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Vegetation degradation alters soil physicochemical properties and potentially affects ecosystem services in green spaces of a tropical megacity (Lubumbashi, DR Congo)

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ABSTRACT

Urban soils are degraded by various human pressures, including vegetation degradation, leading to changes in physical and chemical characteristics and affecting important ecosystem services. Soil physical properties are an important fertility control parameter, providing the basis for sustainable soil use in urban conditions; however, they do not receive sufficient attention in work on tropical cities. We assessed the impact of vegetation degradation in six urban green spaces (bare soils versus vegetated soils) on the physical (texture, soil bulk density and structure) and chemical (pH, cation exchange capacity (CEC), organic carbon (OC), nitrogen (N), phosphorus (P), potassium (K), copper (Cu) and manganese (Mn)) qualities of soils in a tropical megacity (Lubumbashi, DR Congo). Vegetated soils presented better physical and chemical qualities than bare soils. Vegetated soils were characterized by a high clay and silt content and a good consistency (soil structure), while bare soils were characterized by a high sand content and high bulk density. Vegetated soils were characterized by higher pH, OC, N, C/N ratio, CEC, P, and K. There was no significant difference in Mn or Cu between bare and vegetated soils. Cu was highly variable between sites (from 99 ± 61 mg.kg^{-1} in VS to 8559 ± 151 mg.kg^{-1} in BS). Our results demonstrate that the destruction of vegetation, leading to bare soil, negatively affects soil properties and may interfere with ecosystem services provided by urban soils in tropical climates. The physical properties observed in bare soils in this study, including silt, clay, and sand content, soil structure, and soil bulk density, along with chemical properties such as soil pH, cation exchange capacity, and soil organic carbon, can influence the ecosystem services provided by urban soils. These services include regulating water flow and nutrient cycling, enhancing nutrient availability, and supporting ecosystem functions through the cycling of water and nutrients.

1. Introduction

Since the mid-20th century, the world has experienced an increase in urbanization, which is reflected in the growth of the urban population and the geographic expansion of cities (Ferland, 2015; Grosbellet, 2008; Ibrahim et al., 2023). Cities in developing countries are the most affected by this trend of rapid urbanization (Nero and Anning, 2018). Despite some human benefits, urbanization has negative environmental consequences (Ferland, 2015; Lehmann and Stahr, 2007; Pickett et al., 2011).

Urbanization generally causes several ecological problems, mostly associated with loss or degradation of green spaces (e.g. soil degradation) (Useni et al., 2019). In urban areas, soils are typically degraded by a range of modifications including land clearing, topsoil removal, grading, compaction (Chen et al., 2014) and construction of buildings, resulting in soil with low vegetation cover (Kaye et al., 2006). Unvegetated urban areas exert a negative influence on the desirable physical characteristics of the soil (Jim, 1998), leading to soil sealing, which is the main cause of reduced ecosystem services in the urban environment (Lauf et al., 2014; Zhao et al., 2012). These modifications also lead to the alteration of the biogeochemical cycles of soils in urban areas (Ferreira et al., 2018; Zhang et al., 2019). When the soil is degraded, its ability to perform its functions decreases, which causes not only a decrease in its own viability but also an increase in the occurrence

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of extreme natural events (erosion, flooding, landslides) (Roose et al., 2015).

In the city of Lubumbashi, the health of the local vegetation has been profoundly affected due to an accelerated and uncontrolled spatial dynamic (Useni et al., 2019). In several tropical cities, the destruction of soil structure by the loss of vegetation due to the mismanagement of green spaces causes important damage (Tchotsoua, 1994). For instance, in Yaoundé and Ngaoundéré in Cameroon, the ferralitic soils (Tchotsoua, 1994; Tchotsoua and Bonvallot, 2001), and in Ivory Coast, tropical soils (Rakotoarimanana et al., 2008) of cities are subject to erosion because of the mismanagement of green spaces.

Mineralization of organic matter (OM) is essential in the transformation of litters, corpses, and various organic wastes into humus and subsequently the gradual restoration of soil nutrients (N, P, trace elements, etc.) (Asabere et al., 2018; Roose et al., 2015). When green space vegetation is degraded and the regular supply of litter or organic residues is eliminated, the soil microbial community feeds on the humus and organic matter responsible for soil structural stability (Sugihara et al., 2014; Varvel, 2006). In most tropical regions, the representation of OM should be at least 0.5% for sandy soils and 1.2% for clay soils (Varvel, 2006). Below these thresholds, the soil structure collapses, and crusts form on the soil surface, which reduces infiltration, accelerates runoff and erosion, dries out the profile and accelerates nutrient depletion (Roose et al., 2015).

However, very few studies have focused on the ecosystem services provided by soils. Soils are still poorly taken into consideration to enhance the sustainable development of urban ecosystems (Morel et al., 2015). Despite the excessive destruction and mismanagement of green spaces in many parts of the world and in Africa in particular, studies on urban green spaces with particular emphasis on the challenges they face are less focused on Africa (Mensah, 2014). Few studies have analysed soil nutrient levels and variation in soil physicochemical properties across different urban green spaces in selected cities in Africa. Many of the interrelations between urbanization and soil functioning remain unclear, especially for African cities (Asabere et al., 2018; Nero and Anning, 2018).

This study examines the impact of green space vegetation degradation on major physical and chemical parameters of soils in a tropical mega-city (Lubumbashi, Democratic Republic of Congo) following a bare soil–vegetated soil comparison approach. It aims to assess the impact of the destruction of urban vegetation (i) on the texture, soil bulk density and structure of soils and (ii) on the chemical quality of soils.

2. Materials and methods

2.1. Study area

This study was conducted in the city of Lubumbashi located in the southeast of the DRC (11°27′ to 11°47′S and 27°19′ to 27°40′E) in 2020. The climate of this region is classified as Cw6 according to the Koppën classification (Malaisse et al., 1978), characterized by the alternation of a rainy season (November to March) and a dry season (May to September) with October and April as transition periods. The average annual rainfall is approximately 1270 mm, and the average annual temperature is 20 °C with an annual relative humidity of 60% (Malaisse, 1997). The soils of Lubumbashi are mostly very weathered and acidic, mainly ferralsols (Mujinya et al., 2011). The surface areas of soils contaminated with heavy metals are constantly increasing due to the intensification of mining activity (Shutcha et al., 2018).

2.2. Selection and assessment of green spaces

City boundaries proposed by (Useni et al., 2019) were used to circumscribe the study area, and the identification of green spaces was performed based on Google Earth images and site prospecting. A total of six urban green spaces (UGSs), with at least one-third of the total area covered by trees and shrubs (Useni et al., 2019), and their nearby bare soils were selected. These are the Zoological Garden of Lubumbashi (ZOO), Safina Salama (SA), "Polytechnique/UNILU" (POL), "Cité des Jeunes" (CJ), "Cercle Hippique de Lubumbashi" (CHL) and "Arboretum/FSA/UNILU" (ARB) (Fig. 1).

To enhance the comparability between bare and vegetated soils, we ensured that both are closely situated, share the same soil type, topographic position, and altitude. Sites associated with institutions or enclosed areas were specifically chosen to reduce the impact of human activities and management practices, leveraging their controlled environments to limit heterogeneity.

For the six UGSs studied, a total of 43 tree species were observed (28 native species and 15 exotic species) (Fig. S1). The specific richness and the relative abundance of native and exotic species vary greatly from one site to another: from 20 species (ZOO) to two species (POL) and from 75% of individuals being native species (CHL) to 0% of individuals being native species (POL) (Table 1).

The soils at the ZOO (A2) and CHL (A3 and AG3) (Fig. 1 and Table 1) sites are classified as ferralsols derived from shale and are yellow or red, deep, sandy clayey to heavy clayey, well drained, and highly weathered. The soils at CJ (D6) (Fig. 1 and Table 1), derived from recent alluvium, very poorly to poorly drained, and light clayey to very clayey, are classified as Fluvisols. The soils at the SA (g), ARB (g), and POL (g) sites (Fig. 1 and Table 1), derived from laterite, well drained, and clayey to heavily clayey, are classified as plinthosols (Van Ranst et al., 2010; WRB, 2022).

2.3. Soil sampling and analysis

Soil sampling was carried out in May 2020 at the start of the dry season. At each study site, samples were collected from two different land cover types: bare soil (BS) and vegetated soil (VS). In this study, bare soil corresponded to areas of at least 100 m^2 occupied by a maximum of 3 scattered trees and <15% herbaceous cover. Vegetated soil corresponded to areas at least 100 m^2 occupied by >3 trees (Table 1) and >95% herbaceous cover. In each green space, four 100 m^2 quadrats were delimited for each type of land cover. Four 5 × 5 m sampling areas were delimited in each 100 m^2 quadrat. In each 25 m^2 sampling area, a composite sample (0–30 cm deep, ~2.5 kg) was made from 4 randomly located subsamples (Fig. 2). A total of 192 composite samples were taken from the six sites. For soil physical analysis, the soil block broken by dropping was used to conduct a visual soil assessment (VSA) to evaluate structure. The indicators on the score card were identified in the soils using the comparative photographs of the field guide manual proposed by (Shepherd, 2000). We used the scores to characterize the soil structure (2 = good consistency, 1 = average consistency and 0 = poor consistency).

The particle size analysis was carried out on soil samples dried in open air and sieved with 2 mm mesh. This was done after the destruction of calcium carbonate ($CaCO_3$) and elimination of organic matter with hydrogen peroxide (H_2O_2 30% vol) and peptization with sodium hexametaphosphate (Na6018P6 5%). Different fractions were separated: fine sands (> 50 μm and ≤ 200 μm), silts (> 2 μm and ≤ 20 μm) and clays (< 2 μm). The fractions are expressed as a percentage of the fraction of the soil finer than 2 mm.

The texture was classified according to the FAO textural triangle, commonly used for tropical soils (Chapelle, 2018), based on the three fractions (<2 μm; between 2 μm and 50 μm; >50 μm) and expressed as percentage mass. Soil bulk density was measured by the calibrated cylinder method (Alongo and Kombele, 2009). Soil samples were taken from the stratum 0–10 cm deep; the volume was estimated immediately on site, and the weight was assessed in the laboratory after drying and weighing.

Chemical analyses were performed on air-dried soil fractions (< 2 mm). The soil pH was measured potentiometrically in a 1:2.5 (*W*/*V*) suspension of H_2O, and the organic carbon content (OC, Walkley and

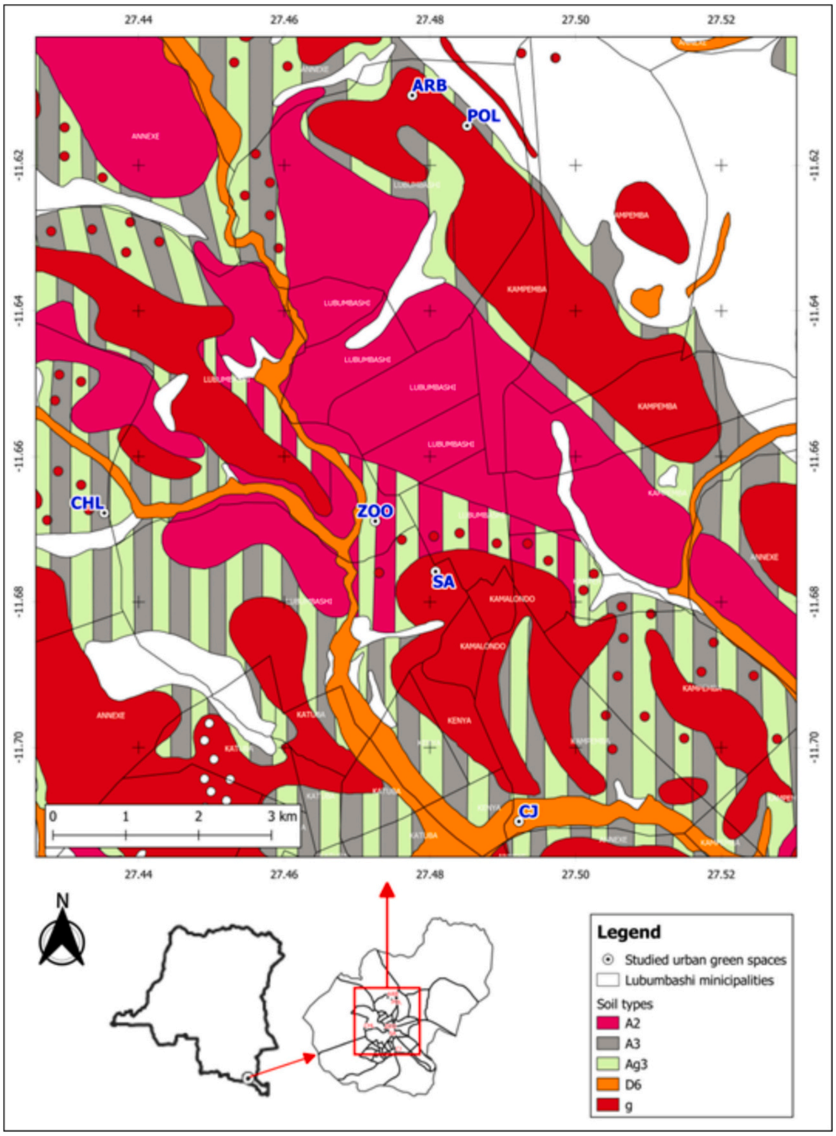

Fig. 1. Soil map of selected green spaces (based on the soil map of Sys and Schmitz, 1959; digitization and uniformization of the legend: Van Ranst et al., 2010). A2, A3, Ag3: Ferralsols; D6: Fluvisols, g: Plinthosols (WRB, 2022).

Black method), total nitrogen (N, Kjeldahl method), available phosphorus (P, Bray 2 method), and CEC (1 M NH_4OAc at pH 7) were determined using the procedure outlined by Van Ranst et al. (1999). Copper (Cu), manganese (Mn) and potassium (K) levels were determined using an X-ray fluorescence analyser (Van Ranst et al., 1999).

2.4. Statistical analyses

The relationships between the different physical parameters on the one hand and chemical parameters on the other hand, according to land cover and site, were highlighted by principal component analysis (PCA) using the FactoMineR and Factoextra R packages. Then, two-way analysis of variance (ANOVA 2) was performed to compare the means of different variables among sites and land cover types. Before running ANOVA, the assumptions of normally distributed residuals and homogeneous variances were tested using Shapiro–Wilk and Levene's tests. As all variables deviated from the ANOVA assumptions, we performed log-transformation. The analysis of variance revealed significant effects of the site X land cover interaction (Table S1), and the physical and chemical parameters were compared between vegetated soils and bare soils for each site individually by Student's *t*-test. All statistical analyses were performed using R software (R version 4.3.0), with a p value <0.05 as the level of significance.

3. Results

3.1. Texture and structure according to land cover and site

Vegetated soils (VSs) and bare soils (BSs) were globally separated on the texture triangle despite variations between sites (Fig. 3). VSs were characterized by clayey silt, loam, and sandy clay loam textures, while BSs were characterized by sandy–loamy, silty–clayed–sandy and loamy textures. Visual soil assessment (VSA) of soil structure (Table 2) showed that BS was characterized by poor consistency (score 0) and VS was characterized by moderately good (score 1) to good (score 2) consistency.

3.2. Physical and chemical properties of soil according to land cover and site

The first two axes of the principal component analysis explained 83.3% of the variability (Axis 1 = 47.2%; Axis 2 = 36.1%) in physical

Table 1
General information on selected green spaces and soil classification (Van Ranst et al., 1999; WRB, 2022).

Site	ARB	CHL	CJ	POL	SA	ZOO
	UGS1	UGS2	UGS3	UGS4	UGS5	UGS6
Soil type	g	A3 and Ag3	D6	G	G	A2
Long °, Lat °	27.47, −11.61	27.43, −11.66	27.49, −11.71	27.48, −11.61	27.48, −11.67	27.47, −11.66
Parent rocks	Laterite (gravelly substrate)	Shale	Recent alluvium and colluvium	Laterite (gravelly substrate)	Laterite (gravelly substrate)	Shale
WRB, 2022	Plinthosols	Feralsols	Fluvisols	Plinthosols	Plinthosols	Ferralsols
Number of individual trees per site	65	43	61	66	66	68
% of individuals belonging to native species	67	75	18	0	62	52
% of individuals belonging to exotic species	33	25	82	100	38	48
Frequency of anthropogenic activities present at the study sites						
Regular pedestrian crossing	+	+	+	+	+	+
Building activities	+	++	++	++	++	++
Breeding	−	++	++	−	+	++
Regular collection of fallen leaves	−	−	−	−	−	+

Legend:
+++: high.
++: medium.
+: low.
–: absent.
UGS: urban green space.

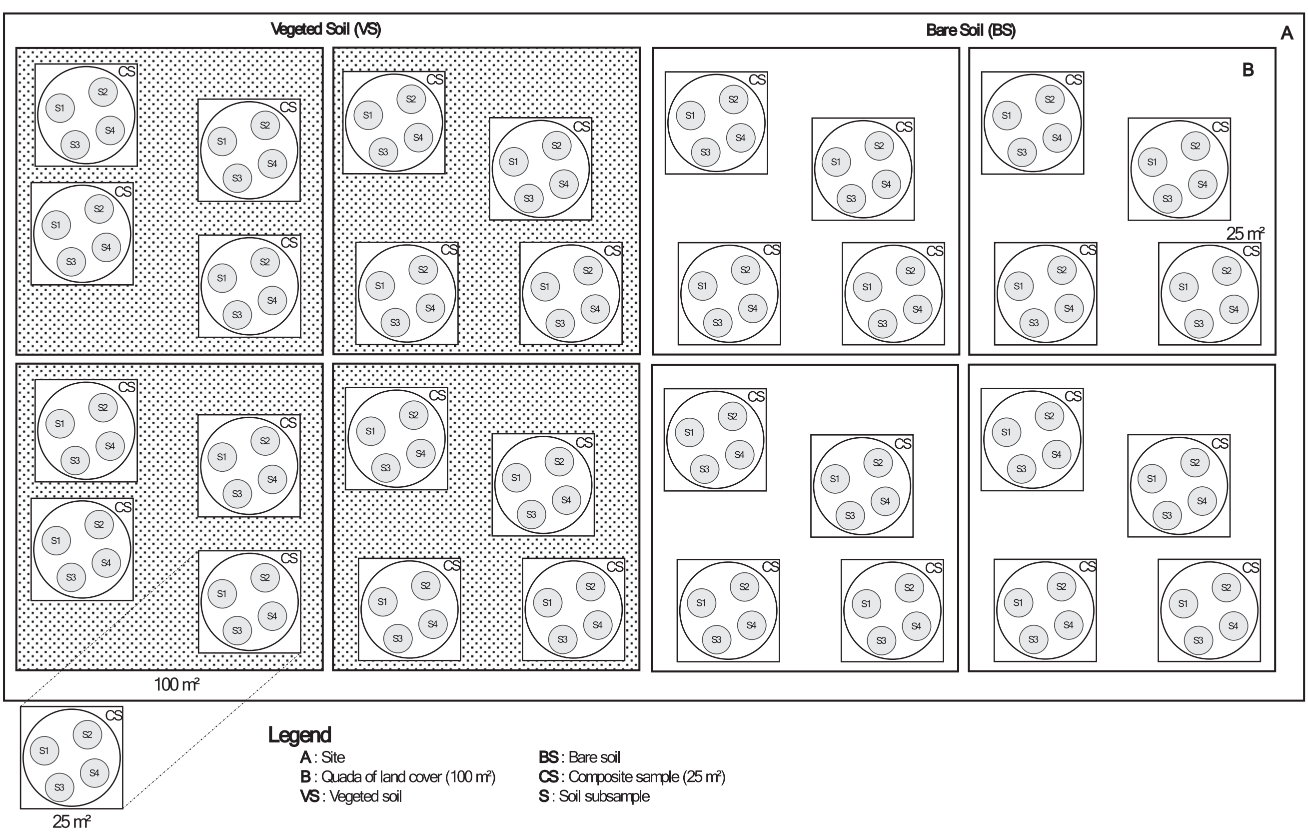

Fig. 2. Soil sampling strategy in six urban green spaces of Lubumbashi city.

properties among soil samples (Fig. 4a-b). The most important variable was land cover, with vegetated soil (VS) separated from bare soil (BS) along Axis 1, independent of site. VSs were characterized by a high clay and silt content. BSs were characterized by a high sand content (Fig. 4a). The second axis was correlated with SBD (soil bulk density) and separated soil samples from sites with high SBD (soil bulk density) (ZOO site, POL site) from those collected from sites with lower SBD (soil bulk density) (SA site), with samples from other sites displaying a more continuous separation along Axis 2.

The effect of vegetation on soil physical properties was assessed by mean comparisons between bare soil (BS) and vegetated soil (VS) at each site. The sand content was significantly higher in BS (range: 49.5% - 65.5%) than in VS (range: 31.2% - 39.7%) at all sites, with an average difference of 22%. The silt and clay contents were significantly higher in

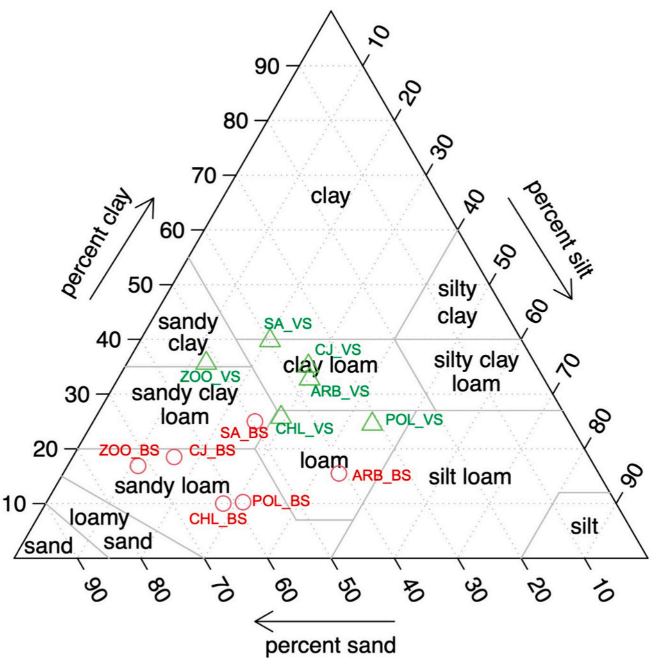

Fig. 3. Textural classification of soil for the studied green spaces (ARB, SA, ZOO, CHL, CJ, POL) according to land cover (VS: vegetated soil, green triangles; BS: bare soil, red circles).

VS (silt range: 24.5% - 39.7%, clay range: 20.5% - 44.2%) than in BS (silt range: 10.0% - 35.1%, clay range: 16.0% - 31.0%) at all sites, except for ARB and SA for clay, with an average difference of 15.4% for silt and 6.1% for clay. Mean comparisons by site showed that SBD (soil bulk density) was significantly higher in BS (range: 1.11 $g.cm^{-3}$ - 1.56 $g.cm^{-3}$) than in VS (range: 0.95 $g.cm^{-3}$–1.3 $g.cm^{-3}$) at 4 of 6 sites, with an average difference of 9.3%. It was significantly lower in BS than in VS at one site (SA) and not significantly different between BS and VS at one site (POL) (Table 3).

The first two axes of the principal component analysis of chemical properties explained 62.7% of the variability (Axis 1 = 41.0%, Axis 2 = 21.7%) in the chemical properties between the soil samples. VS samples were globally separated from BS samples but not strictly along a single dimension of the PCA (Fig. 4c-d). Axis 1 was positively correlated with measures of organic matter (OM, OC), mineralization (C/N) and the main nutrients (N, P_Av, K). Axis 1 tended to separate VS samples (positive coordinates on Axis 1) from BS samples (negative coordinates on Axis 2), except for two samples from ARB and three samples from SA. Axis 2 was strongly positively correlated with pH and CEC and negatively correlated with K. The VS samples (positive coordinates on Axis 2) were globally separated from the BS samples (negative coordinates on Axis 2).

Strong differences in chemical properties between VS and BS were assessed by mean comparisons between the two soil types at each site. Significant differences were found at all sites between VS and BS for pH (average difference: 12.1%) and CEC (average difference: 21%), with significantly lower pH in BS (range: 4.41–5.41) than in VS (range: 5.13–7.26) and significantly higher CEC in VS (range: 10.6 $mol.kg^{-1}$ - 44.25 $mol.kg^{-1}$) than in BS (range: 8.2 $mol.kg^{-1}$ to 22.7 $mol.kg^{-1}$) at all sites, except ARB. At all sites, significant differences were found between VS and BS for total OC (average difference: 42.4%) and C/N (average difference: 24.8%), with total OC being significantly lower in BS (range: 1.15% - 5.15%) than in VS (range: 2.4% - 11.7%), and the C/N ratio was also significantly lower in BS (range: 6.7–17.4) than in VS (range: 11.65–37.1) (Table 3).

Significant differences were found for nutrients between the VS and BS at all sites (N average difference: 19.2%; P_Av average difference: 51.1%; K average difference: 5.8%), except for total N and K at ARB and SA. At all sites, the nutrient contents (N, P_Av, K) were lower in BS (N range: 0.16% - 0.3%; P_Av range: 0.47 $mg.kg^{-1}$ - 9.2 $mg.kg^{-1}$; K range: 137 $mg.kg^{-1}$ - 450 $mg.kg^{-1}$) than in VS (N range: 0.24% - 0.36%; P_Av range: 2.56 $mg.kg^{-1}$ - 38.78 $mg.kg^{-1}$; K range: 149 $mg.kg^{-1}$ - 691 $mg.kg^{-1}$) (Table 3).

Statistically, the difference was not significant for total Mn and Cu between BS (Mn range: 148 $mg.kg^{-1}$ - 1228 $mg.kg^{-1}$; Cu range: 113 $mg.kg^{-1}$ - 8559 $mg.kg^{-1}$) and VS (Mn range: 154 $mg.kg^{-1}$ - 589 $mg.kg^{-1}$; Cu range: 99 $mg.kg^{-1}$ - 2615 $mg.kg^{-1}$). Total Cu was highly variable between sites (from 99 ± 61 $mg.kg^{-1}$ in VS-CHL to 8559 ± 151 $mg.kg^{-1}$ in BS-ZOO) (Table 3).

4. Discussion

4.1. Physical properties of soil

The conversion of vegetated areas of the studied green spaces into bare soil modified the physical soil structure. Vegetated soils, with lower bulk density (SBD) and higher silt and clay contents, were characterized by better soil physical properties than bare soils rich in sand. We also found that vegetated soils present higher levels of organic matter than bare soils. A high organic matter content is a good indicator of structural strength and resistance to compaction. It also improves aggregate stability (Jim, 1993; Lehmann and Stahr, 2007). Jim (1993, 1998) asserted that leaving soil unvegetated exerts a negative influence on physical characteristics desirable for the provision of ecosystem services (regulation of water quantity and quality, erosion control, floods, etc.). Water regulation, a very important ecosystem service in the urban environment, is closely linked to soil structure and texture (Chen et al., 2014). Clay plays an important role in soil water regulation (Tahirou et al., 2022). It consolidates soil aggregates and provides better resistance to water erosion. In a study on floods in the city of Lubumbashi, (Kalombo, 2021) emphasized that the impact of precipitation intensity on the environment (soil erosion, runoff, and flooding) is relative and depends on several factors (nature of the soil, anthropogenic influences) but more particularly on vegetation cover. However, based on the reference values of no anthropized tropical soils, the ranges of the bulk density found in this study for both bare soils and vegetated soils were higher than those in no anthropized tropical soils (0.7 g/cm^3 to 1.2 g/cm^3) (Obidike-Ugwu et al., 2023; Tomasella and Hodnett, 2004). Even the vegetated soils of the green spaces studied retained the characteristics of urban soils in terms of bulk density. Many studies have revealed high bulk densities in urban soils (Scharenbroch et al., 2005). Human activities similar to those observed in the studied green spaces (pedestrian traffic, paving of hard spaces, etc.) considerably modify urban soil, and these alterations distinguish urban soils from those of other systems (forests and savannahs) (Joimel et al., 2016).

Table 2
Visual field assessment of soil structural quality scores (VSA) (Shepherd, 2000), model inspired by (Moncada et al., 2014) ($N = 192$).

Site	ARB		CHL		CJ		POL		SA		ZOO	
Land cover	BS	VS	BS	VS	BS	VS	BS	VS	BS	VS	BS	VS
Soil structure	0	2	0	1	0	2	0	1	0	2	0	2

BS: bare soil, VS: vegetated soil, 2 = good consistency, 1 = average consistency and 0 = poor consistency.

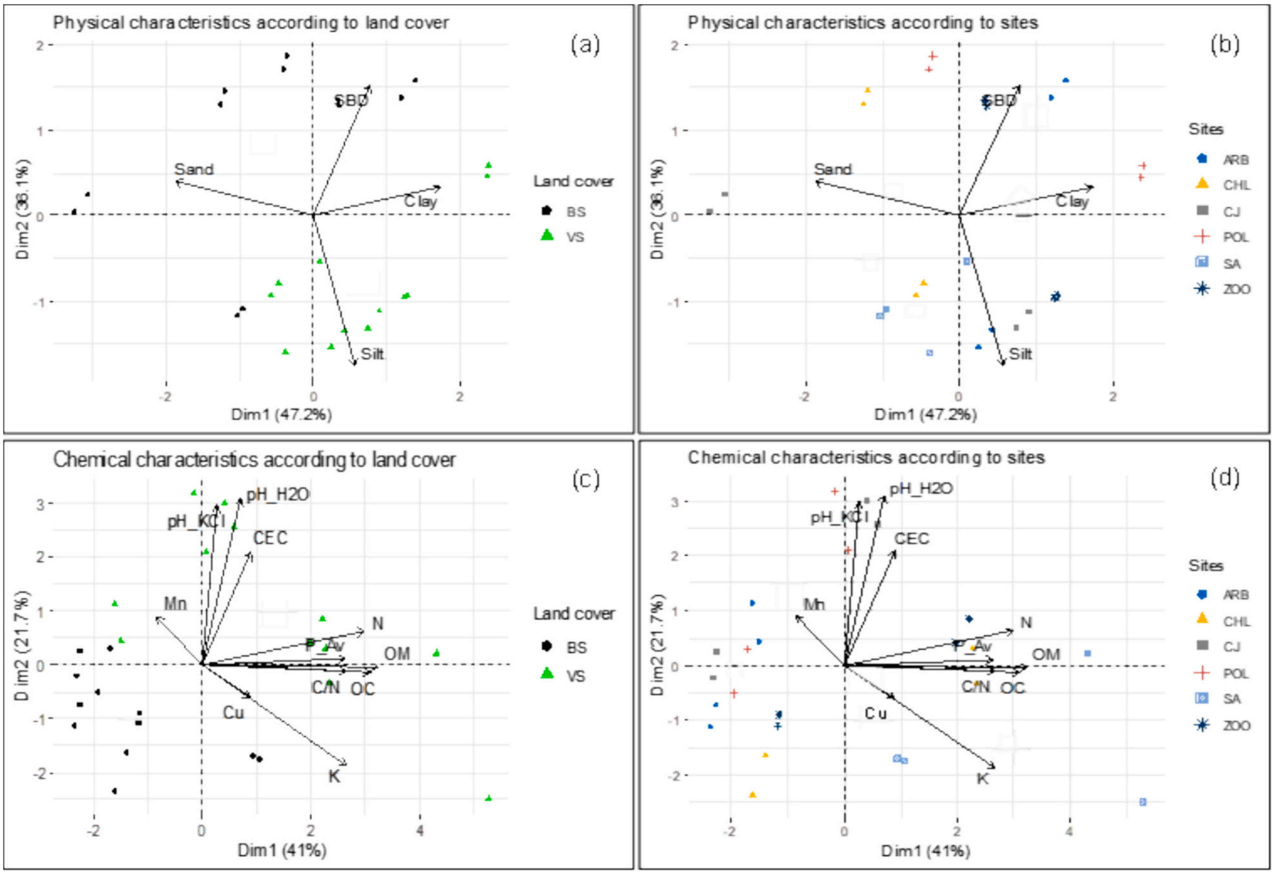

Fig. 4. Principal component analysis (PCA) of four soil physical characteristics and eleven soil chemical characteristics according to land cover (a and c) and site (b and d). The first dimension explains 47.2% of the variability in the data, whereas the second dimension explains 36.1% of the variability in soil physical characteristics according to land cover and site (a and b). For soil chemical characteristics according to land cover and site (c and d), the first dimension explains 41% of the variability, while the second dimension explains 21.7%. VS: vegetated soil, BS: bare soil, SBD: soil bulk density, OC: total OC, N: total N, C/N: C/N ratio, K: total K, P_Av: available P, Cu: total Cu, Mn: total Mn.

4.2. Chemical characteristics of soil

4.2.1. Soil fertility parameters

Cation exchange capacity (CEC), organic matter (OM) and nutrient contents are indicators linked to the important ecosystem service of soil fertility maintenance. CEC indicates the capacity of the soil to store nutrients in the form of cations. Vegetated soils with a high CEC and a large quantity of organic matter promote ecosystem services related to nutrient cycling (Blanchart et al., 2017). A high organic matter content is a good indicator of soil fertility (Jim, 1993; Lehmann and Stahr, 2007). The cation exchange capacity (CEC), organic matter (OM), and overall nutrient contents (N, available P, K) were lower in bare soils than in vegetated soils. Globally, the destruction of vegetation had an impact on the fertility of soils at the studied sites. Our results corroborate those of (Andriamaniraka, 2016; Feller et al., 1994), who asserted that following deforestation, soils become very easily erodible and poor in nutrients, especially ferralitic soils. These ferralitic soils are generally acidic with varying degrees of fertility; however, when bare, they are very susceptible to erosion and degradation. Owusu-Bennoah et al. (2000) added that in tropical soils, litter reduction involves decreased organic matter recycling, decreased pH, and decreased N, K and CEC. This feature leads to phosphorus fixation problems. In our study, the pH was approximately 1.2–1.3 times higher in vegetated soils (VSs) than in bare soils (BSs). Deforestation of urban green spaces acidifies soils to the point of promoting very low pH values. Compared to vegetated urban soils, bare soils (BSs) are more exposed to urban waste, which could explain their high acidity (Joimel et al., 2016). The results of the study by Soumaré et al. (2003) on the physico-chemical parameters of the tropical soils of Mali showed less K at the sites where the soils were exposed to leaching than at the sites where the soils were protected by vegetation.

However, based on the classes of references made by Bassole et al. (2023) for tropical soils, the studied soils presented globally high values of fertility indicators. According to the interpretation of Bassole et al. (2023) for the CEC values found in tropical soils, the average values found in bare soil fall within the high-CEC value range (15 $mol.kg^{-1}$ to 20 $mol.kg^{-1}$), while the values for vegetated soil fall within the very-high-CEC value range (> 20 $mol.kg^{-1}$). The estimated concentrations of N and K in both bare and vegetated soils of the studied green space should be considered very high (bare soils: $N = 0.16\%$, vegetated soils: $N = 0.3\%$, reference high value: > 0.14%; bare soils: K = 269 $mg.kg^{-1}$, vegetated soils: K = 331 $mg.kg^{-1}$, reference high value: > 200 $mg.kg^{-1}$). In contrast, available P (P_Av) concentrations should be considered low in bare soils (bare soil: 4.5 $mg.kg^{-1}$, reference low value <5 $mg.kg^{-1}$) but high in vegetated soils (vegetated soils: 20.5 $mg.kg^{-1}$, reference high value: [20 $mg.kg^{-1}$ - 30 $mg.kg^{-1}$]).

Mineralization was also affected by vegetation degradation at the studied sites, with a lower C/N ratio in bare soils than in vegetated soils. The C/N ratio is an indicator of the level of degradation of organic matter. It is commonly accepted that the higher the C/N ratio of organic matter is, the slower it decomposes in the soil and the more stable the humus obtained. C/N ratios >12 in urban soils, as found in vegetated soil in our study, indicate slow decomposition of organic matter and stable humus (Assandri et al., 2020) and may optimize regulating and supporting ecosystem services (water cycle, biogeochemical cycles, primary production, and self-maintenance services) (Walter et al.,

Table 3
Comparison of physical and chemical parameters according to land cover at each site (*t*-test). Values with the same letter are not significantly different ($p < 0.05$). ($N = 192$).

Site		ARB		CHL		CJ		POL		SA		ZOO	
Land cover		BS	VS	BS	VS	BS	VS	BS	VS	BS	VS	BS	VS
SBD	$g.cm^{-3}$	1.44 ± 0.02a	1.00 ± 0.02b	1.34 ± 0.02a	0.95 ± 0.03b	1.11 ± 0.02a	1.08 ± 0.06b	1.42 ± 0.02a	1.42 ± 0.02a	0.94 ± 0.02b	1.33 ± 0.20a	1.56 ± 0.02a	1.30 ± 0.01b
Clay	%	43.50 ± 0.58a	30.25 ± 0.96b	28.00 ± 4.32b	40.25 ± 0.96a	16.00 ± 1.41b	28.88 ± 7.60a	31.00 ± 0.82b	44.25 ± 0.96a	25.50 ± 0.58a	20.50 ± 1.00b	21.12 ± 1.11b	37.50 ± 5.00a
Silt	%	15.50 ± 1.00b	32.75 ± 1.50a	10.00 ± 0.00b	25.75 ± 0.96a	18.50 ± 1.29b	35.12 ± 5.01a	10.25 ± 0.5b	24.50 ± 0.58a	25.00 ± 0.82b	39.75 ± 0.96a	16.88 ± 1.25b	30.62 ± 4.27a
Sand	%	41.00 ± 0.82a	37.00 ± 0.82b	62.00 ± 4.32a	34.00 ± 0.82b	65.50 ± 0.58a	36.00 ± 2.71b	58.75 ± 0.96a	31.25 ± 1.50b	49.50 ± 1.29a	39.75 ± 0.96b	62.00 ± 1.47a	31.88 ± 8.51b
pH		5.19 ± 0.01b	6.63 ± 0.29a	4.41 ± 0.47b	5.38 ± 0.16a	5.13 ± 0.04b	7.18 ± 0.01a	5.41 ± 0.38b	7.26 ± 0.44a	4.74 ± 0.11b	5.93 ± 0.97a	5.41 ± 0.47b	6.38 ± 0.16a
CEC	$mol.kg^{-1}$	8.65 ± 0.06a	5.85 ± 0.06b	17.00 ± 0.58b	39.20 ± 0.35a	22.70 ± 0.23b	32.35 ± 0.64a	17.95 ± 0.17b	44.25 ± 0.29a	8.20 ± 0.12b	10.60 ± 0.12a	18.80 ± 0.58b	40.75 ± 0.87a
OM	%	2.00 ± 0.00b	4.50 ± 0.58a	2.50 ± 0.58b	13.50 ± 1.73a	2.50 ± 0.58b	7.50 ± 0.58a	2.50 ± 0.58b	6.50 ± 0.58a	7.50 ± 0.58b	19.50 ± 1.73a	2.50 ± 0.58b	7.50 ± 0.58a
OC	%	1.25 ± 0.06b	2.40 ± 0.12a	1.35 ± 0.06b	4.25 ± 0.06a	1.75 ± 0.06b	4.40 ± 0.35a	1.80 ± 0.12b	3.55 ± 0.06a	5.15 ± 0.06b	11.70 ± 0.58a	1.15 ± 0.06b	4.15 ± 0.06a
N	%	0.19 ± 0.01a	0.17 ± 0.01a	0.16 ± 0.02b	0.36 ± 0.02a	0.18 ± 0.01b	0.29 ± 0.01a	0.17 ± 0.01b	0.24 ± 0.01a	0.30 ± 0.01a	0.32 ± 0.01a	0.16 ± 0.01b	0.36 ± 0.01a
C/N		6.70 ± 0.12b	14.55 ± 1.21a	8.70 ± 0.58b	11.95 ± 0.75a	9.95 ± 0.64b	15.40 ± 1.5a	10.85 ± 0.29b	15.10 ± 0.12a	17.40 ± 0.12b	37.10 ± 1.15a	7.40 ± 0.12b	11.65 ± 0.06a
P_Av	$mg.kg^{-1}$	0.47 ± 0.04b	2.56 ± 0.07a	9.25 ± 0.75b	37.78 ± 0.77a	3.70 ± 0.23b	16.79 ± 0.33a	2.17 ± 0.01b	7.29 ± 0.14a	20.65 ± 0.64a	19.37 ± 0.66a	9.01 ± 0.12b	38.78 ± 0.77a
K	$mg.kg^{-1}$	161 ± 1a	138 ± 5b	426 ± 17b	477 ± 19a	137 ± 3b	149 ± 2a	177 ± 2b	201 ± 3a	450 ± 17b	691 ± 18a	427 ± 17b	478 ± 13a
Cu	$mg.kg^{-1}$	166 ± 1a	293 ± 103a	175 ± 34a	99 ± 61a	113 ± 26a	145 ± 16a	113 ± 39a	99 ± 61a	2863 ± 121a	2615 ± 133a	8559 ± 151a	5984 ± 336a
Mn	$mg.kg^{-1}$	282 ± 2a	536 ± 39a	148 ± 84a	310 ± 222a	1228 ± 40a	589 ± 21a	148 ± 84a	355 ± 275a	453 ± 264a	154 ± 75a	354 ± 57a	490 ± 27a

BS: bare soil, VS: vegetated soil, SBD: soil bulk density, OC: total OC, N: total N, C/N: C/N ratio, P_Av: available P, K: total K, Cu: total Cu, Mn: total Mn.

2015).

4.2.2. *Heavy metals in soil*

Copper pollution is a major problem in Katanga, a region of intense mining activity. In urban soils of green spaces in Lubumbashi, land cover (VS, BS) had no significant effect on copper (Cu) concentrations. In the Katanga Copperbelt region, even undisturbed areas such as forests can have soils with significantly more Cu than ecosystems subject to direct human activity such as croplands (Mpinda et al., 2021). In the Katanga Copperbelt in general and in the Lubumbashi region in particular, mining activities have probably modified the natural metal content of the soil, making comparisons with international or regional reference values inappropriate for environmental studies (Mpinda et al., 2021). The highest content observed at ZOO could be explained by its exposure to smoke pollution from the GECAMINES chimney; indeed, the presence of bare soil at ZOO in Lubumbashi would be due not only to the clearing occurring there but also to the effects of the smoke from the GECAMINES chimney on the vegetation. According to Vranken (2010), the geographer Chapelier mentioned the effect of smoke on the vegetation in Elisabethville in the 1950s. Downstream of the plant, the high concentration of Cu at the ZOO site may also result from the site being crossed by the Lubumbashi River. The waste, dumped directly into the Lubumbashi River, heavily polluted it (Vranken, 2010).

4.3. *Potential implication of soil physical and chemical properties in the assessment of ecosystem services*

The contribution of soils to human well-being beyond food production requires appreciation and this can be addressed by integrating soils into the ecosystem services framework and linking it to the multitude of functions it provides (Adhikari and Hartemink, 2016). Soil ecosystem services depend on soil properties and their interactions and are mainly influenced by its use and management (Adhikari and Hartemink, 2016; Dominati et al., 2010, 2014; McBratney et al., 2014).

Indeed, the results of this study demonstrate that the destruction of vegetation in urban green spaces, leading to bare soils, negatively affects soil properties and interferes with the ecosystem services provided by urban soils. Thus, vegetated soils were characterized by better physical properties (lower soil bulk density and higher silt and clay contents) than bare soils rich in sand content. The same trend was observed for chemical properties, cation exchange capacity (CEC), organic matter (OM) and overall nutrient content (N, available P, K) were lower in bare soils than in vegetated soils, the pH was approximately 1.2 to 1.3 times higher in vegetated soils (VS) than in bare soils (BS).

As a result, the reduction in the quality of physical properties observed in bare soils affects the supply of regulating ecosystem services linked to the quality and quantity of water and regulating ecosystem services linked to the control of water erosion and flooding. However, water regulation is a very important ecosystem service in the urban environment. The decrease in the quality of chemical properties in bare soils affects supporting ecosystem services linked to primary production (nutrient cycling) and supporting ecosystem services linked to soil formation and supporting ecosystem functions.

5. Conclusions and outlook

Our study demonstrated that the destruction of vegetation has a negative impact on the soil physical and chemical qualities of green spaces in a tropical city. Despite the variability in soil properties among sites, there was clear differentiation between vegetated and bare soils. Our results demonstrated that vegetation degradation in the green space of a tropical city alters physical and chemical soil quality, even if both bare and vegetated soils retain the characteristics of urban soil. The destruction of vegetation, giving way to bare soils, particularly affects the structure of the soil and chemical properties, and can affect ecosystem services of prime importance in urban contexts, such as water regulation. The bare soils of Lubumbashi should be revegetated to restore all their physical and chemical qualities in order to optimize ecosystem services.

Ethics approval

N/A.

Consent to participate

N/A.

Consent for publication

N/A.

CRediT authorship contribution statement

Grace Queen Mashagiro: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Bazirake Basile Mujinya:** Supervision. **Gilles Colinet:** Supervision, Methodology, Funding acquisition. **Grégory Mahy:** Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

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