Urban Ecosystems (2023) 26:197–207
https://doi.org/10.1007/s11252-022-01296-7

Assessment of four urban forest as environmental indicator of air quality: a study in a brazilian megacity

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Accepted: 16 September 2022 / Published online: 18 October 2022

Abstract
Vehicular emissions comprise a main source of air pollutants, especially particulate matter (PM), which contains toxic compounds. Brazil has been restricting vehicular emissions for more than 30 years to minimize the impacts of fleet vehicles, but despite the restrictive legislation, several Brazilian cities still suffer from the effects of atmospheric pollution. The adoption of nature-based solutions (NbS) is being hailed as a sound alternative for improving urban air quality. In this sense, trees are a true reflection of the NbS concept since they can directly decrease PM levels by intercepting and resuspending particles, as well as altering pollution dispersion patterns. We wanted to understand the practical outcome of urban forest fragments as an NbS. Therefore, using litterfall in urban forest fragments, this study reported the role of green areas in reducing air pollution concentrations in 4 urban parks in Sao Paulo Megacity, Brazil. Air contaminants (Cd, Cu and Pb) varied from the edge to the core of urban forests. Multivariate analysis revealed that areas with different vehicle fleets influenced the input of air pollutants into these forest fragments. Our study further showed that trees serve as a natural barrier against PM. It can be concluded that this low-cost NbS alternative can reduce air pollution and has a potential to improve human health and well-being, and should be incorporated into municipal policies and programs, especially in critical locations of high human density. and poorly managed green areas.

Keywords Urban forests · Strategic environmental planning · Urban ecology · Nature-based solutions · Urban environmental policies

Introduction

The impact of human activities on natural ecosystems remains a global challenge, even more worrying since the Earth has been experiencing extreme weather events. The increase in surface temperature affects many functions of natural ecosystems, such those related to the water cycle, reducing the water supply. According to IPCC (202), the level of stress on the planet is expected to increase, especially in urban areas where huge and largely unplanned changes occur in land use and the atmosphere.

Cities in the global South face several challenges inherent to the urban ecosystem, among which stand out social inequality, extreme poverty in part of the population and fragility in the public health system (Randolph and Storper 2022). This scenario requires the active participation of public management, academy and civil society in engaging in socio-environmental transformation (Shackleton et al. 2021). For this purpose, municipal policies and programs must converge on national and international proposals discussed within agencies that aim at sustainable development and planning for healthy cities (UN – Habitat 2016). The achievement of the main goal also implies commitment to its environmental targets; consequently, air pollution control is closely related to these goals (Kroll et al. 2019; Mainali et al. 2018; Zhu et al. 2022).

Likewise other cities, in the Brazilian urban areas, air pollution has become a major environmental health challenge owing to the construction of infrastructure, industrial activities, power plants and the huge expansion of the vehicular fleet (Cardoso-Gustavson et al. 2016; Theophilo et al. 2021; Ribeiro et al. 2021).

Among air contaminants, particulate matter (PM), a complex mixture of extremely small particles and liquid droplets,

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Extended author information available on the last page of the article has several adverse effects on human health (Nowak et al. 2018; Ferreira et al. 2017a).

Vehicular emissions constitute the main source of PM, discharging several chemical elements designated as heavy metals, such as cadmium (Cd), copper (Cu), and lead (Pb). Depending on particle size, PM, once inhaled, can pass through the throat, and nose and enter the lungs, promoting serious health problems, such as respiratory and cardiovascular diseases (Lin et al. 2017; Zeng et al. 2016).

The Brazilian commitment to minimizing the impacts of the vehicular fleet precedes the 2030 Agenda. The country has been controlling vehicular emissions since 1986 through the Program for the Control of Air Pollution Emissions by Motor Vehicles (PROCONVE), which sets limits for the emission of contaminants. Pollutant emissions were reduced by 70% because of this program (Carvalho et al. 2015). The most remarkable consequences of PROCONVE were the removal of Pb from gasoline and the reduction of sulfur (S) content in diesel fuel.

Nowadays, the total Brazilian vehicular fleet is 104,784,375 units, most of which are in the southern and southeastern regions, where the Sao Paulo megacity is located. According to the Environmental Agency of Sao Paulo (CETESB 2019), the vehicular fleet was responsible for about 40% of PM emissions. Despite the decrease of emissions owing to PROCONVE (Carvalho et al. 2015), atmospheric pollution control remains a challenge for Sao Paulo authorities.

Besides public programs focused on the reduction of vehicular emissions, many cities around the world have been promoting the expansion of their natural greenspace, such as urban forests to reduce air pollution (Nowak et al. 2013; Nowak et al. 2014; Nowak et al. 2018; Carvalho and Szlafsztein 2019; Kumar et al. 2019). According to Endreny (2018), urban forests support the SDGs since their spaces provide host of ecosystem benefits, including the prevention of diseases, especially those related to air pollution. These spaces also favor cultural interaction among visitors by improving the quality of life for the local population. Scientific evidence points to urban forests as providers of ecosystem services related to the reduction in PM concentration and other air contaminants (Nowak et al. 2018; Han et al. 2020).

The presence of trees alters the levels of PM in the atmosphere by intercepting and resuspending particles and altering dispersion patterns (Nowak et al. 2018). Thus, the greening strategy of cities is essential to reduce the negative impacts of urbanization (Ferreira et al. 2017b; Sanesi et al. 2017; Nowak et al. 2018; Escobedo et al. 2019).

The use of nature and its elements, i.e., nature-based solutions (NbS), has been considered an efficient method to promote environmental quality (Kabisch et al. 2016; Marando et al. 2016). NbS is linked to several natural alternatives to minimize a series of socio-environmental issues (Calfapietra and Cherubini 2018). The use of natural resources to assess air quality might be considered an NbS since vegetation can trap chemical contaminants, and live organisms can act as a biological monitor of environmental pollution (Ferreira et al. 2012, 2017b; Xing and Brimblecombe 2020; Zabotto et al. 2020). Thus, NbS has the potential to mitigate urban pollutants and provide a better quality of life for urban inhabitants.

Costly alternatives in urban mobility and replacement of the fossil fuel-powered fleet are relatively distant from the budgetary and strategic reality of the richest city in Brazil, being low-cost and environmentally sustainable alternatives the most viable for the strategic environmental planning of the megacity. In this context, nature-based solutions play a key role in the mitigation of pollutants that aggravate aspects of public health and affect biodiversity, typical problems of urban ecosystems (Nakazato et al. 2021; Belaire et al. 2022; Southerland et al. 2022).

The efficiency of indicators that attenuate air pollution can be a strategic tool for promoting urban greening in strategic locations in the city. Municipal policies and programs of afforestation and promotion of healthy and sustainable environments in Sao Paulo lack strategic information for the implementation of Nbs.

Although there are urban forestry studies in the megacity of São Paulo (Ferreira and Uchiyama 2015; Ferreira et al. 2018, 2019, 2021; Arratia et al. 2020), its association with air pollution is still under development. In this study, heavy metal pollutants from PM (Cd, Cu and Pb) were assessed from litterfall samples collected in four different urban forest fragments of the megacity of Sao Paulo. These forest fragments were in areas reflecting different land use changes, driving patterns and high-traffic corridors. The aim was to obtain quantitative indicators of atmospheric contaminants in the area to evaluate the role of urban forests as a mitigation tool that can be applied or extrapolated to different areas and sectors of the city of Sao Paulo, contributing to the city's environmental plans.

Material and methods

Study area

The study was carried out in Sao Paulo megacity, Sao Paulo State, Brazil. It is the largest city in South America with the 7th largest metropolitan region in the world with about 20 million inhabitants and with a daily circulation of around 7.5 million fleet vehicles (IBGE 2010).

Historically, the urbanization of Sao Paulo has taken place according to its hydrographic network and not necessarily from the center to the outside (Monbieg 1954; Jannuzzi and Jannuzzi 2002). Throughout the twentieth century, industrial districts were established in areas far from the central region, now peripheral neighborhoods with low-income populations. For example, the East Zone of the city is a dense urban area with few green areas. As such, it can be assumed that this region has high levels of pollutants and, consequently, should receive priority in developing green infrastructure programs.

According to CETESB, the air quality of the city has been deeply affected by local emissions of its vehicular fleet, despite the intensity of industrial activity, (CETESB 2019). The Environmental Sanitation Technology Company (CETESB–*initials in Portuguese*) is responsible for the "Air Quality Information System" (QUALAR, in Portuguese), with a total of 16 fixed automatic networks, established to measure atmospheric conditions in Sao Paulo megacity. All locations present different economic and physical characteristics but monitoring only does not reflect the total spatial scope and dispersion of pollution in the urban territory.

The municipality is subdivided into 32 city district managements, each one having from 130,000 to 600,000 inhabitants, indicating the importance of studies to investigate the levels of atmospheric contaminants and the mitigation capacity of green areas from the city center to the peripheries (Coelho 2020). For this reason, four fragments of urban forests were chosen, as follows:

(i) Trianon Park (PT) is situated in the central area of the city and is formed by dense rainforest with a slight hilly southern slope. The park covers an area of 4.86 ha and occupies two blocks connected by a pedestrian bridge, which crosses over an avenue with intense vehicular traffic. This forest fragment is located in one of the highest region of the city (805 m a.s.l.) and has no water outcropping (Sao Paulo 2018). Its surroundings are characterized by roads with heavy low-speed traffic and a large concentration of heliports, according to data from the Airspace Control Department (DECEA 2018).

(ii) Alfredo Volpi Park (PAV) is a forest fragment composed of dense rainforest with accentuated reliefs and is located 6 km southwest downtown. The park has a total area of 14.24 ha with elevation between 730 m a.s.l. at the lowest level and 785 m a.s.l. at the highest level. Some water bodies occur in the park area, forming small streams and lakes. In its surroundings, roads can be found with heavy vehicular traffic, predominantly cars and motorcycles. Another part is characterized by a residential area with light traffic. It is close to approach and takeoff zones of Congonhas Airport (DECEA 2018). Congonhas Airport serves domestic flights and is the second busiest airport in the country.

(iii) Fontes do Ipiranga State Park (PEFI) is located 11 km southeast downtown and has undulating relief with the presence of springs, streams, and lakes. The fragment is formed by heterogeneous forests and dense ombrophilous forest with elevation between 760 m a.s.l. at the lowest level and 825 m a.s.l. at the highest level (Sao Paulo 2018). The park has a total area of 540 ha, and in its surroundings, moderate to heavy vehicular traffic can be observed, as well as a highway that connects Sao Paulo megacity to the largest Brazilian port, which lies some 0.5 km from the fragment with cars and trucks. The area also comprises part of the Congonhas Airport approach and takeoff zone (DECEA 2018), in addition to shopping centers with heliports.

(iv) Carmo Park (PC) is a more peripheral forest fragment, located 19 km east downtown. It consists of heterogeneous forests and dense rainforest. The area has characteristics similar to those of PAV with wavy relief. The fragment consists of approximately 150 ha and elevation between 775 m a.s.l. at the lowest level and 855 m a.s.l. at the highest level. PC is inserted at the East Zone of the city. This area is significantly urbanized with high population density. The surroundings of this forest fragment are characterized by roads with relatively light car and motorcycle presence. A few traffic lights moderate the speed of vehicles. This region does not have heliports, and it is not inserted within the approach and takeoff zones of airports (DECEA 2018).

The details of extent and type of surroundings can be found in Fig. 1.

Litterfall sampling

In each fragment of urban forest, 21 litterfall samples were collected in the dry season (July 2017). Seven samples were collected from the edge of the green area (0–30 m away from the street), seven samples in the middle of the park (30–70 m away from the street) and seven samples in the middle of the urban forest (70 m or more away from the street). A hollow mold (25 cm × 25 cm) randomly thrown on the forest floor within the previously described zones was used to collect the material (Ferreira et al. 2017b). The litterfall was removed up to soil layer. If the hollow mold circumvented any living vegetation, it was ignored as the purpose was to collect the deposited material. This methodology has been used by Martins et al. (2015) and Ferreira et al. (2017b). After sampling, litterfall was packed in cellulose paper bags and sent to the laboratory for analysis.

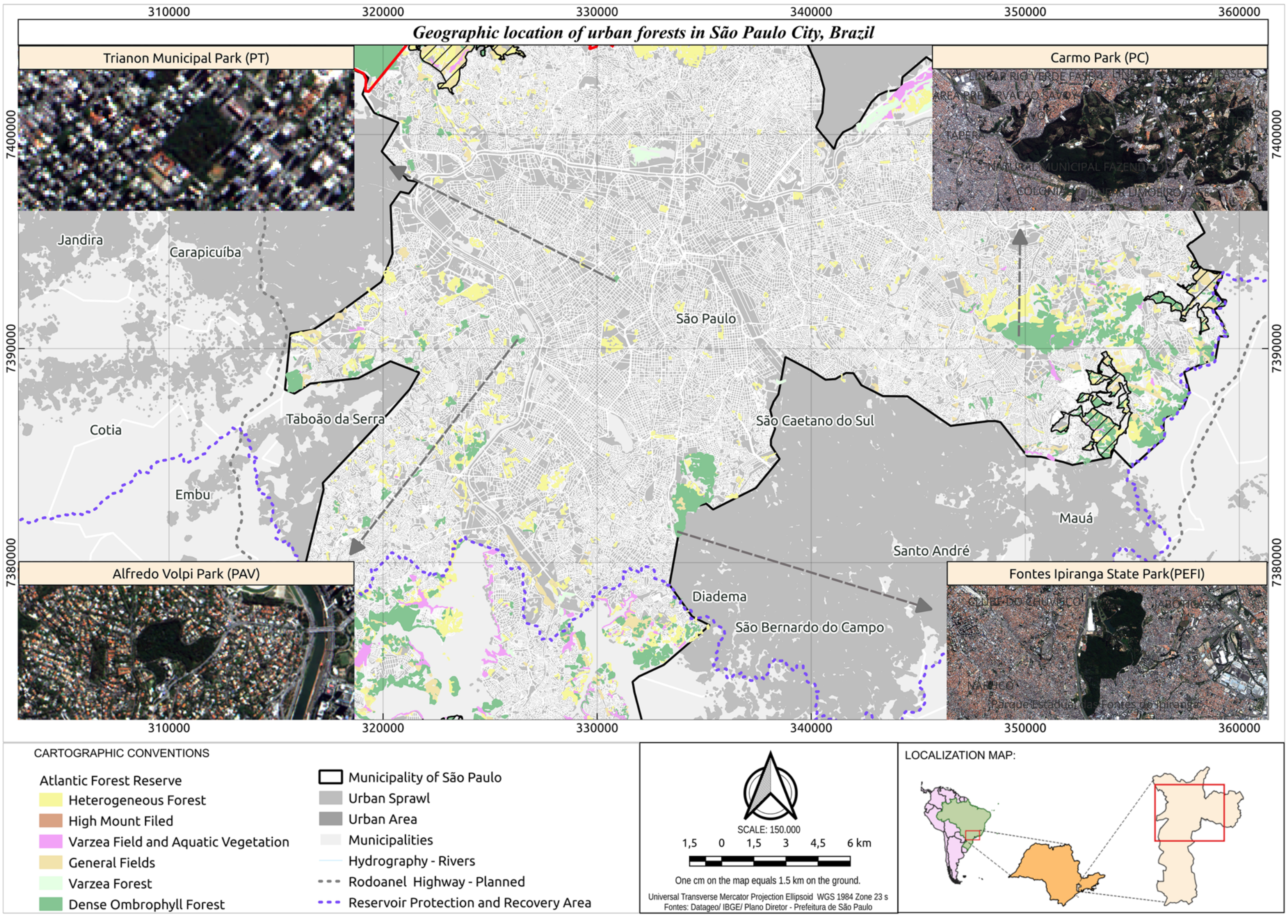

Fig. 1 Aerial view of fragments of urban forests and their respective locations in the municipal territory

Litterfall analysis

Litterfall samples were dried in a forced ventilation oven at 40 °C for one week. The dried samples were ground with a knife mill and sieved on a 0.25 mm mesh. Each sample containing about 20 g of homogeneous solid material was sent for chemical analysis.

Concentrated nitric acid (4 mL) and concentrated hydrofluoric acid (1 mL) were added to samples (0.3 g each) to facilitate the dissolution of fibrous tissues, rich in silicon and colloids. The samples were digested in a closed-system microwave oven (CEM MARS-6) at high pressure and temperature. The homogeneous solutions were subjected to Graphite Furnace Atomic Absorption Spectrometry (GF AAS) (Perkin-Elmer AAnalyst800) for Cd, Cu and Pb mass fractions determination. The certified reference material NIST SRM 1547 (peach leaves) (NIST 2019) was also analyzed to ensure data accuracy (trueness and precision). Results presented bias < 10% and coefficient of variation < 12%, which were considered adequate for this kind of study.

Statistical analysis

Two non-parametric statistical tests were used to evaluate significant differences in relation to the analyzed pollutants and specific forest fragments, hence, not requiring the assumption of normal distribution of the obtained results, since the sample size was small for the normality test assumptions. The two-sample Wilcoxon test was used to compare element mass fractions at each two parks at 95% confidence level using R software (Team 2021). A non-parametric Mutivariate Analysis of Variance (MANOVA) test with level of significance of 5% was used with R software, using the “adonis” command of the Vegan package in order to verify if there was any impact of the position of litterfall sampling (edge, middle and core) to the various pollutant levels along the different forest fragments (Anderson 2001; McArdle and Anderson 2001; Oksanen et al. 2018). Trace element boxplots as well as the two-sample Wilcoxon test were also applied to complement this evaluation. Both were prepared with R software.

Table 1 Comparison (*p*-value) of air pollutants among urban forests by the Wilcoxon non-parametric test

Element	Comparison and *p*-value					
Cd	PEFI > PT	PEFI > PC	PEFI < PAV	PT > PC	PT < PAV	PC < PAV
	0.0369*	0.0007*	0.6730	0.0168*	0.0073*	2.81e⁻ 05*
Cu	PEFI < PT	PEFI > PC	PEFI < PAV	PT > PC	PT > PAV	PC < PAV
	4.2e⁻ 08*	0.1185	0.0288*	3.6e⁻ 08*	1.6e⁻ 05*	0.0005*
Pb	PEFI < PT	PEFI > PC	PEFI > PAV	PT > PC	PT > PAV	PC < PAV
	0.1101	2.6e⁻ 07*	0.6174	3.8e⁻ 09*	0.0381*	6.48e⁻ 08*

*Significant difference considering alpha < 5%

Results and discussion

Cd, Cu and Pb in the litterfall presented different behaviors among the parks. Cd mass fraction was significantly higher in PAV and PEFI, followed by PT and PC (Table 1). Even though it is also present in the chemical composition of gasoline, Cd is more appropriately evaluated in emissions of diesel engines, the main fuel for heavy duty vehicles (Coufalík et al. 2019; Shukla et al. 2017). PAV and PEFI present a heavy-duty vehicular fleet with high traffic, since these parks are close to highways that allow access to cities within the state's interior and to the Port of Santos, the largest in Latin America. As a result, samples of litterfall from these parks presented the highest Cd contents, a marker of diesel fuel burning (Coufalík et al. 2019).

The surroundings of PT are characterized by light duty vehicles with heavy low-speed traffic and high Cu contents associated with road traffic materials, such as brake linings (Barros et al. 2019; Vianna et al. 2011; Ribeiro et al. 2012).

The highest Pb levels were observed at PT and PEFI. Although the use of leaded gasoline in cars is banned, this metal still appears as an important additive of aviation diesel (Cassella et al. 2011). PT is located directly under air traffic, and PEFI is located within the approach and takeoff zones of Sao Paulo/Congonhas airport which explains the higher Pb contents in these fragments (DECEA 2018).

Metal mass fractions in the litterfall of edge, middle and core were different and can be explained by the impact of vehicle sources from both outside and inside the parks. PT and PAV forests showed significant difference in these levels (PT: $F = 10.51$, $p < 0.05$; PAV: $F = 1.183$; $p < 0.1$). These forest fragments are located the nearest of the center of the city (Table 2).

A key distinction is how metal contents in the litterfall from the edge of fragments of urban forests differ from those in the interior and core. The highest mass fractions were observed in samples collected in areas adjacent to streets and avenues, while the lowest mass fractions were recorded within the parks (Fig. 2).

Based on MANOVA tests (Table 3), the independent and interaction variables had significant effects on differences in the average concentration values of Cd, Cu and Pb. Nonparametric MANOVA showed that the interaction of factors was significant ($F = 2.353$; $p < 0.05$). The results present evidence of differences in the average concentration of the three pollutants, considering simultaneously the sampling sites, edge, middle and core of the four parks studied.

The pollutants presented similar behavior. However, apart from geographic location, the tree density of each park might explain the trapping of air contaminants. Recent studies focused on ecosystem services have indicated that trees have the capacity to remove PM (Arroyave-Maya et al. 2019; Nowak et al. 2018, 2013). Computer simulations considered tree cover and estimated the benefit of trees for several cities in the United States of America. According to Nowak et al. (2013), the net removal amounts per square meter of canopy cover varied

Table 2 Nonparametric MANOVA with *F* test values and significance to evaluate the effect of pollutant levels on each forest fragment*

Forest	Variable	DF	SS	MS	*F*	*p*-value
PT	Site	2	0.183	0.091	10.51	0.009
	Residual	18	0.156	0.008		
PAV	Site	2	0.051	0.025	1.183	0.099
	Residual	18	0.226	0.012		
PEFI	Site	2	0.050	0.025	1.271	0.288
	Residual	18	0.354	0.019		
PC	Site	2	0.022	0.011	0.927	0.485
	Residual	18	0.222	0.012		

**DF* degrees of freedom, *SS* sum of squares, *MS* mean of squares

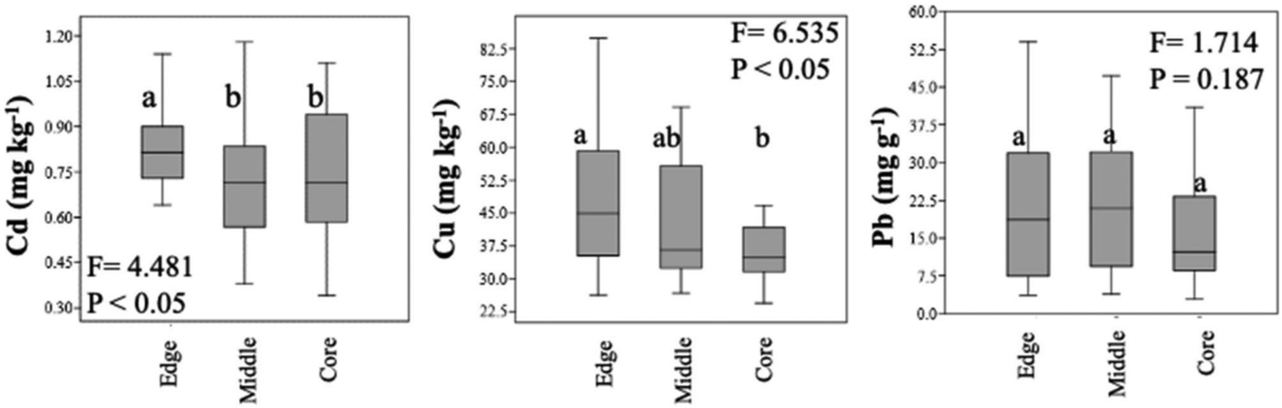

Fig. 2 Boxplots showing the significant differences obtained with the Wilcoxon test on metal mass fractions among sampling positions (edge, middle and core). Different lowercase letters represent significant differences at the 5% level

from 0.13 g m^{-2} yr^{-1} in Los Angeles to 0.36 g m^{-2} yr^{-1} in Atlanta. The average annual percent air quality improvement was 0.24% in Atlanta. The estimated public health value varied from US$ 122 million to US$ 6.2 billion in New York; reduced mortality was as high as 7.6 people per year in New York City.

New York City encompasses a total area of 783 km^2 with 21% tree cover (US Forest Service 2018). Sao Paulo occupies 1,522 km^2 with 40.6% tree cover (Sao Paulo 2020). Despite prominent social differences between New York and Sao Paulo, the cities have a similar population and intensive emission from their respective vehicular fleets. Consequently, the New York City data (Nowak et al. 2013) could roughly indicate the potential positive impacts of tree cover in Sao Paulo.

Accordingly, our results showed that the central urban parks of Sao Paulo could filter atmospheric pollutants by trapping PM in a manner independent of size. Kremer et al. (2019) reported that urban parks are essential for livable and sustainable cities. Therefore, the use of so-called green infrastructure to promote human well-being has turned toward a new direction, namely urban planning (Kumar et al. 2019), especially in cities with rapid and disordered urban growth, such as Sao Paulo (Carvalho and Szlafsztein 2019).

Table 3 Nonparametric MANOVA with *F* test and *p*-values and significance in relation to forests and sampling sites*

Variable	DF	SS	MS	*F*	*p*-value
Forest	3	1.005	0.335	25.11	0.0009
Site	2	0.118	0.059	4.458	0.0049
Interaction	6	0.188	0.031	2.353	0.0079
Residuals	72	0.960	0.013	-	-

**DF* degrees of freedom, *SS* sum of squares, *MS* mean of squares

Sao Paulo: trends in environmental planning and future potencials

Policies aimed at urban planning are regulated in Brazil by Law No. 10,257/2001, the so called the City Statute. This law strengthened local proposals, especially the Municipal Master Plan (MMP), making it an instrument of urban policy and development, aiming to promote a democratic management (Santos and Montandon 2011).

In the latest revision of the Sao Paulo MMP, special attention was given to the creation of new zones (like new spread centers) in different parts of the city, avoiding long displacements of the peripheral population, given that most low-income people live on the outskirts of the city and work in central regions. It is suggested that these new centralities be planned with strategic urban green areas in mind and that they consider implementing the NbS concept, thus providing a healthier environment for the local population. In this context, the Sixth Assessment Report (AR6) of the IPCC promoted by Working Group II (WGII) discussed the vulnerability and exposure of ecosystems and people. Among other key factors of climate change adaptation, social issues are still the greatest challenges as cities adapt to climate change (IPCC 2022).

Sao Paulo must directly confront this problem since its periphery lies in the poorest part of the city and is one of regions in Latin America with the highest population densities, but with low relative quantity of green areas. Martins et al. (2004) reported that the health effects of PM_{10} in the city of Sao Paulo was negatively correlated with high family income and positively related to the percentage of people living in slums.

These public policies indicate the need to expand green infrastructure to these critical areas (Sao Paulo 2021), with the center of Sao Paulo receiving special attention. Indeed, despite the forests studied and their role in providing ecosystem services, Sao Paulo still lacks urban green areas. According to Ribeiro et al. (2021), treescape is observed in the central and eastern regions of the city with 2.00 to 6.00 m^2 of greenery per inhabitant. Another study conducted by Buckeridge (2015) reported that the urbanized part of Sao Paulo, leaving aside the central, eastern, and peripheral areas, showed an average of 0.06 to 0.60 trees per inhabitant in the eastern region and a maximum of 2.0 trees per inhabitant in the western region. Moreover, 22 out of 28 city districts presented less than 1.00 tree per inhabitant (Buckeridge 2015).

Considering the physical environment of the city of Sao Paulo and the characteristics of its vehicle fleet, data that support the capacity to filter air pollutants might assist responsible government agencies to prioritize the search for homogeneity of official green areas, or protected areas, and democratize access to these spaces. Especially, the management of vegetation and arboreal typology on the edges of urban green areas would improve air quality, bringing multiple benefits to people and biodiversity (Belaire et al. 2022). This effort becomes even more relevant when considering that only 4 out of the 106 municipal parks in the megacity of Sao Paulo have a management plan for green areas. Thus, our results corroborate the importance of promoting adequate management at the edges of urban green areas, particularly using evergreen species, in addition to greening strategic areas of the city through urban afforestation programs.

Some authors have reported on the importance of structure, composition and functional attributes of vegetation to the provision of ecosystem services in the attenuation of air pollution. Indeed, implementation of the NbS concept is an example of strategic environmental planning owing to its potential social benefits commonly associated with urban parks (Marando et al. 2016; Vieira et al. 2018; Bulbovas et al. 2020). Similarly, van den Bosch and Sang (2017) promoted the use of urban green areas as a strategy for NbS in the context of delivering ecosystem services, such as decreased mortality related to cardiovascular disease or infectious and autoimmune diseases among vulnerable populations (Rook et al. 2015, 2014).

These effects may be realized in central areas of the city where our work showed the highest levels of atmospheric pollutants adsorbed to litterfall. These are, coincidentally, also areas with the highest average surface temperatures (Ferreira 2019; Ribeiro et al. 2021). Thus, it is easy to understand how the expansion of urban forests in the central area of the city could, as an NbS, promote ecosystem services to critical populations living in the central city. This becomes more evident when analyzing in Fig. 1 the intense gray mesh of the megacity of Sao Paulo, highlighting the role that green areas (or potential open spaces) have in mitigating atmospheric pollution from vehicular traffic corridors.

It was surprising that PC, which is located in a high-density urban area, did not have high levels of contaminants, possibly mitigated by the moderate traffic. Nonetheless, we urge decision-makers to promote the gradual reduction in the use of fossil fuels related to greenhouse gas emissions and encourage the use of renewable sources. However, while the costly transition does not take place, we foster decision-makers to mitigate air pollution through low-cost solutions with multiple environmental and social benefits (Benchimol et al. 2017).

This increase in urban sustainability through NbS can be optimized with the participation of stakeholders, who complement, through specific competencies and skills, the knowledge about the urban ecosystem that both the scientific community and public management cannot solely achieve (Reed 2008). This participation of society in the city's environmental decisions increases local governance and promotes attitudes based on collective thoughts (Soma et al. 2018). Stakeholder participation in strategic environmental planning is essential to fill gaps between science and public management, holding decision-makers accountable for actions to be taken and pointing out necessary directions for urban scientific knowledge (Beck and Storopoli 2021).

The strategies employed by PROCONVE to achieve this goal of reducing vehicular emissions and developing new technologies to make cleaner-burning fuel are commendable (Carvalho et al. 2015), despite the tendency to compromise public policies so prevalent in Brazil (Machado et al. 2015).

Conclusions

The dynamics of PM deposition vary with traffic gradients, indicating that vehicular sources have impacts both outside and inside forests, depending on the size of the forest fragment. Moreover, by analyzing the toxic elements in litterfall, our results showed the functionality of forest fragments in removing PM from polluted air and as a barrier to atmospheric pollution from the automotive fleet, evidencing the potential of this bioindicator.

The central part of Sao Paulo is particularly impacted by high air pollution, as well as high density of population and vehicles. However, this work has addressed the use of treescape as a means of both adapting the city for the current automotive fleet, as well as promoting ecosystem services to secure the health and well-being of the citizens.

In this sense, our research brings a new approach to the old problem of this Sao Paulo Megacity–air air pollution. The results indicated that the trees work as attenuator of PM; therefore, can be managed in strategy locations as a part of environmental municipal programs that aim at urban sustainability, especially in places that focus on aspects of public health, as well as the maintenance of biodiversity. Such planning must insert scientific information and the knowledge of stakeholders, thus leading the promotion of a sustainable urban ecosystem.

Notwithstanding this has not evaluated the morphological types of canopy or leaves, as well as ecological parameters, ie. tree density, on the edges of forest fragments, a fact that can enhance the role of NbS as a tool for mitigating atmospheric pollution, our results highlight the role of urban forest fragments in air decontamination, potentially with regard to guide planners to requalify urban green areas, especially in critical spaces, such those with high levels of atmospheric contamination from vehicular fleets.

Acknowledgements MLF, APR and PBC thank Sao Paulo Research Foundation (FAPESP) for financial support to develop this research under project numbers 2019/24325-2, 2017/50343-2 and 2020/05383-9. APR also acknowledges the grant provided by the National Council for Scientific and Technological Development (CNPq), under the project 317071/2021-1.

Authors' contributions All authors contributed to the study conception and design. Material preparation, data collection and chemical analysis were performed by MR, APR, CYST, EGM, PBC and MLF. The treatment of data set was performed by MR, APR, CABP, EFS, AGD, DN and MLF. The first draft of the manuscript was written by MR, APR, ART and MLF and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Availability of data and material Detailed information on the dataset is available from authors on sensible request.

Code availability Nothing to declare.

Declarations

Ethics approval Nothing to declare.

Consent to participate Nothing to declare.

Consent for publication Nothing to declare.

Financial interests The author declare no financial interests.

Conflicts of interest The authors declare no conflicts of interest.

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