPa in the 0–10 cm layer. In deeper layers, UP and PP approached 2.5 MPa, while UGI and UPC exceeded it, reaching up to about 2.75 MPa. Forest soils consistently showed low PR across all depths. When considering the full dataset across all depths and plots, PR ranged from 0.56 to 3.85 MPa. These values align with those reported in other European cities (Paradelo et al. 2025), although higher maximum values have been documented in comparable urban environments (Johnston et al. 2016). Taken together, these findings suggest that PR values observed in this study are generally not high enough to impair vegetation health. While some localised compaction may occur—particularly in the deeper layers of intensively used sites—the overall levels do not indicate critical constraints for root growth.

Moreover, penetrometer readings tend to overestimate the actual resistance experienced by roots by a factor ranging from 2 to 8, according to various authors (Atwell 1993; Gregory 1994). Unlike roots, which can grow around obstacles or use fissures and biopores, the penetrometer is inserted vertically and is strongly affected by barriers such as stones or construction debris (Lampurlanés and Cantero-Martínez 2003). In addition, root growth is not restricted to the vertical axis: many species extend laterally without negative effects on plant health (Hamza and Anderson 2005).

To summarise, marked differences were observed between peri-urban and more central green spaces. In peri-urban sites, soils retained semi-natural features—such as low BD, sub-acidic pH and moderate nutrient levels—consistent with their conception as parks reproducing elements of natural environments. Their current properties likely reflect also legacy effects: they were agricultural lands directly converted into public parks. In contrast, soils in more central sites showed clearer signs of alteration, including higher BD, elevated phosphorus levels and pH values approaching neutrality or slight alkalinity. These areas have been exposed to sustained anthropogenic pressure over time, including trampling, surface reworking and intensive ornamental management, and some of them represent the oldest green spaces in the city. Time plays a crucial role: the longer and more continuous the urban pressure, the more pronounced its imprint on soil properties (Scharenbroch et al. 2005). While these trends are consistent with patterns observed in other cities, soil conditions remain closely tied to site-specific land-use histories. Past uses, transformations and management practices critically shape soil development, making local context essential for interpretation (Hazelton and Murphy 2021).

5 | Conclusions

The combined evaluation of physical and chemical properties indicates that the urban soils we investigated are, for the most part, not compacted, rich in organic matter and not excessively altered by anthropogenic activities. Despite the urban context, artificial features were limited and key parameters remained within favourable ecological ranges. These findings suggest that soils in Milan's public green spaces maintain ecologically relevant properties that could support soil-based ecosystem services, providing further scientific evidence that urban soils are not uniformly or heavily degraded, as often assumed. Moreover, our work confirms that BD, PR, pH and available P may serve as sensitive indicators of differentiated human impacts on surface soil characteristics in urban landscapes (Pouyat et al. 2007). Their variation reflects differences in management intensity, recreational pressure, vegetation cover and location, and is most pronounced in the topsoil, where anthropogenic pressures are strongest. Taken together, these results may contribute to the development of a methodological framework that could be replicated in other urban contexts to guide soil assessment in public green spaces.

The generally good condition of urban soils in Milan highlights the importance of preserving and, where possible, improving this still undervalued component of urban ecosystems. Careful and site-specific management can help to maintain favourable physical and chemical properties, for instance by reducing unnecessary soil disturbance, limiting heavy machinery use and promoting practices that sustain vegetation cover and organic matter content. In this regard, leaving leaf litter and mowed grass on site supports nutrient cycling, contributes to organic matter accumulation, and provides a physical buffer against soil compaction. Moreover, where fertilisation is carried out, it should be preceded by soil analyses in order to avoid unnecessary phosphorus inputs in areas where its availability is already high. However, any soil protection strategy must be carefully balanced with the essential role of urban green spaces in providing opportunities for people to experience nature and to access cultural ecosystem services (Burghardt et al. 2015). For example, while restricting access in selected areas can help reduce surface compaction, such measures may not always be appropriate in public parks (Millward et al. 2011).

Overall, our findings may help foster greater recognition of the ecological role and value of urban soils in public green spaces, supporting their protection and informing more effective management decisions.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Mean ± sd by green area categories. Layer: depth in cm. C:*N* = C:N ratio, PP = peri-urban park, PPf = peri-urban forest, SOC = soil organic carbon, tN = total nitrogen, UGI = urban green island, UP = urban park, UPC = urban park centre.