Ecological Indicators 160 (2024) 111743

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Carbon and nitrogen stock in soils of subtropical urban forests: Isotopic $\delta^{13}C$ and $\delta^{15}N$ indicators for nature-based solutions in a megacity

Mauro Ramon [a,1], Raffaele Lafortezza [b,2], Andreza Portella Ribeiro [c,3], Plínio Barbosa de Camargo [d,4], Marisa Domingos [e,5], Eduardo Pereira Cabral Gomes [f,6], Armando dos Reis Tavares [g,7], António Guerner Dias [h,8], Claudia Terezinha Kniess [i,j,k,9], Maurício Lamano Ferreira [b,h,l,10,*]

[a] Division of Urban Data, Coordination of Registration, Data Analysis and Electronic Licensing System, Secretary of Urbanism and Licensing of São Paulo City, Rua São Bento, 405, 01011-100, São Paulo, Brazil
[b] Department of Soil, Plant and Food Sciences, University of Bari Aldo Moro, Via Amendola 165/A, 70126 Bari, Italy
[c] Graduate Program in Smart and Sustainable Cities, University Nove de Julho, Rua Vergueiro, 235 – Liberdade, 01525-000 São Paulo, Brazil
[d] Center for Nuclear Energy in Agriculture, University of São Paulo, Av. Centenário, 303, 13400-970 Piracicaba, Brazil
[e] Biodiversity Conservation Center, Environmental Research Institute, Av. Miguel Estefno 3687, 01061970 São Paulo, Brazil
[f] Sustainable Use of Natural Resources Centre, Environmental Research Institute, Av. Miguel Estefno 3687, 01061970 São Paulo, Brazil
[g] Advanced Center for Technological Research in Fruit Agribusiness, Agronomic Institute of Campinas, Avenida Luiz Pereira dos Santos, 04301092 Jundiaí, Brazil
[h] Institute of Geosciences, Environment and Spatial Planning, University of Porto, Rua Campo Alegre 687, 4169-007 Porto, Portugal
[i] Department of Administration, Federal University of São Paulo, EPPEN - Rua Oleska Winogradow, 100, Osasco, 06120-042, Brazil
[j] Graduate Program in Civil Engineering, São Judas Tadeu University, Rua Taquari, 546, São Paulo, 03166-000, Brazil
[k] Graduate Program in Administration, University of Southern Santa Catarina, Av. Pedra Branca, 25, Palhoça - SC 88137-270, Brazil
[l] Department of Basic and Environmental Sciences, University of São Paulo, Estrada Municipal do Campinho, s/n 12602-810, Brazil

ARTICLE INFO

Keywords:
Carbon cycle
Nitrogen cycle
Soil conservation
Urban forests
Urban sustainability

ABSTRACT

Urban forest soils play a pivotal role in enhancing the environmental sustainability of cities, contributing to various natural processes, including plant–microbe interactions, microbial activity, and the decomposition of organic matter. Consequently, urban forest soils emerge as effective NBS, underscoring their potential to mitigate environmental challenges and foster sustainable urban ecosystems. In these sense, this manuscript aimed at evaluating how soil attributes of the urban forests of São Paulo, Brazil, with different adjacent land uses, influence the capacity to store the excess of C and N from anthropogenic emissions, making this ecosystem an important reservoir of urban anthropogenic emissions. Three hundred urban forest soil samples were collected from the surface to a depth of 50 cm. All samples were analyzed for C and N content (and their stable isotopes). In addition, granulometric tests were also carried out to classify the soils. It was found that the most central forest fragment has the highest C and N contents at all analyzed depths, probably due to the association with physical aspects of soil texture. For all layers, the most central fragment soil sample, the only one with a clay soil, presented approximately twice as many elements when compared to the soil samples of the other sites. In general, C and N stocks (and their stable isotopes, $\delta^{13}C$ and $\delta^{15}N$, respectively) varied significantly in forests located in the center-periphery direction (%N - $F = 24.58$, $p < 0.05$; %C - $F = 22.48$, $p < 0.05$; $\delta^{15}N$ - $F = 4.27$, $p < 0.05$; $\delta^{13}C$ -

---

* Corresponding author.
E-mail addresses: mauecologia@yahoo.com.br, lamano@usp.br (M.L. Ferreira).
[1] ORCID: 0000-0001-8900-4603.
[2] ORCID: 0000-0003-4642-8435.
[3] ORCID: 0000-0002-1763-4558.
[4] ORCID: 0000-0002-0696-3778.
[5] ORCID: 0000-0001-5861-7968.
[6] ORCID: 0000-0002-3537-2977.
[7] ORCID: 0000-0001-6006-4741.
[8] ORCID: 0000-0002-1848-2234.
[9] ORCID: 0000-0002-1961-2037.
[10] ORCID: 0000-0002-7647-3635.

https://doi.org/10.1016/j.ecolind.2024.111743
Received 31 August 2023; Received in revised form 15 December 2023; Accepted 19 January 2024

$F = 19.8$, $p < 0.05$; C/N - $F = 14.56$, $p < 0.05$). This more central forest fragment with higher vehicle emissions showed greater potential to store these atmospheric elements and with greater neutralizing efficiency than the other forest fragments. $\delta^{13}C$ and $\delta^{15}N$ contents together with the C:N ratio indicated the efficiency of biogeochemical cycling, through decomposition, in different urban forest fragments. More peripheral fragments showed high efficiency in C and N cycling along the analyzed soil profiles, while in the most superficial layer, the most central fragment was highly efficient. These shed light results how integrating NbS principles into strategic urban planning and city-level climate policies can bolster the effectiveness of urban green areas. The integration not only promotes carbon sequestration and efficient nutrient cycling in the soil but also fosters sustainable practices, contributing to a more resilient urban landscape.

1. Introduction

Urban soils are key components to support ecosystem services and strategies for climate change adaptation in cities, especially in terms of offsetting greenhouse gases emitted by human activities (Lorenz and Lal, 2015; Li et al., 2022; Zhan et al., 2023). The atmospheric, hydrological, and thermal conditions of urban environments influence nutrient cycling in soils, thus limiting the use of biogeochemical models of non-urban ecosystems in cities. This compartment, called “brown infrastructure” (Pouyat and Trammell, 2019), offers a series of important ecosystem services to cities including nutrient cycling, carbon sequestration and water purification. It supports the set of trees in cities i.e., green infrastructure) that optimize carbon sequestration and storage, in addition to helping control water content in urban ecosystems. Thus, the coupling between trees and soil together offers greater resilience to cities (Chen, 2015). This underscores the need for a more in-depth understanding of biogeochemical patterns and processes in urban areas.

The classic concept of urban ecology assumes that anthropogenic drivers influence the control of ecosystem structure and functions (Alberti 2008), in addition to considering that anthropogenic effects decrease in a linear gradient from the center to the periphery of cities (Theobald, 2004). This may be a flawed concept due to the non-linear and complex growth of cities. Urbanization is nonetheless estimated to decrease the capacity to store carbon, contributing to the loss of up to 0.05 Pg C annually from forest biomass in pan-tropical regions, either by changes in land use or by the intensification of erosive processes (Seto et al., 2012). Furthermore, specific uses of urban areas, i.e., roads and avenues with intense vehicular traffic or excessive industrial activity, can interfere with the stock of elements in the soil as well as the size and age of the city or functional zoning (Vasenev and Kuzyakov, 2018). In addition, switching vegetation typology, e.g. from grassy fields to wooded parks, or vice versa, can change carbon isotope ratios ($^{13}C/^{12}C$) as well as the significant input of carbon from fossil fuels in soils (Spencer et al., 2009; Pereira et al., 2022). Nevertheless, soils play a critical role in the carbon balance, being responsible for storing up to two-thirds of all the forest carbon present in cities (Richter et al., 2020).

The vehicular fleets and industrial processes adjacent to cities also contribute to high amounts of N deposition in soils, changing the availability of the element over time (Du et al., 2022; Cui et al., 2016; Decina et al., 2020). This slow and continuous process of atmospheric deposition can interfere not only with the amount of available nitrogen (N) to plants in the soil but also determine the values present at different depths, depending on soil type. Such N values in different soil layers may result from specific geochemical or biological processes, which can be reliably evidenced by the abundance of isotopic N, $\delta^{15}N$.

Urban forests are subject to the continuous effects of heat islands; therefore, it is expected that high temperatures increase the rate of mineralization in the soil and interfere in N transformation processes when compared to natural systems (Trammell et al., 2020). This temperature effect is not limited to N and is also associated with lower C stock in urban forest soils (Pouyat et al., 2006; Pouyat et al., 2017).

In recent decades, there has been a growing interest in studies related to carbon and nitrogen in urban forests worldwide (Pouyat and Trammell, 2019; Trammell et al., 2020; Du et al., 2022). However, in countries of South America, where urban adaptation to environmental challenges is imperative, information is still lacking in this field. The gap is even more significant when considering the isotopic approach ($\delta^{13}C$ and $\delta^{15}N$) in urban forests, with only a few studies exploring this aspect (Pereira et al., 2022). Indeed, the spatial distribution patterns of the abundance of ^{13}C and ^{15}N, whether as potential indicators of contamination sources or of ecophysiological processes, are not well understood in the tropics. Here, soils are generally poor in nutrients, acidic and highly dependent on the cycling dynamics of organic matter deposited on the surface (Bonilla-Bedoya et al., 2022).

The use of isotopic methodologies to accurately assess C and N can shed light on the efficiency of urban forest soils in capturing and storing these elements. Applying such approaches to vulnerable cities in Latin America, as highlighted by Bonilla-Bedoya et al. (2022), can help update management strategies to increase the soil carbon storage capacity in urban-rural-natural gradient environments and contribute to local, regional, and global climate variations. Furthermore, the greater capacity to store C and N can be an instrument for selecting priority areas destined for conservation and carbon neutralization in urban sites. This research approach can also be extended to manage forest fragments in other vulnerable socio-ecological environments and support policy decisions for expanding green infrastructure to adapt to large cities as well as megacities in future climate change scenarios.

Increasing C and N stock through urban forests can serve as an effective nature-based solution (NbS) to mitigate disturbances in coupled systems, thereby ensuring the sustainability of social and ecological systems (Pereira et al., 2021). Epelde et al. (2022) evaluated the application of NbS under two conditions, ‘Feasible’ and ‘Ideal’, in an urban district in Donostia-San Sebastián City, Spain, to optimize carbon sequestration and storage in urban green areas. The soil sequestered between 71% and 82% of the total amount of C and stood out for its key role in climate change adaptation and mitigation strategies. Thus, by combining the management of soils and vegetation, NbS increase the amount of organic C and provide multiple benefits to soils, e.g., increase edaphic biodiversity and pluvial flood control. Based on this premise, we aimed to address the following research question: Considering the need to neutralize excess atmospheric C and N emitted by human activities in large subtropical cities, what would be the potential of urban forest soils to store this surplus?

In our study, we hypothesized that C and N (%C, %N, δ13C and δ15N) in urban forests located along a center-periphery gradient in the megacity of São Paulo would indicate the efficiency of soils being enriched by these elements, making them efficient NbS for adaptation to cities. Different land uses adjacent to forest fragments can be crucial in enriching C and N content, especially in downtown urban soils (Trammell et al., 2020; Pereira et al., 2022). Additionally, higher rates of N redox in downtown urban soils may lead to a stronger discrimination of ^{15}N, increasing soil $\delta^{15}N$ availability, especially in the upper soil layers (Craine et al., 2009; Elmore et al., 2016). We also hypothesized that %C stock is spatially related to land use and soil type (e.g., clay soils), and that $\delta^{13}C$ values respond better to soil processes (e.g., litter production and decomposition) showing a strong relationship with deep soil. Our supposition was found to align with previous research (Martinelli et al., 2017; Ngaba et al., 2019).

This work is the first to investigate the main soil attributes of urban forests in São Paulo, a Latin American megacity. We specifically aimed to evaluate the physical–chemical structure, depth, and land use of the surrounding soil, which influence the ability to store C and N, making this compartment an important reservoir of urban anthropogenic emissions.

Simple and low-cost alternatives to resolve complex issues are increasingly desired, especially with regard to biodiversity and climate, as well as settlements with great socio-environmental challenges. This work points out, through isotopic indicators, the greater or lesser accumulation of C and N in urban forest soils, thus offering a tool for the management and expansion of urban forests in cities facing multiple socio-ecological challenges.

2. Materials and methods

2.1. Study area

The area selected for our study is the megacity of São Paulo, Brazil, covering more than 1,500 km^2. It is situated almost entirely in the Atlantic Forest biome at an altitude of more than 700 m a.s.l. A set of water reservoirs in the *peri*-urban region guarantees water security for the population. Unfortunately, these reservoirs have been threatened by challenges with irregular occupation on their banks. São Paulo has the highest Gross Domestic Product in the continent. With a population of approximately 11,500,000 inhabitants, the city presents severe economic and socio-environmental challenges (IBGE, 2023). Despite its location in the richest region, a large part of the population lives on the borderline of poverty and destitution, facing problems such as lack of sanitation.

Severe environmental changes have recently taken place in the municipality of São Paulo, marked by vast urban expansion and subsequent intense deforestation of the Atlantic Forest in an area of humid forests interspersed with sedimentary river plains. This urban expansion was accompanied by concentrated emissions of atmospheric pollution, creating hotspots of air contamination in the territory (Ferreira et al., 2012; Ferreira et al., 2017), in addition to inducing other relevant impacts, i.e., extreme heat island phenomena and the introduction of exotic species.

Large green areas immersed in a gray matrix are evident on the boundaries of the municipal territory, i.e., in *peri*-urban areas and districts with high-income populations (São Paulo, 2020; Arantes et al., 2021). Forest fragments of different sizes are spread throughout the city, which play an important role in flood control, biogeochemical processes, and the maintenance of urban biodiversity.

Precisely in the central region of São Paulo is located Trianon Park (TP). This forest fragment lies at an altitude of 805 m a.s.l. and covers an area of 4.86 ha; it is divided into two green blocks connected by a pedestrian walkway crossing a busy avenue with heavy vehicular traffic. TP is the only studied forest fragment without water bodies. Alfredo Volpi Park (AVP) is situated in the western zone of the city, covering an area of 14.24 ha ranging from 730 to 785 m a.s.l. This forest fragment is located 6.0 km from the city center. Fontes do Ipiranga State Park (FISP) is located in the southern zone and lies 11 km from the city center; it covers a vast area of 495 ha and is dominated by dense forest remnants. The altitude of this fragment varies between 759 and 837 m a.s.l. (for details see Petri et al., 2018; Vieira et al., 2022). For this study the soil samples were taken from a forest patch near the visitation area of the Botanical Garden (area 2 in Petri et al., 2018). Carmo Park (CP), the most distant fragment from the city center (19 km), is situated in the eastern zone and covers an area of 150 ha within its polygon. The altitude of CP ranges from 775 to 855 m a.s.l. (Fig. 1). TP is the forest fragment with the greatest floristic diversity and most advanced successional stage when compared to the AVP, FISP and CP fragments. The latter is the most disturbed forest fragment, as it is periodically vulnerable to fire occurrence (Aragaki, 2017; Silva et al., 2006).

2.2. Collection and analysis of edaphic material

Each forest fragment in this study had been previously divided into

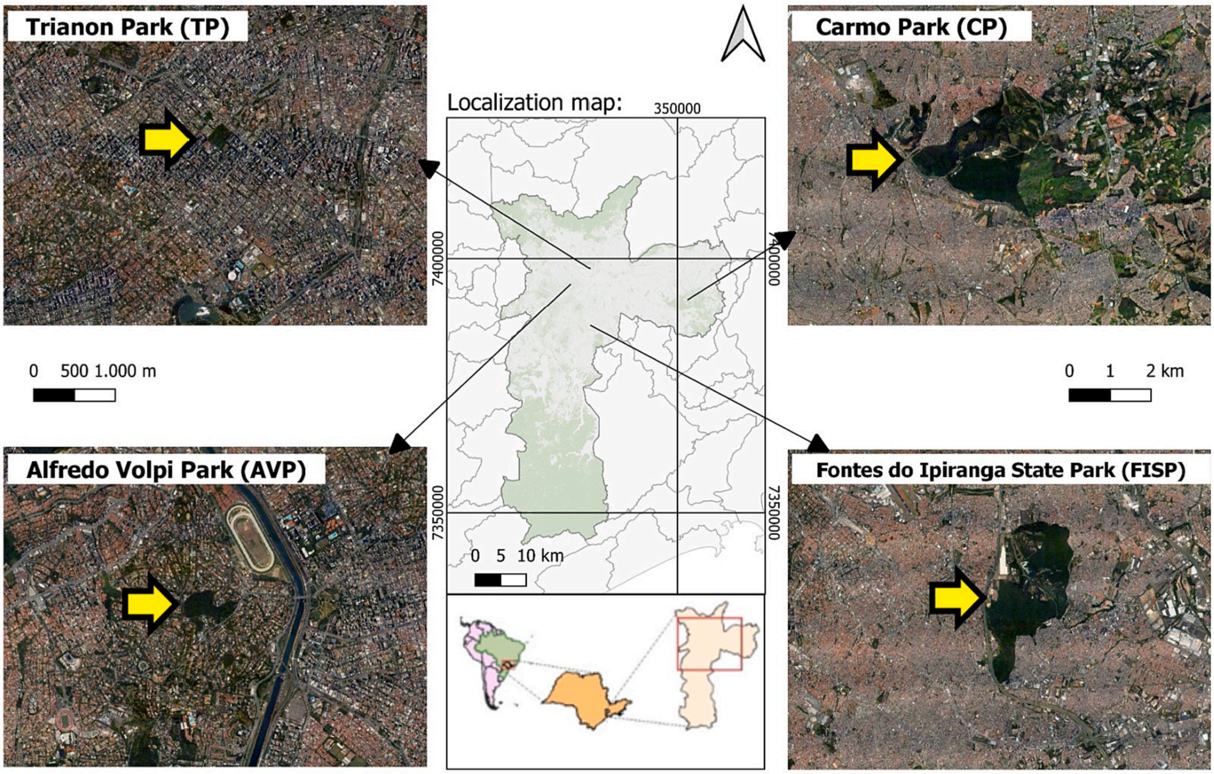

Fig. 1. Location of forest fragments in the megacity of São Paulo.

100 sub-plots of 10 m × 10 m, totaling 1 ha of studied area per fragment. The exact location of the subplots followed a random procedure of geographic coordinates which were assembled in 2019. Some works have already been carried out in these forest fragments (Martins et al., 2021; Pereira et al., 2022; Ramon et al., 2023) ensuring the sampling design for ecological studies.

In each urban forest fragment (TP, AVP, FISP, and CP), 15 sampling points were selected for soil collection. The sampling points were evenly distributed between the edge, center, and core of each forest, thus avoiding sample heterogeneity. Three soil samples were collected from each sampling point at different depths: 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm.

The collected material was dried in an oven with mechanical ventilation at 45 °C until reaching a constant weight, ensuring a controlled and moderate drying process that prevents the degradation of carbon (C) and nitrogen (N) compounds present in the samples. This approach preserves the chemical integrity, accurately reflecting the original composition for subsequent analyses (González-Rodríguez et al., 2011).

After complete drying, the soil samples were divided into three portions. The first portion was used to estimate bulk soil density, the second was sieved using a 2-mm mesh for granulometry tests (Maquère et al., 2008), and the third portion was ground and sieved through a 0.25-mm mesh for analysis in a mass spectrometer using the Elementary Combustion Analyzer (EA- Carlo Erba) connected to the Mass Spectrometer Delta Plus (Finnigan Mat, San José, CA, USA). This analysis measured the percentages of C, N, $\delta^{15}N$, and $\delta^{13}C$ (Martins et al., 2015).

2.3. Statistical analysis

One-way analysis of variance (ANOVA) was used, followed by Tukey's test, to evaluate the differences in the average percentage and stock of C, N and their respective isotopes within each urban forest, considering alpha <5%. The predictability of parametric tests such as normality and homoscedasticity were verified. To verify probable correlations and groupings between soil depths, a principal component analysis (PCA) was carried out, considering the axes with greater explicability of the analyzed factors. A linear regression curve was designed with all $\delta^{13}C$ and $\delta^{15}N$ values to understand the relationship between the two variables in urban forest soils. All analyses were performed using the Past Statistic Package (Hammer and Harper, 2001).

3. Results

In the TP forest fragment, soil density was approximately 30% lower than in the other fragments and recorded almost twice the percentage of clay compared to the other areas, with only half of the relative values of the sand fraction. Meanwhile, AVP exhibited the highest percentage of silt in the soil, but the values were only slightly above those of the other study areas. TP soil was classified as very clayey, while soils in the other fragments were classified as sandy loam. Across all study areas, soil density increased with soil depth. The greatest difference in average soil density between the deepest and most superficial layers was observed in FISP, with values varying around 25% in both layers (see Table 1).

The percentages of N and C decreased with soil depth, following an inverse relation to soil bulk density. For all layers, TP soil presented approximately twice as many elements when compared to the soils of the other sites (Fig. 2A and B). FISP soil presented the second highest value of %N and %C in the superficial layer; however, in the deepest soil layer FISP showed the lowest values. Soil $\delta^{15}N$ increased with depth in all forest fragments. FISP and CP soils displayed the lowest isotopic values in the most superficial layers, while TP registered the highest, as hypothesized in this work. In the deepest layer CP showed the highest value, with a 60% difference between the most superficial and deepest layers, i.e. an increase of more than 5‰ of the isotope signature. Again, CP soil presented the greatest difference in $\delta^{13}C$ values between the most superficial and deepest layers (Fig. 2D). FISP and CP soils showed the greatest variations of C:N ratio along soil layers, while the TP and AVP curves did not vary (Fig. 2E).

Table 1

Density, granulometric composition, and textures of the soils from four fragments of urban forests, analyzed at different depths.

	Depth (cm)	Density (g cm^{-3})	Sand (%)	Clay (%)	Silt (%)	Texture
TP	0–10	0.79 ± 0.04	19.4	60.6	20.0	VC
	10–20	0.88 ± 0.06	18.3	62.3	19.4	VC
	20–30	0.93 ± 0.13	15.3	68.5	16.2	VC
	40–50	0.97 ± 0.08	12.0	73.3	14.7	VC
Mean	*0–50*	*0.89 ± 0.08*	*16.3*	*66.2*	*17.6*	*VC*
AVP	0–10	1.10 ± 0.22	46.5	34.2	19.3	FCS
	10–20	1.25 ± 0.21	47.5	34.6	17.9	FCS
	20–30	1.33 ± 0.19	42.8	33.8	23.3	FCS
	40–50	1.41 ± 0.25	44.8	39.4	15.8	SC
Mean	*0–50*	*1.27 ± 0.22*	*45.4*	*35.5*	*19.1*	*FCS*
FISP	0–10	1.01 ± 0.10	56.4	26.8	16.8	FCS
	10–20	1.26 ± 0.06	58.1	26.6	15.3	FCS
	20–30	1.41 ± 0.09	59.4	26.5	14.1	FCS
	40–50	1.48 ± 0.15	54.7	32.1	13.2	FCS
Mean	*0–50*	*1.29 ± 0.10*	*57.1*	*28.0*	*14.9*	*FCS*
CP	0–10	1.16 ± 0.13	59.1	25.4	15.5	FCS
	10–20	1.31 ± 0.12	59.7	26.2	14.2	FCS
	20–30	1.44 ± 0.06	60.7	25.8	13.5	FCS
	40–50	1.45 ± 0.13	56.9	30.6	12.5	FCS
Mean	*0–50*	*1.34 ± 0.11*	*59.1*	*27.0*	*13.9*	*FCS*

TP: Trianon Park; AVP: Alfredo Volpi Park, FISP: Fontes do Ipiranga State Park and CP: Carmo Park. Textures: VC - very clayey, FCS - franco clayey sandy, SC - sandy clay.

PCA showed that the %C and %N vectors are associated with the sampling units for the most superficial soil layers, while the $\delta^{13}C$ and $\delta^{15}N$ vectors are more closely associated to the sampling units referring to the deeper parts of the soils (Fig. 3).

When not considering depth, TP soil presented a statistically higher %N value (TP = 0.29%), followed by the FISP (0.19 %N), AVP (0.17 %N) and CP (0.15 %N) soil values. CP and AVP were the fragments with significantly lower %N values (Fig. 4A). The highest $\delta^{15}N$ value was registered in CP soil (one-way ANOVA, $F = 24.58$, $p < 0.05$) (Fig. 4B), embora apenas o FISP tenha apresentado valores estatisticamente inferiores do que PT e PC.

When accounting for soil %C, TP was statistically different from the other areas and showed 4.58% of the element, followed by FISP 2.93%, AVP 2.47%, and CP 2.31% (one-way ANOVA $F = 22.48$, $p < 0.05$; Fig. 4C). The most negative value of $\delta^{13}C$ occurred in AVP soil (−26.18‰), with a statistically lower value (one-way ANOVA, $F = 19.08$, $p < 0.05$). CP presented a higher average value for $\delta^{13}C$ (−24.03‰) compared to FISP (−25.44‰) and TP (−25.36‰) soils (Fig. 4D). TP soil presented a statistically higher value of the C/N ratio, while AVP soil displayed the lowest (one-way ANOVA $F = 14.56$, $p < 0.05$) (Fig. 4E).

By analyzing the correlation between $\delta^{13}C$ and $\delta^{15}N$ as predictor variables, we observed that the soil samples collected in fragments located on the extremities were predominantly marked by lower $\delta^{13}C$ and $\delta^{15}N$ values. For the TP soil samples, $\delta^{13}C$ varied between −24.0‰ and −26.81‰ and $\delta^{15}N$ varied between 5.57‰ and 8.97‰. Sampling units regarding CP soil showed a high amplitude for both $\delta^{13}C$ and $\delta^{15}N$, with values for $\delta^{13}C$ ranging from approximately −21.37‰ to −27.37‰ and those for $\delta^{15}N$ ranging from 3.35‰ to 10.37‰ (Fig. 5A). More enriched values of $\delta^{13}C$ and $\delta^{15}N$ represent greater mineralization of the elements and, consequently, greater efficiency in the biogeochemical cycling of C and N. However, the association between $\delta^{15}N$ and C:N ratio was negative among the variables (Fig. 5B).

In terms of C and N stock in soil, TP soil stored about 25% more C

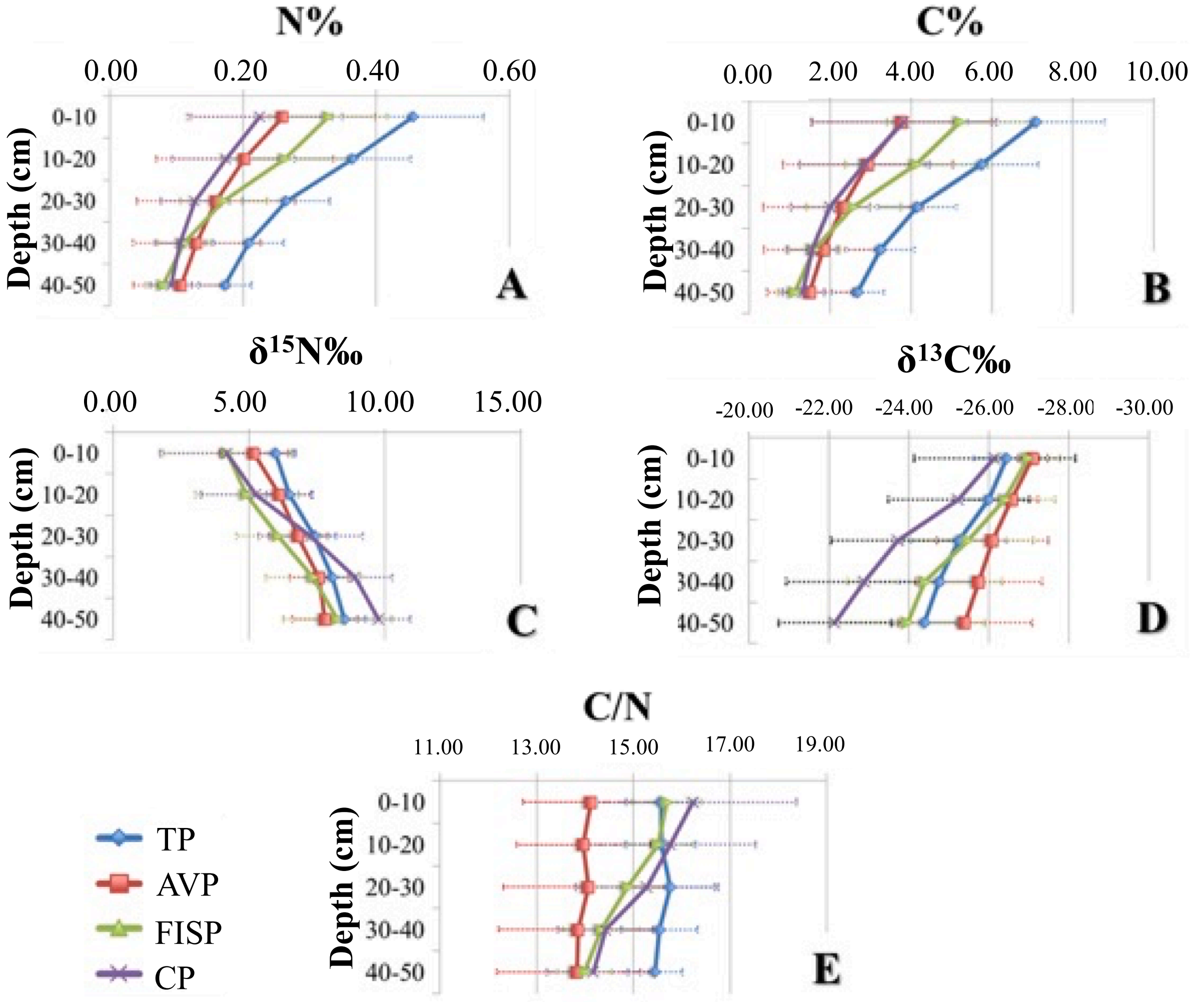

Fig. 2. Variation of %N, %C, δ^{13}C, δ^{15}N and C:N ratio along the soil profile of the four forest fragments. Panels A and B express the percentage values of nitrogen and carbon, panels C and D depict the isotopic values of nitrogen, and panel E the ratio between both chemical elements. TP: Trianon Park; AVP: Alfredo Volpi Park, FISP: Fontes do Ipiranga State Park and CP: Carmo Park.

than the other forest fragments (Fig. 6), with a total of 36.24 tons C ha^{-1}, followed by FISP (29.53 tons C ha^{-1}), AVP (27.09 tons C ha^{-1}) and CP (26.76 tons C ha^{-1}). By means of the F test, one-way ANOVA showed that the fragments presented statistically different carbon ($F = 3.96$; $p < 0.05$) and nitrogen ($F = 4.21$, $p < 0.05$) stocks between the areas. For both elements, TP presented the highest value stored in the soil, while the other fragments did not differ in value.

Several studies regarding latitudinal zones similar to those of this study have shown soil C and N stock values analogous to ours (Table 2).

4. Discussion

4.1. Particle size and C and N stock

The increase in soil bulk density of about 20% to 30% with increasing depth in the four forest fragments suggests a strong effect of forest growth in the soil's physical structure, making the soil surface lighter and more permeable for greater absorption of water and nutrients (Zeng et al., 2014). This may also be a response to the high production of litterfall on the ground, which is typical of subtropical forest systems (Ferreira et al., 2014; Ferreira and Uchiyama, 2015), and the consequent development of fine roots in the most superficial layers.

TP is located in the most central, least green and warmest region of the megacity of São Paulo (Ribeiro et al., 2021). This is the only fragment that does not have a water body in its area, which probably requires greater root growth to search for water, thus altering the physical structure of the soil. Moreover, TP is the forest fragment with the greatest floristic diversity and the highest number of large trees (Aragaki, 2017), in addition to having high litterfall production (Oliveira, 2019). These attributes combined with the higher average air temperature can lead the more superficial soil layer to generate a higher rate of litterfall decomposition and, consequently, present thicker humus layers with lighter and looser soils, which can also explain the high contents of %N and %C. In clay soils, mineralization rates tend to be lower than in sandy soils due to a lower susceptibility to decomposition, since the adsorption of organic matter to finer soil particles protects these from biodegradation (Dungait et al., 2012). Another relevant fact that explains the higher %N in the most central forest fragment is the high deposition of atmospheric N from the vehicle fleet that transits this area of the city (Pereira et al., 2022; Konstantinov et al., 2023). Although our study was carried out in four forest fragments, in three locations the analyzed soils were clayey sandy loam (AVP, FISP and CP) and only very clayey (TP). It is estimated that other urban forest fragments in São Paulo have different types of soil and, consequently, different edaphic C and N stock patterns (Metzger et al., 2006).

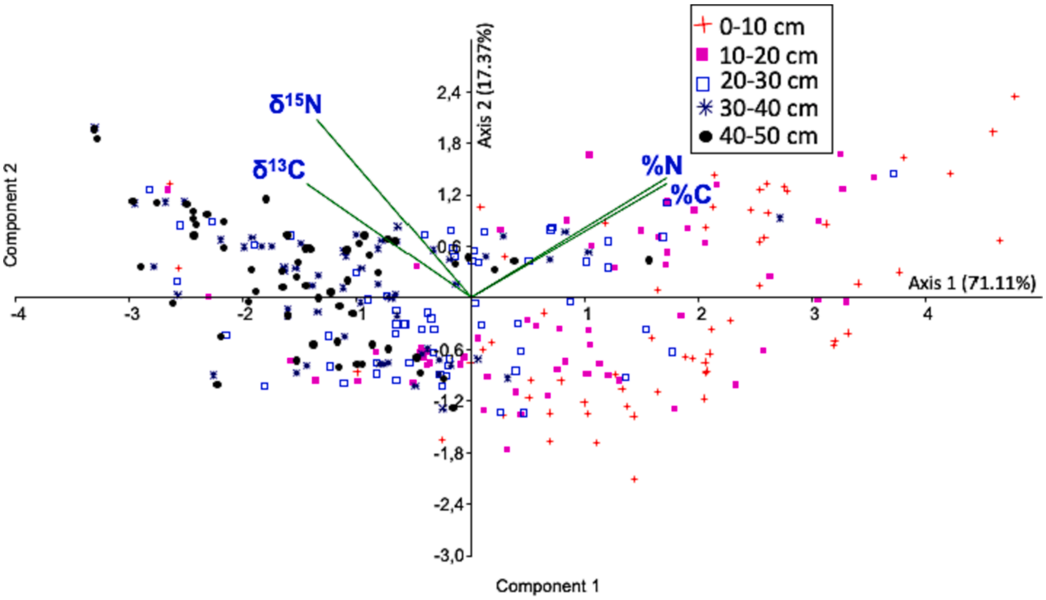

Fig. 3. Principal component analysis, by means of correlation, showing multivariate correlations between the contents of %N, %C, δ13C, and δ15N at different soil depths in the four forest fragments studied. Each sampling unit represents a soil sample at the indicated depth, regardless of the location of the four forest fragments.

4.2. *Local and spatial variations in the isotopic signature of $\delta^{13}C$ and $\delta^{15}N$*

The availability of δ^{15}N increased with soil depth in all forest fragments, since from the most superficial layer to the deepest, geochemical transformations and the decomposition of organic matter prioritize the mineralization of the lightest form of nitrogen, i.e., ^{14}N (Trumbore, 2009). Yet, in absolute terms both forms of N (^{14}N and ^{15}N) decrease in the system due to leaching and reservoir exchanges. The PCA analysis clearly showed that the surface layers in all fragments showed a similar trend in relation to %N and %C, denoting groupings of sampling units. The regression analysis between δ^{15}N and δ^{13}C also corroborates these results, since sample units with low isotopic N values also exhibited more positive isotopic C values. Corroborating this finding it was observed that high values of δ^{15}N were inversely associated with the C:N ratio, which reflects a longer residence time of the organic matter in the soil, since this soil fraction usually presents high values of δ^{15}N with increasing mineral association (Marin-Spiotta et al., 2009; Craine et al., 2015). The amplitudes of δ^{15}N between the superficial and deeper layers are in accordance with values reported in a large review that investigated 88 soil profiles (Hobbie and Ouimette, 2009). The δ^{13}C contents varied between the extreme layers of the soils. FISP and CP were the fragments with the most accentuated curves in the variation of δ^{13}C along the soil profile, emphasizing that decomposition processes and biogeochemical cycling were more efficient in peripheric forest fragments in the megacity of São Paulo. The biogeochemical processes identified in different forest fragments, as well as the δ^{15}N and δ^{13}C content along the soil profiles correspond with the C:N ratio curves of different soil depths (Marin-Spiotta et al., 2009).

Depending on the rate of litterfall decomposition, heterotrophic respiration, and consequent emission of greenhouse gases (CO_2, CH_4 and N_2O) should be higher in soils with greater mineralization efficiency. However, Souza et al. (2022) showed that there are no significant differences in the emissions of these compounds between the soils of these four forest fragments. This indicates that these urban soils are efficiently absorbing C and N from the atmosphere, and that geochemical processes facilitate the storage of such elements in different soil layers. This can be driven by the differences in microbiota existing in the soils of these urban parks, which are selected based on the physical conditions of the urban environment (Wu et al., 2022; Tang et al., 2023), e.g., atmospheric pollution, soil management, use of insecticides and pesticides, or age of urban parks (Lo, 2010; Hui et al., 2017).

4.3. *Urban forest soils as efficient nature-based solutions*

Our study results shed light on an excellent urban equipment that contributes to offsetting anthropogenic emissions in urban areas. The expansion, maintenance, and restoration of managed urban forest fragments with native vegetation and the consequent generation of litter can be an NbS that optimizes C and N stock in the edaphic compartment. Moreover, the use of urban soils with specific physical properties, i.e., high amount of clay fraction as well as idle peripheral forest fragments, can be considered key ecosystem in the stock of elements, as has been reported in different systems (Li et al., 2023). This prospect can help large cities and megacities to offset part of the high emissions within their own territory, resolving part of the anthropization problem on a local/regional scale.

This solution for adapting cities to climate change based on urban forests is an NbS that should be incorporated into strategic environmental planning and local climate policies, since emissions occur within the megacity spatial scale. In this sense, Lafortezza et al. (2018) highlight the importance of developing climate change adaptation strategies by means of NbS to provide more resilient responses and enhance carbon storage. Such information can be widely used in public policies to expand qualified green areas, i.e., urban parks that protect wildlife. Actions such as this one have been proposed by São Paulo City Hall (e.g., Municipal Plan for the Atlantic Forest, Municipal Plan for Adaptation to Climate Change, and Municipal Plan for Protected Areas, Green Areas and Open Spaces) with the intention of increasing the city's green infrastructure, thus aiming to adapt the megacity to future climatic and environmental scenarios. Much has been discussed in this regard among public management, academia and the third sector. However, the ecological indicators for the selection of such areas are clearly lacking; we believe our work brings results that can subsidize decisions in this direction.

Although this study reported a higher stock of C and N in the TP forest fragment, all the fragments stood out in terms of C and N values in soils when compared to other forest systems. This fact clearly denotes the importance of using urban soils as NbS for the planning of sustainable cities, aiming not only at maintaining ecosystem patterns and

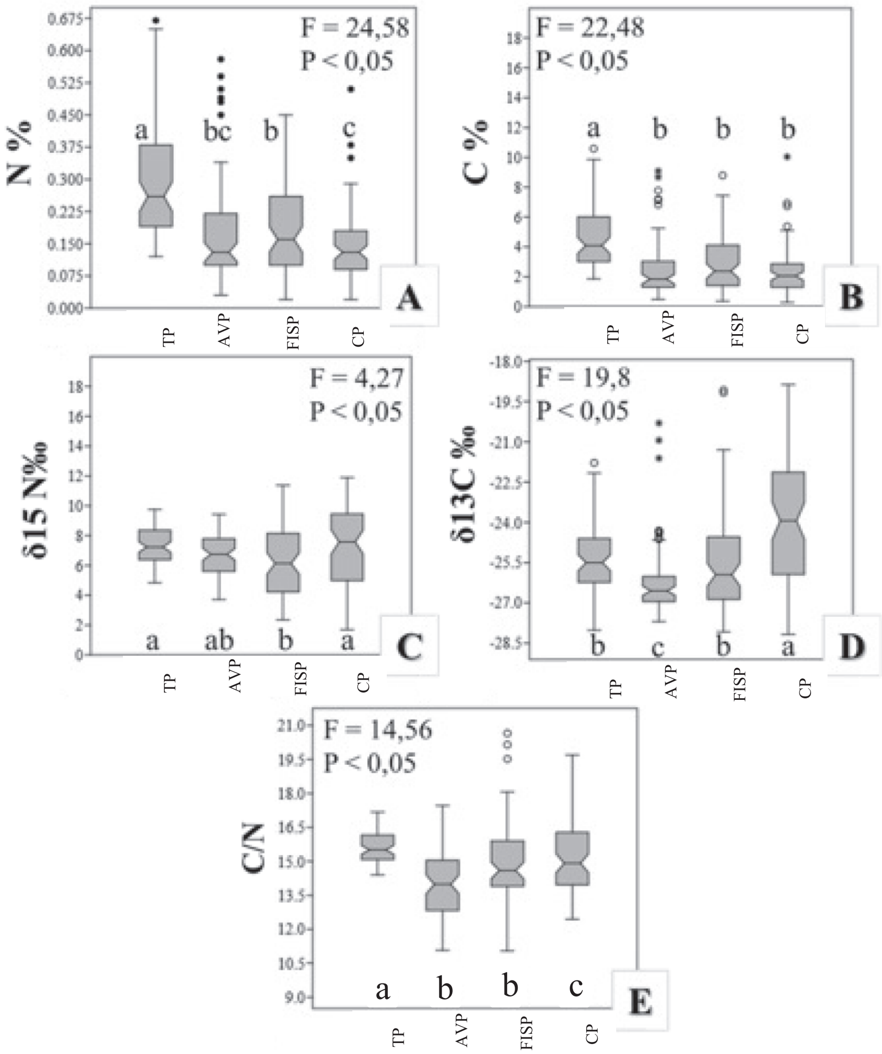

Fig. 4. Variations in the relative contents of nitrogen - %N (A), carbon - %C (B), isotopic nitrogen - δ^{15}N (C), isotopic carbon - δ^{13}C (D) and carbon:nitrogen - C:N ratio (E) in the soils of the study areas. Panels A and B express the percentage values of N and C, panels C and D depict the isotopic values of N and C, and panel E the ratio between both chemical elements. TP: Trianon Park; AVP: Alfredo Volpi Park, FISP: Fontes do Ipiranga State Park and CP: Carmo Park.

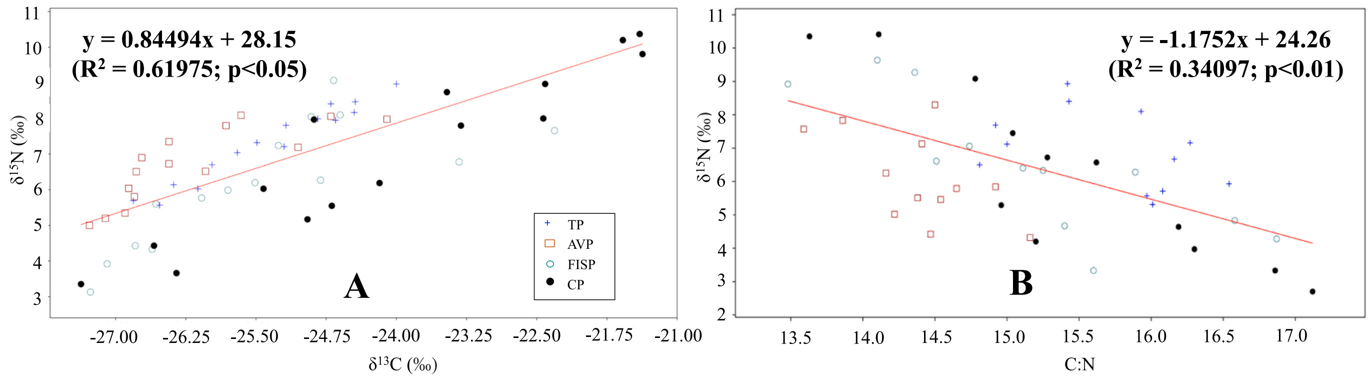

Fig. 5. Linear regression model displaying the associations between δ^{13}C and δ^{15}N. Sample units with various symbols represent the different study areas. Panel A expresses the association between δ^{13}C and δ^{15}N, and panel B the association between δ^{15}N and C:N. TP: Trianon Park; AVP: Alfredo Volpi Park, FISP: Fontes do Ipiranga State Park and CP: Carmo Park.

processes but also at developing the social component, since the consequences of climate change affect both the ecological system and social system (Nassary et al., 2022).

5. Conclusion and future research

Soils of the urban forest fragments of São Paulo have demonstrated various potentials in storing C and N in their profiles and, consequently,

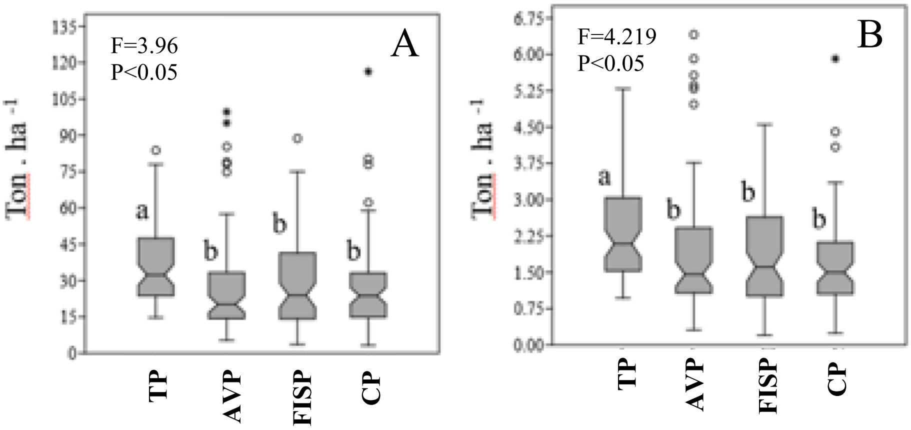

Fig. 6. Variations in carbon and nitrogen stock in the soils of different forest fragments. Panel A – soil carbon stock; panel B – soil nitrogen stock. Panel A depicts the values of carbon stock and panel B the values of nitrogen stock. TP: Trianon Park; AVP: Alfredo Volpi Park, FISP: Fontes do Ipiranga State Park and CP: Carmo Park.

Table 2
Comparative table with carbon and nitrogen stock values of urban soils (this and other studies).

Author/Year	[C] Mg ha^{-1})	[N] Mg ha^{-1})	%C	%N	^{13}C (‰)	^{15}N (‰)	Local
This study	36.24 ± 15.83	2.32 ± 1.00	4.58	0.29	−25.36	7.30	TP
	27.09 ± 21.36	1.88 ± 1.36	2.47	0.17	−26.18	6.70	AVP
	29.53 ± 20.09	1.92 ± 1.15	2.93	0.19	−25.44	6.17	FISP
	26.76 ± 18.80	1.68 ± 0.96	2.31	0.15	−24.03	7.08	CP
Nagy et al. (2014)	10.00 ± 1.00	0.30 ± 0.00	NA	NA	NA	NA	Florida, USA
	14.00 ± 2.00	0.40 ± 0.10	NA	NA	NA	NA	Florida, USA
	18.00 ± 3.00	0.60 ± 0.10	NA	NA	NA	NA	Florida, USA
	21.00 ± 4.00	0.70 ± 0.10	NA	NA	NA	NA	Florida, USA
	48.00 ± 13.00	1.40 ± 0.40	NA	NA	NA	NA	Florida, USA
	38.00 ± 9.00	1.10 ± 0.20	NA	NA	NA	NA	Florida, USA
Martins (2010)	15.83 ± 5.80	0.90 ± 0.20	NA	NA	− 28.3 ± 0.5	2.0 ± 0.6	Ubatuba, Brazil
	24.12 ± 8.21	1.75 ± 0.63	NA	NA	−27.5 ± 0.5	5.6 ± 0.8	Ubatuba, Brazil
	29.74 ± 6.51	2.33 ± 0.45	NA	NA	− 28.5 ± 0.9	4.3 ± 0.7	Ubatuba, Brazil
	29.45 ± 1.76	2.21 ± 1.00	NA	NA	27.9 ± 0.5	4.6 ± 1.5	Ubatuba, Brazil
Silva (2017)	57	5	NA	NA	− 27.4 ± 0.3	6.7 ± 0.7	Joinville, Brazil
Medeiros (2019)	20.4	NA	NA	NA	−25.64	NA	Rio de Janeiro, Brazil
Konstantinov et al. (2023)	NA	NA	3.09	0.22	−27.11	5.95	Tyumen, Russia
Norra et al. (2005)	NA	NA	6.1	0.4	−25.5	2.6	Karlsruhe, Germany

NA – Not available; TP: Trianon Park; AVP: Alfredo Volpi Park, FISP: Fontes do Ipiranga State Park and CP: Carmo Park.

different capacities in contributing to the neutralization of these elements emitted by human activities. Our results suggest that soil type, combined with vegetation management, can optimize the potential for storage of C and N and enhance the performance of NbS. Moreover, the location of the forest system, as well as the use of adjacent land, seem to have a strong influence on edaphic C and N reservoirs. Therefore, certain attributes such as atmospheric pollution, heat islands or the inadequate management of urban parks can alter soil biota and, consequently, biogeochemical cycling.

These results also highlight that stable isotopes of C and N are efficient indicators of distinct biogeochemical cycling patterns in the fragments of this study, showing that the use of soil adjacent to the forest fragment alters the behavior of δ^{15}N and δ^{13}C in different soil layers. Thus, isotopic indicators can assess the efficiency of subtropical soils of urban forests to be considered NbS that bring benefits to the urban ecosystem and serve as adaptation instruments in cities. This approach can contribute to the development of resilient urban ecosystems, positively impacting environmental quality and biodiversity.

Despite these contributions, it is crucial to acknowledge the limitations of our study. The focus on specific forest fragments and soil layers may limit the extrapolation of our findings. Additionally, further research is needed to explore the long-term effects of soil-atmosphere interactions in urban environments. Future studies could expand this work by investigating additional isotopic indicators and considering broader geographical contexts.

However, our findings point to C and N stocks (and their isotopes) as potential indicators to be used in the selection of priority areas for conservation and management. It is suggested that these results are applied in the implementation of municipal policies for the conservation or promotion of urban afforestation, especially those that recommend the expansion of urban green spaces. In conclusion, this research not only advances the understanding of biogeochemical processes in urban forests but also provides practical insights for policymakers and urban planners.

CRediT authorship contribution statement

Mauro Ramon: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Raffaele Lafortezza:** Data curation, Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing. **Andreza Portella Ribeiro:** Data curation, Formal analysis, Investigation, Validation, Writing – original draft, Writing – review & editing. **Plínio Barbosa de Camargo:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Marisa Domingos:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Eduardo Pereira Cabral Gomes:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Armando dos Reis Tavares:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **António Guerner Dias:** Data curation, Formal analysis, Investigation, Methodology, Writing – original draft. **Claudia Terezinha Kniess:** Data curation, Writing – original draft. **Maurício Lamano Ferreira:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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

Data will be made available on request.

Acknowledgements

The authors thank The São Paulo Research Foundation (FAPESP) for financial support under the project 2019/24325-2 and the Municipal Secretary of Green and the Environment for the permission to research the urban forests of São Paulo city (Project 2016-0.119.002-2).

References

Alberti, M., 2008. Advances in Urban Ecology: Integrating Humans and Ecological Processes in Urban Ecosystems. Springer.

Aragaki, S. 2017. Floristic composition and structure of five urban fragments in the city of São Paulo SP, Brazil. Doctoral Thesis. Institute of Botany of São Paulo. Available at: https://www.infraestruturameioambiente.sp.gov.br/pgibt/dissertacoesteses/sonia-aragaki-dr/. Access: August 28, 2023.

Arantes, B.L., Castro, N.R., Gilio, L., Polizel, J.L., da Silva Filho, D.F., 2021. Urban forest and per capita income in the mega-city of Sao Paulo, Brazil: a spatial pattern analysis. Cities 111, 103099.

Bonilla-Bedoya, S., Herrera, M.Á., Vaca, A., Salazar, L., Zalakeviciute, R., Mejía, D., López-Ulloa, M., 2022. Urban soil management in the strategies for adaptation to climate change of cities in the Tropical Andes. Geoderma 417, 115840.

Chen, W.Y., 2015. The role of urban green infrastructure in offsetting carbon emissions in 35 major Chinese cities: a nationwide estimate. Cities 44, 112–120.

Craine, J.M., Elmore, A.J., Aidar, M.P., Bustamante, M., Dawson, T.E., Hobbie, E.A., Wright, I.J., 2009. Global patterns of foliar nitrogen isotopes and their relationships with climate, mycorrhizal fungi, foliar nutrient concentrations, and nitrogen availability. New Phytol. 1834, 980–992.

Craine, J.M., Brookshire, E.N.J., Cramer, M.D., Hasselquist, N.J., Koba, K., Marin-Spiotta, E., Wang, L., 2015. Ecological interpretations of nitrogen isotope ratios of terrestrial plants and soils. Plant Soil 396, 1–26.

Cui, Y., Lin, J., Song, C., Liu, M., Yan, Y., Xu, Y., Huang, B., 2016. Rapid growth in nitrogen dioxide pollution over Western China, 2005–2013. Atmos. Chem. Phys. 1610, 6207–6221.

Decina, S.M., Hutyra, L.R., Templer, P.H., 2020. Hotspots of nitrogen deposition in the world's urban areas: a global data synthesis. Front. Ecol. Environ. 182, 92–100.

Du, E., Xia, N., Guo, Y., Tian, Y., Li, B., Liu, X., De Vries, W., 2022. Ecological effects of nitrogen deposition on urban forests: an overview. Front. Agric. Sci. Eng. 93, 445–456.

Dungait, J.A., Hopkins, D.W., Gregory, A.S., Whitmore, A.P., 2012. Soil organic matter turnover is governed by accessibility not recalcitrance. Glob. Chang. Biol. 186, 1781–1796.

Elmore, A., Nelson, D., Craine, J., 2016. Earlier springs are causing reduced nitrogen availability in North American eastern deciduous forests. Nat. Plants 2, 16133.

Ferreira, M.L., Uchiyama, E.A., 2015. Litterfall assessement in a fragment of secondary tropical forest, Ibiúna, SP, southeastern Brazil. Revista Árvore 39, 791–799.

Ferreira, M.L., Esposito, J.B.N., de Souza, S.R., Domingos, M., 2012. Critical analysis of the potential of Ipomoea nil 'Scarlet O'Hara'for ozone biomonitoring in the sub-tropics. J. Environ. Monit. 147, 1959–1967.

Ferreira, M.L., Silva, J.L., Pereira, E.E., Lamano-Ferreira, A.P.D.N., 2014. Litter fall production and decomposition in a fragment of secondary Atlantic Forest of São Paulo, SP, southeastern Brazil. Revista Árvore 38, 591–600.

Ferreira, M.L., Ribeiro, A.P., Albuquerque, C.R., Ferreira, A.P.D.N.L., Figueira, R.C.L., Lafortezza, R., 2017. Air contaminants and litter fall decomposition in urban forest areas: the case of São Paulo-SP, Brazil. Environ. Res. 155, 314–320. https://doi.org/10.1016/j.envres.2017.02.023.

González-Rodríguez, H., Domínguez-Gómez, T.G., Cantú-Silva, I., Gómez-Meza, M.V., Ramírez-Lozano, R.G., Pando-Moreno, M., Fernández, C.J., 2011. Litterfall deposition and leaf litter nutrient return in different locations at Northeastern Mexico. Plant Ecol. 212, 1747–1757.

Hammer, Ø., Harper, D.A., 2001. Past: paleontological statistics software package for education and data analysis. Palaeontol. Electron. 41, 1.

Hobbie, E.A., Ouimette, A.P., 2009. Controls of nitrogen isotope patterns in soil profiles. Biogeochemistry 95, 355–371.

Hui, N., Jumpponen, A., Francini, G., Kotze, D.J., Liu, X., Romantschuk, M., Setälä, H., 2017. Soil microbial communities are shaped by vegetation type and park age in cities under cold climate. Environ. Microbiol. 193, 1281–1295.

IBGE 2023 Instituto Brasileiro de Geografia e Estatísticas. Cidade de São Paulo. Available at: https://cidades.ibge.gov.br/brasil/sp/sao-paulo/panorama. Accessed: 20th August 2023.

Konstantinov, A., Konstantinova, E., Smirnov, P., Minkina, T., Batalin, G., Gareev, B., Loiko, S., 2023. Assessment of soil development during rapid urbanization using the carbon and nitrogen stable isotope composition. Environ. Geochem. Health 1–12.

Lafortezza, R., Chen, J., Van Den Bosch, C.K., Randrup, T.B., 2018. Nature-based solutions for resilient landscapes and cities. Environ. Res. 165, 431–441.

Li, T., Cui, L., Scotton, M., Dong, J., Xu, Z., Che, R., Cui, X., 2022. Characteristics and trends of grassland degradation research. J. Soil. Sediment. 227, 1901–1912. https://doi.org/10.1007/s11368-022-03209-9.

Li, T., Cui, L., Liu, L., Chen, Y., Liu, H., Song, X., Xu, Z., 2023. Advances in the study of global forest wildfires. J. Soil. Sediment. 1–15 https://doi.org/10.1007/s11368-023-03533-8.

Lo, C.C., 2010. Effect of pesticides on soil microbial community. J. Environ. Sci. Health B 455, 348–359.

Lorenz, K., Lal, R., 2015. Managing soil carbon stocks to enhance the resilience of urban ecosystems. Carbon Manage. 61–2, 35–50.

Maquère, V., Laclau, J.P., Bernoux, M., Saint-Andre, L., Gonçalves, J.L.M., Cerri, C.C., Ranger, J., 2008. Influence of land use savanna, pasture, Eucalyptus plantations on soil carbon and nitrogen stocks in Brazil. Eur. J. Soil Sci. 595, 863–877. https://doi.org/10.1111/j.1365-2389.2008.01059.x.

Marin-Spiotta, E.R.I.K.A., Silver, W.L., Swanston, C.W., Ostertag, R., 2009. Soil organic matter dynamics during 80 years of reforestation of tropical pastures. Glob. Chang. Biol. 156, 1584–1597.

Martinelli, L.A., Lins, S.R., dos Santos-Silva, J.C., 2017. Fine litterfall in the Brazilian Atlantic forest. Biotropica 494, 443–451.

Martins, S.C., Souza-Neto, E., Piccolo, M.C., Almeida, D.Q., Camargo, P.B., Carmo, J.B., Porder, S., Lins, R.M.S., Martinelli, L.A., 2015. Soil texture and chemical characteristics along an elevation range in the coastal Atlantic Forest of Southeast Brazil. Geoderma Regional 5, 106–116.

Martins, A.P.G., Ribeiro, A.P., Ferreira, M.L., Martins, M.A.G., Negri, E.M., Scapin, M.A., Lafortezza, R., 2021. Infraestrutura verde para monitorar e minimizar os impactos da poluição atmosférica. Estudos Avançados 35, 31–57.

Martins, S.C., 2010. In: Caracterização de solos e serapilheira ao longo do gradiente altitudinal da Mata Atlântica, estado de São Paulo / Characterization of soils and litterfall along the altitudinal gradient of the Atlantic Forest, state of São Paulo. Tese de doutorado. Universidade de São Paulo. University of São PAulo, Brazil.

Medeiros. A. D. S. (2019). Influência do uso da terra sobre o comportamento da matéria orgânica do solo e o estoque de carbono, Parque Nacional do Itatiaia-RJ. Influence of land use on the behavior of soil organic matter and carbon stock, Itatiaia Park-RJ. Tese de doutorado. Universidade Federal Rural do Rio de Janeiro, Brasil. Doctoral thesis. Federal Rural University of Rio de Janeiro, Brazil.

Metzger, J.P., Alves, L.F., Goulart, W., Teixeira, A.M.D.G., Simões, S.J.C., Catharino, E.L.M., 2006. Uma área de relevante interesse biológico, porém pouco conhecida: a Reserva Florestal do Morro Grande. Biota neotropica 6.

Nagy, R.C., Lockaby, B.G., Zipperer, W.C., Marzen, L.J., 2014. A comparison of carbon and nitrogen stocks among land uses/covers in coastal Florida. Urban ecosystems 17, 255–276.

Nassary, E.K., Msomba, B.H., Masele, W.E., Ndaki, P.M., Kahangwa, C.A., 2022. Exploring urban green packages as part of Nature-based Solutions for climate change adaptation measures in rapidly growing cities of the Global South. J. Environ. Manage. 310, 114786.

Ngaba, M.J.Y., Hu, Y.L., Bol, R., Ma, X.Q., Jin, S.F., Mgelwa, A.S., 2019. Effects of land use change from natural forest to plantation on C, N and natural abundance of 13C and 15N along a climate gradient in eastern China. Sci. Rep. 91, 1–12.

Norra, S., Handley, L.L., Berner, Z., Stüben, D., 2005. 13C and 15N natural abundances of urban soils and herbaceous vegetation in Karlsruhe, Germany. Eur. J. Soil Sci. 565, 607–620.

Oliveira, P.B. 2019. Carbon flux via litter fall in urban forests of São Paulo: understanding the functioning of the city green infrastructure. Master's dissertation.

University Nove de Julho. Available at: https://bibliotecatede.uninove.br/handle/tede/1998. Access: August 28, 2023.

Pereira, P., Inácio, M., Karnauskaitė, D., Bogdzevič, K., Gomes, E., Kalinauskas, M., Barcelo, D., 2021. Nature-based solutions impact on urban environment chemistry: air, soil, and water. In: Nature-Based Solutions for Flood Mitigation: Environmental and Socio-Economic Aspects, pp. 79–137.

Pereira, M.A.G., Domingos, M., da Silva, E.A., Aragaki, S., Ramon, M., de Camargo, P.B., Ferreira, M.L., 2022. Isotopic composition δ13C and δ15N in the soil-plant system of subtropical urban forests. Sci. Total Environ. 851, 158052.

Petri, L., Aragaki, S., GomesS, E.P.C., 2018. Management priorities for exotic plants in an urban Atlantic Forest reserve. Acta Botanica Brasilica 32 (1), 1–31. https://doi.org/10.1590/0102-33062017abb0317.

Pouyat, R.V., Trammell, T.L., 2019. Climate change and urban forest soils. Dev. Soil Sci. 36, 189–211.

Pouyat, R.V., Yesilonis, I.D., Nowak, D.J., 2006. Carbon storage by urban soils in the United States. J. Environ. Qual. 354, 1566–1575.

Pouyat, R.V., Yesilonis, I.D., Egitto, B.A., Zhu, W., 2017. Soil carbon and nitrogen cycling and ecosystem service in cities. In: Urban Soils. CRC Press, pp. 121–136.

Ramon, M., Ribeiro, A.P., Theophilo, C.Y.S., Moreira, E.G., de Camargo, P.B., de Bragança Pereira, C.A., Ferreira, M.L., 2023. Assessment of four urban forest as environmental indicator of air quality: a study in a brazilian megacity. Urban Ecosyst 261, 197–207.

Ribeiro, A.P., Bollmann, H.A., de Oliveira, A., Rakauskas, F., Cortese, T.T.P., Rodrigues, M.S.C., Ferreira, M.L., 2021. The role of tree landscape to reduce effects of urban heat islands: a study in two Brazilian cities. Trees 1–14.

Richter, S., Haase, D., Thestorf, K., Makki, M., 2020. Carbon pools of Berlin, Germany: organic carbon in soils and aboveground in trees. Urban For. Urban Green. 54, 126777.

Seto, K.C., Guneralp, B., Hutyra, L.R., 2012. Global forecasts of € urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Nat. Acad. Sci. USA 109, 1608316088.

Silva, M.M., Mucci, J.L.N., Pelicioni, M.C.F., 2006. A área de proteção ambiental 'Fazenda e Parque do Carmo': os problemas ambientais, as dificuldades de gestão e a influência na qualidade de vida da população. O mundo da saúde 304, 544–550. https://doi.org/10.15343/0104-7809.200630.4.3.

Silva, J. C. S. (2017). Estoques e fluxos de carbono e nitrogênio acima e abaixo do solo em fragmentos de Floresta AtlÂntica no Sul do Brasil. Stocks and fluxes of carbon and nitrogen above- and belowground in fragments of the southern Brazilian Atlantic Forest. Dissertação de mestrado. Universidade de São Paulo, Brasil. Mater's dissertation. University of São Paulo, Brazil.

Souza, R.C., Xavier, C., Camargo, P.B., Ferreira, M.L., 2022. Soil-atmosphere interaction and emissions of greenhouse gases CO2, CH4 and N2O in urban forests of Sao Paulo, SP, southeastern Brazil. In: Org. Maurício Lamano Ferreira (Ed.), Biogeochemistry and Ecosystem Services in Urban Green-Blue Systems, 1ª ed. ANAP, Tupã, p. 153.

Spencer, C.N., Matzner, S.L., Smalley, J., Bukrey, M., Onberg, J., Chapman, M., Steck, M., 2009. Forest expansion and soil carbon changes in the Loess Hills of eastern South Dakota. Am. Midl. Nat. 1612, 273–285.

Sao Paulo 2020 Municipal Secretary of Green and the Environment/Coordination of Environmental Planning. Digital Mapping of Vegetation Coverage in the Municipality of São Paulo. Final Report/Coordination: OLIVEIRA, Vivian Prado de. São Paulo/Secretaria Municipal do Verde e do Meio Ambiente/Coordenação de Planejamento Ambiental. Mapeamento Digital da Cobertura Vegetal do Município de São Paulo. Relatório Final/Coordenação: OLIVEIRA, Vivian Prado de. São Paulo: SVMA, 2020.

Tang, L., Xue, K., Pang, Z., Jiang, L., Zhang, B., Wang, W., Wang, Y., 2023. Plant community associates with rare rather than abundant fungal taxa in alpine grassland soils. Appl. Environ. Microbiol. 891, e01862–e01922. https://doi.org/10.1128/aem.01862-22.

Theobald, D.M., 2004. Placing exurban land-use change in a human modification framework. Front. Ecol. Environ. 23, 139–144.

Trammell, T.L., Pataki, D.E., Pouyat, R.V., Groffman, P.M., Rosier, C., Bettez, N., Steele, M., 2020. Urban soil carbon and nitrogen converge at a continental scale. Ecol. Monogr. 902, e01401.

Trumbore, S., 2009. Radiocarbon and soil carbon dynamics. Annu. Rev. Earth Planet. Sci. 37, 47–66.

Vasenev, V., Kuzyakov, Y., 2018. Urban soils as hot spots of anthropogenic carbon accumulation: review of stocks, mechanisms and driving factors. Land Degrad. Dev. 296, 1607–1622.

Vieira, M.S., Dos Santos, A.R., Lopes, M.I., Gomes, E.P., 2022. Litter decomposition in a remnant of Atlantic Rain Forest and bamboo dominance. Forest Systems 31 (3), e019. https://doi.org/10.5424/fs/2022313-18791.

Wu, W., Wang, F., Xia, A., Zhang, Z., Wang, Z., Wang, K., Cui, X., 2022. Meta-analysis of the impacts of phosphorus addition on soil microbes. Agr. Ecosyst. Environ. 340, 108180 https://doi.org/10.1016/j.agee.2022.108180.

Zeng, X., Zhang, W., Cao, J., Liu, X., Shen, H., Zhao, X., 2014. Changes in soil organic carbon, nitrogen, phosphorus, and bulk density after afforestation of the "Beijing–Tianjin Sandstorm Source Control" program in China. Catena 118, 186–194.

Zhan, Y., Yao, Z., Groffman, P.M., Xie, J., Wang, Y., Li, G., Butterbach-Bahl, K., 2023. Urbanization can accelerate climate change by increasing soil N2O emission while reducing CH4 uptake. Glob. Chang. Biol. 2912, 3489–3502.