Ecological Indicators 158 (2024) 111386

Contents lists available at ScienceDirect

Ecological Indicators

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

Original Articles

Spatiotemporal monitoring of subtropical urban forests in mitigating air pollution: Policy implications for nature-based solutions

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A R T I C L E I N F O

Keywords:
Air quality
Biological monitoring
Environmental policies
Urban forestry
Urban green areas

A B S T R A C T

Air pollution remains a major global challenge in addressing environmental and health issues requiring continuous and immediate action. Nevertheless, the extensive adverse effects from atmospheric pollution are mainly experienced by communities and people in lower- and middle-income countries, such as the medium- and large-sized cities in Latin America including the coastal city of Guaruja in Brazil. Urban forests, as integral parts of the city landscape, play a crucial role in mitigating air pollution and should therefore be considered in environmental policies. This study aimed to evaluate the spatiotemporal concentrations of air pollutants using the biological monitoring method with *Tillandsia usneoides* L. to highlight the capacity of urban forests to act as nature-based solutions (NbS) in improving air quality and providing other ecosystem services. Based on the quantification of chemical indicators of vehicle emissions, scientifically recognized as traffic-related elements (TREs) such as cadmium (Cd), Copper (Cu) and lead (Pb) in the biomonitoring samples, the results showed spatiotemporal variations in their concentrations. This finding demonstrates that urban fragments in the low-income settlement of the city exhibited higher values for TREs during the wet season. Cu values were the highest during the wet season in all study areas, underscoring the intensity of the light vehicle fleet. Forest fragments attenuated air pollution, highlighting their importance as features of environmental planning. The identification of atmospheric pollution hotspots in the territory guided the strategic implementation of NbS through tree planting, thus promoting a healthier environment with greater mitigation potential. This study is the first in Brazil to explore the spatiotemporal relationship between air pollution and urban forests in highly dense and low-income settlements providing quantitative indicators toward the benefits of NbS.

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https://doi.org/10.1016/j.ecolind.2023.111386
Received 30 June 2023; Received in revised form 29 October 2023; Accepted 1 December 2023

1. Introduction

Issues related to the reduction of air contaminants have been introduced on public agendas for several years, as exemplified by the Clean Air Act of 1970 in the United States. The program has always focused on creating regulations that not only require reductions in air pollutants but also direct industrial activities to invest in the development of new technologies capable of preventing the release of more pollutants into the atmosphere. In fact, since its creation, the Clean Air Act has resulted in remarkable statistics for Americans. Over 230,000 premature deaths, 200,000 cases of acute myocardial infarction, millions of respiratory-related cases such as acute bronchitis and asthma attacks, and 135,000 hospital admissions have been prevented (USEPA, 2023).

Despite the latest advances in policy and technology (Gopalakrishnan et al., 2019), air pollution remains the main concern related to global heath and is still responsible for several adverse effects on human well-being, causing about 9 million deaths per year, which corresponds to 1 in 6 deaths worldwide (Fuller et al., 2022). Its cumulative and negative consequences mostly affect vulnerable populations, such as children and the elderly (Kabisch et al., 2017; Aghamohammadi and Isahak, 2018; Sadrizadeh et al., 2022). Furthermore, Saldiva et al. (2023) discussed the associations between exposure to air pollution in pregnant women and the expected impacts on the future generation of the Brazilian population. The authors highlighted the urgency to discuss health policies integrated with other issues, i.e., development of technology and the environment.

In addition to human health, high levels of atmospheric pollution also affect natural ecosystems and have been causing changes in ecological patterns and biodiversity processes. In the litter and soil compartments of urban and periurban forests, neighboring petrochemical complex, and mining areas, high levels of atmospheric pollutants have been found to interfere with nutrient cycling processes (Bulbovas et al., 2020; Nakazato et al., 2021). Furthermore, in the urban forests of São Paulo (Southeastern Brazil), atmospheric pollution has been considered the main driver of the reduction in litterfall decomposition rate (Ferreira et al., 2017a).

Therefore, mounting levels of urban air pollution are hampering the transition towards a more sustainable, inclusive and equitable society, as foreseen by the 2030 Agenda for Sustainable Development, especially Sustainable Development Goal (SDG) 11, which focuses on low-income urban settlements in developing countries (Vardoulakis et al., 2020). The premises of the 2030 Agenda emphasize the inclusion of sustainable alternatives alongside traditional engineering practices to promote the achievement of the SDG.

The concept of 'nature-based solutions' (NbS) has been popularly reported in scientific literature to highlight their importance (Martín et al., 2020; Stefanakis et al., 2021; Koutika et al., 2022). Although NbS had been previously discussed in the fields of science, policy, and practice in relation to the management of the natural environment (MEA, 2005; World Bank, 2008; IUCN, 2012), it was only in 2016, at the World Conservation Congress, that the International Union for Conservation of Nature officially defined NbS as "actions to protect, sustainably manage, and restore natural or modified ecosystems that effectively and adaptively address societal challenges, while simultaneously providing benefits to human well-being and biodiversity" (IUCN, 2016). Therefore, the concept of NbS involves the utilization of inherent properties and functions of ecosystems to promote human well-being and biodiversity conservation, including the provision of benefits such as air quality and climate regulation (Sanesi et al., 2007, Gopalakrishnan et al., 2019; Davies et al., 2021; Koutika et al., 2022).

Despite the publication of numerous studies, researchers recognize that knowledge gaps still exist when it comes to monitoring the effectiveness of NbS approaches in environmental management; in other words, there is a need for indicators that provide data on how NbS may strengthen public policies aimed at sustainable urban planning (Waylen et al., 2014; Nesshöver et al., 2017; Raymond et al., 2017; Stefanakis et al., 2021). Moreover, applying NbS in low- and middle-income economies is even more challenging, since these countries have undergone accelerated growth with huge disturbances in their socio-ecological systems (Lechner et al., 2020, Chausson et al., 2020). This is the scenario of medium and large cities in Latin America, including Brazilian cities (Ferreira et al., 2023). In fact, throughout the 20th century, these large cities experienced significant urbanization having focused largely on economic development and neglected social and environmental factors. However, to achieve the targets of SDG 11 (Martín et al., 2020; Koutika et al., 2022), cities need to be conceptualized as healthy environments under all aspects. They should strive to be economically viable, socially equitable and participatory, ensuring broad access to an ecologically balanced environment (Tramonte et al., 2016; Nesshöver et al., 2017, Locosselli et al., 2019).

To address these issues, this work presents a case study conducted in Guaruja, which is renowned as one of Brazil's foremost tourist cities and boasts significant remnants of the Atlantic Forest; the city also accommodates the activities of the Port of Santos, the largest in Latin America. Both factors give rise to conflicting situations for residents, i.e., on the one hand the local economy experiences a boost, while on the other hand various environmental and health issues emerge, particularly related to vehicle traffic air pollution (Theophilo et al., 2021).

Regarding air quality, the São Paulo State Environmental Company (CESTEB) is responsible for overseeing monitoring activities in accordance with the guidelines outlined in State Decree No. 59.113/2013. Specific parameters and measurement techniques are employed to ensure accurate assessment. However, in the case of Guaruja the monitoring efforts are relatively recent, having begun in 2016. Currently, the unique sampling station in the city focuses solely on measuring particulate matter (PM_{10}), with a diameter of 10 μm or larger (CETESB, 2019). PM_{10} – or smaller – is composed of so-called traffic-related elements (TREs), such as cadmium (Cd), copper (Cu), and lead (Pb), which have toxic potential (Figueiredo and Ribeiro, 2014). Therefore, Guaruja lacks data on substances that may be inhaled and cause serious health problems (Lin et al., 2017; Zeng et al., 2016). Notably, only a few studies have been carried out solely in relation to TREs, with initial findings highlighting the impact of heavy-duty fleets that access the Port of Santos (Theophilo et al., 2021).

In this perspective, our research aimed to: (1) assess the spatiotemporal relationship between urban forests and air pollution in the city of Guaruja; (2) model the temporal variation of air pollution across multiple sites and (3) assess NbS implementation by means of urban tree planting initiatives for air pollution mitigation. To achieve these goals, biological monitoring was applied to identify strategic hotspots to implement NbS actions as a contribution to urban planning with the intent to introduce the concepts of resilience and sustainability.

The scientific worth of this combination (i.e., air quality biomonitoring and identification of strategic locations) is explained by the fact that, as mentioned above, anthropic activities, particularly in urban areas, have led to significant air pollution posing risks to human health and the environment. In this context, the use of biological monitoring has emerged as a reliable approach to track areas impacted by human pressure and identify the urgent need for sustainable practices. Indeed, biological monitoring is an essential tool to indicate highly polluted sites where NbS should be prioritized, i.e., increase tree plantings with mitigating potential in air pollution hotspots that lack urban trees (Grote et al., 2016; Barwise and Kumar, 2020).

A key aspect of the successful implementation of NbS is that its benefits are quantifiable and easily understood by decision makers and civil society. A practical example is the integration of a common problem (e.g., atmospheric pollution) to the inhabitants of medium and large cities with one of its solutions (i.e., urban tree enrichment) (Lafortezza and Giannico, 2019; Bayulken et al., 2021). Such an approach can highlight the benefits of NbS in multiple dimensions and promote its incorporation in policies aimed at equity, resilience and improved air quality in cities (van der Jagt et al., 2019).

We believe that the biological monitoring method (Theophilo et al., 2021; Ramon et al., 2021) will indicate temporal variations due to tourist seasonality of the region and the input of vehicles that transit in the city during the summer (rainy season), as well as the spatial variations due to the strong human footprint and lack of urban mobility planning in the logistics sector of the Port of Santos. Accordingly, our research hypothesis suggests that the presence of well-maintained urban forests in low-income areas of the city will correlate with lower concentrations of TREs, due to their capacity to absorb and attenuate air pollution. Therefore, strategic urban tree planting in the areas where atmospheric pollution hotspots are observed can enhance air quality and promote a healthier environment for local communities. Such actions reinforce the benefits of urban forests on human health and wellbeing (Marziliano et al., 2013; Nowak et al., 2018; Ribeiro et al., 2021; Aoki et al., 2023) and could reduce inequalities, not only in terms of local air pollution exposure but also in supporting research around the globe, especially in low- and middle-income countries. The combination of air quality biomonitoring and identification of strategic locations to implement NbS constitutes an action that, to date, has not been carried out in Brazilian urban forests, especially in territories with considerable social inequality. The results obtained in this study can be used not only in Brazil but also in other countries facing similar socioeconomic development.

2. Materials and methods

2.1. Study areas

Guaruja is a coastal city in São Paulo state, located 70 km from the megacity of São Paulo, Southeastern Brazil, with high touristic potential and a population of approximately 320,000 inhabitants. The city presents three singular scenarios of socio-economic development. In the first, Guaruja hosts the largest port in Latin America, the Port of Santos, which is responsible for the largest flux of crops and grains produced in the country. The city daily accommodates thousands of trucks from all regions of Brazil and South America, which transit and park while waiting for discharge in urban and residential neighborhoods, precisely at the Vicente de Carvalho district. The district lacks basic sanitation, is characterized by high heavy vehicle traffic (due to the greater port activity), has the lowest rate of green areas in the urban perimeter, is subject to periodic flooding in certain neighborhoods and poses a threat to the mangrove ecosystem through the construction of illegal housing (Martins et al., 2021a; Guaruja. Guaruja City Hall, 2021a). Most of the native population in this area is predominantly low-income (IBGE, 2022).

The second scenario, adjacent to the port, is the urban core that presents a mosaic of green spaces immersed in a gray matrix where the main public hospitals, registry offices and services are located. This area also constitutes the residence of middle-income families as well as the location for a series of hotels and vacation homes for tourists.

The third and last and contrasting scenario refers to the geographic aspect of São Paulo, namely crowded beaches in the summer season, especially between December and February, with high-end condominiums for the social elite of São Paulo Megacity. This high-income settlement is located in the northeastern part of the city and is inserted between two Environmental Protected Areas, allowing for residential construction according to Brazilian law (SNUC, 2000). With luxury homes close to the beach, the location presents low urban density. Some highways that connect Guaruja to Bertioga, another tourist city, pass near these condominiums. This northeastern region of Guaruja is considered a biodiversity hotspot that provides multiple ecosystem services. It has received special attention from international biological conservation and climate change agencies and bodies (i.e., CNCFlora, ICLEI) for its ecological importance.

In terms of weather conditions, the City of Guaruja belongs to the southeastern region of Brazil, which is characterized by two distinct seasons throughout the year – the dry season (between April and September) and the wet season (between October and March). Accordingly, the driest months of June and July are also the coldest, with rainfall values below 100 mm per month and average air temperatures around 18 °C. The rainiest and warmest months are December, January, and February (~300 mm and 30 °C, respectively). This period coincides with a demographic explosion in the city by tourists who seek the beautiful beaches of the region for summer holiday, which also increases the intensity of vehicle traffic (Estancia de Guaruja, 2022). Regarding the topography of the city, the undulating relief presents slopes with remnants of Atlantic Forest that vary from sea level to 300 m a.s.l., with variations in ecological patterns at different altitudes (Sousa-Neto et al., 2017).

While the attractive beaches of Guaruja are occupied by tourists, 70 % of the native population lives in precarious settlements on the outskirts of the city. The Vicente de Carvalho district features topographically rugged areas below sea level prone to flooding during the wet season. The combination of air pollution and flooding affects this low-income and high-density urbanized (gray) area of the city, which represents the major socio-environmental challenge of environmental injustice (Rocha et al., 2018). The total vehicle fleet that accessed the City of Guaruja in 2020 was estimated to be 80,574 units. Table 1 presents the total number of units based on the category of each vehicle type (CETESB, 2022).

2.2. Air quality: Biological monitoring and defining areas for NbS

A robust air quality management system is essential to urban planning, as it provides protection to public health in the face of technological impacts and environmental change. However, according to the United States Environmental Protection Agency (EPA), efforts from environmental agencies with regard to guidance to public managers are required to properly use the information generated (Synder et al., 2013). Sophisticated air pollution diagnostics systems still require skilled specialists in sensor use and data interpretation. The EPA promotes workshops focused on streamlining these technologies and traditional monitoring networks, with automatic installations, which are still expensive and complex (Snyder et al., 2013). The World Health Organization WHO (2012) has encouraged the development of environmental studies to verify the feasibility of adopting simplified techniques such as biomonitoring to measure air pollution.

Biological monitoring has been considered a low-cost and effective tool for identifying the impacts of external factors on ecosystems by comparing unpolluted against polluted areas, or their long-term consequences, at a specific site (De Temmerman et al., 2004; Markert et al., 2011). Based on receptor responses to environmental stress, some assumptions may be raised about risks to humans (Markert et al., 2011). Living organisms, such as plant leaves, lichens, and tree bark, are receptors of atmospheric contaminants (Norouzi et al., 2015; Cardoso-Gustavson et al., 2016; Ferreira et al., 2017b).

In this study, plants from the same batch of *T. usneoides* L. were used as biomonitors to evaluate the spatiotemporal concentrations of air pollutants in the city of Guaruja. *T. usneoides* L. was acquired from a nursery specializing in bromeliad production located in an area free of anthropogenic pollution. This plant has been widely used in biomonitoring programs in tropical and subtropical regions and has a desirable accuracy for indicating atmospheric pollutants (Giampaoli

Table 1
Number of vehicle fleets in Guaruja during 2020.

Light-duty vehicles			Heavy-duty vehicles		Total
Passenger	Commercial	Motorcycle	Trucks	Buses	
42,982	6,178	29,627	1,369	423	80,579

Source: CETESB (2022).

et al., 2016, 2021; Theophilo et al., 2021). However, before being exposed in the urban forests of Guaruja, some aliquots of biomonitors underwent chemical analysis to determine the background values of Cd, Cu, and Pb.

The plants were exposed to two distinct seasons, the first between June and September 2019 (dry season) and the second between January and March 2020 (wet season). Although the standard exposure time of plants is 60 consecutive days (Cardoso-Gustavson et al., 2016), we selected an exposure time of 75 days so that the retention time of air pollutants would not exceed the capacity of the plants to adsorb air contaminants (Giampaoli et al., 2021).

Three sites were chosen for the exposure of the biomonitors, with distinct vehicle fleet profiles and different urban characteristics. The first is located adjacent to the Vicente de Carvalho district, with a predominance of heavy vehicle fleet, dominated by trucks discharging commodities at the Port of Santos. The Piaçaguera forest Area (hereafter PIA) is located beside the poorest and grayest residential area of the city. The second exposure site is in an Urban Forest fragment (hereafter UFO) located in the middle of the urban settlement of Guaruja, a central region of the city which offers a wide range of products and services, characterized by light vehicle fleet traffic consisting mostly of cars and vans. The third plant exposure site is a biodiversity Protected Area (hereafter PAR), with little local traffic and a marked seasonal flux of people, predominantly high-income tourists (Fig. 1).

Our study method differs from those of previous works carried out in tropical and subtropical cities (Cardoso-Gustavson et al., 2016; Giampaoli et al., 2016, 2021; Theophilo et al., 2021), because in addition to promoting a spatiotemporal approach of atmospheric pollution, biomonitoring is employed to test the biological filter capacity of urban green areas in attenuating the particulate matter emitted by urban vehicle fleets. For the exposure sites, each of the 30 samples containing 15 g of *T. usneoides* L. was hung on a tree branch. The samples were arranged in six lines, with five samples per line. The lines were labeled as L1 (indicating that the samples were exposed on trees located at the boundary between the green area and the roadway), L2 (the samples were placed 10 m from L1), and so forth to L6. The exposure of plants in the PAR did not border with streets or avenues since it was used as a control area (Fig. 1).

Based on the literature (Albert et al., 2021; Rödl et al., 2022) and considering that our study focused on atmospheric pollution disturbance in Guaruja, to monitor and evaluate NbS the initial steps involved were: (i) defining the study area, (ii) identifying indicators that could be associated with the primary source of air contaminants in the city, (iii) developing a data collection strategy, (iv) establishing laboratory analysis protocols, (v) identifying critical areas suitable for the implementation of NbS approaches, (vi) communicating findings to policymakers, and (vii) proposing a cost-effective NbS approach (Fig. 2). Accordingly, using the levels of TREs determined in bromeliad samples –

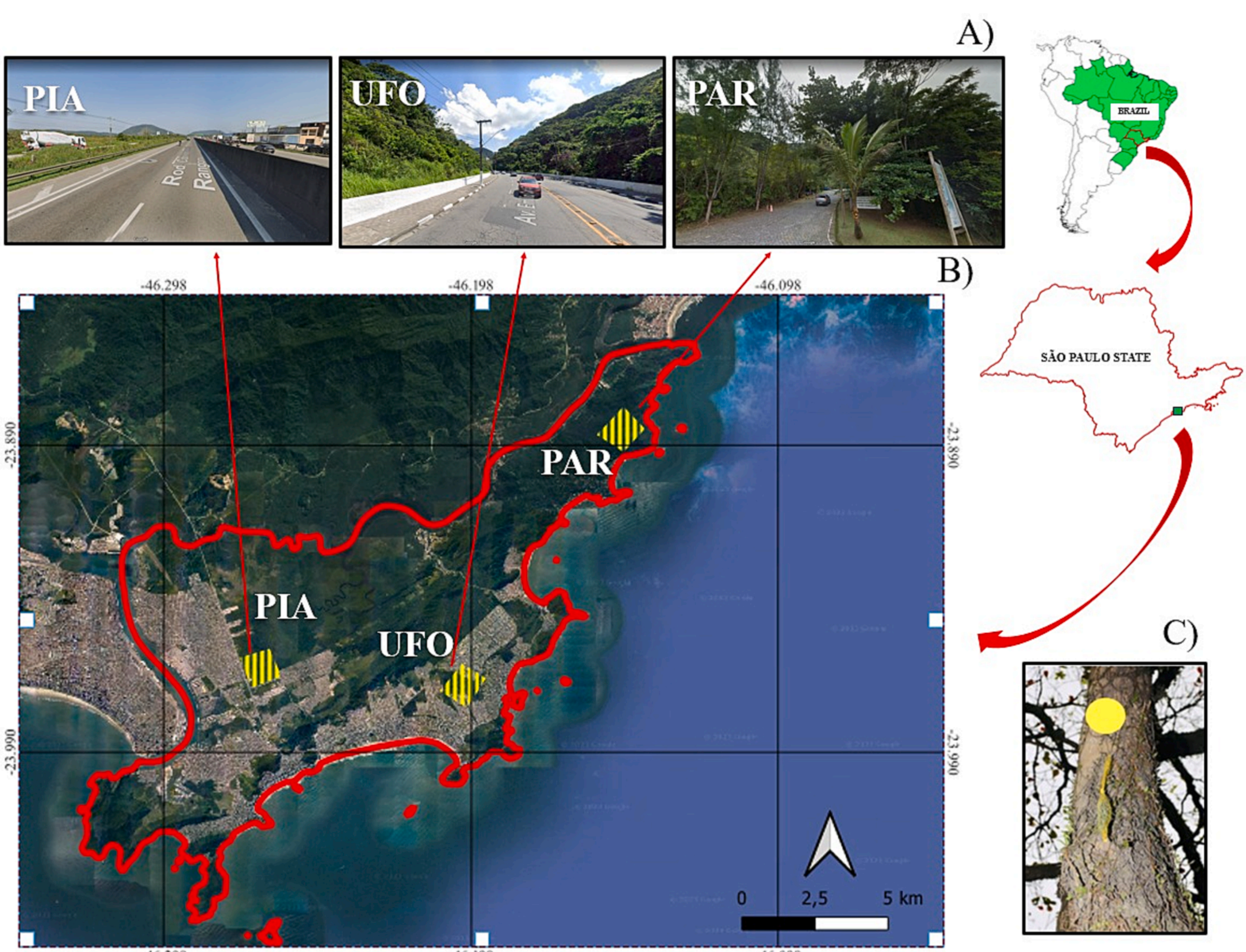

Fig. 1. Images of the streets and avenues where *Tillandsia usneoides* L. samples were exposed (A), and aerial view of the evaluation sites and sample distribution (B). Yellow and black lines represent the sites where the bioindicator plants (C) were exposed.

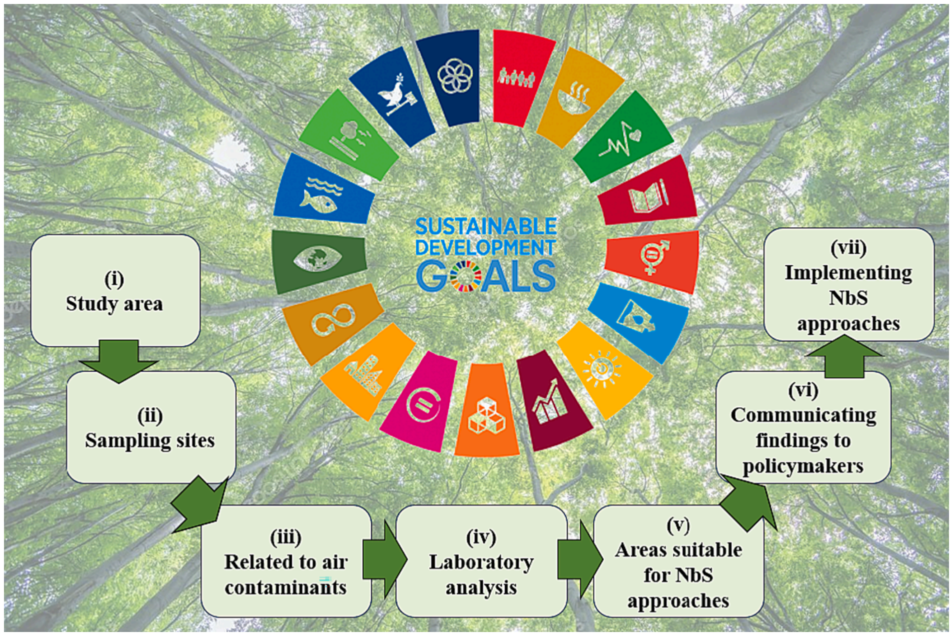

Fig. 2. Representation of the methodological stages of the study.

before and after exposure – in the urban forest fragments (PIA, UFO, PAR) it was possible to identify the most critical areas in terms of atmospheric pollution. This involved determining the highest concentration values for the entire dataset and quantifying how much these values exceeded the background levels. Additionally, characteristics of the urban landscape surrounding the forests were taken into account. Subsequently, areas were identified in which the implementation of the NbS approach should be prioritized.

2.3. TRE analysis

After collection, the *T. usneoides* L. samples were stored in paper bags to prevent cross-contamination. Subsequently, they were kept in the freezer, freeze-dried, and ground in a cryogenic mill. Aliquots between 0.2 and 0.35 g of each sample, 7 mL of HNO_3, 2 mL of HF and 2 mL of 30 % H_2O_2 (v/v) were added to PFA tubes and digested in the microwave CEM MARS6, using Plant Material digestion. The digestion program consisted of three steps: ramp time (20 min), hold time (10 min) and cooling time (10 min). The temperature reached 200 °C and the power varied between 1030 and 1800 W. Digested samples were diluted in 15 mL of deionized water. The TREs (Cd, Cu and Pb) under study were quantified by electrothermal atomic absorption spectrometry (AAanalyst 800, Perkin Elmer, Germany). These elements have been used in biomonitoring studies on atmospheric pollution in subtropical regions and are particularly suitable for assessing vehicular pollution (Ferreira et al., 2017a; erreira et al., 2017b, Theophilo et al., 2021). The detection and quantification limits of the TREs are presented in Table 2. They were estimated using the standard deviation obtained by reading several blank aliquots, according to the equations as described in Welz (1999). To ensure the quality of the results obtained, each batch was analyzed with aliquots of CRM INCT-MPH-2, Mixed Polish Herbs, and reagent blanks.

Table 2
Limits of detection (LD), quantification (LQ) of traffic-related elements (TREs) and levels prior to exposure.

TREs	LD*	LQ*	Background**
Cd (μg/kg)	5.0	16.0	35.0
Cu (mg/kg)	0.056	0.177	118.0
Pb (mg/kg)	0.019	0.617	0.5

* Refers to the analytical technique.
** Values from the nursery for bromeliad production (prior to exposure).

2.4. Data analysis

A multivariate analysis of variance (MANOVA) was carried out to assess the effect of the sites (PIA, UFO, PAR), lines (L1-L6) and seasons (dry and rainy) on the variability of TRE concentrations. Because the variables did not pass the multivariate normality test and multivariate outliers (Mahalanobis distance), non-parametric MANOVA (multivariate Kruskal-Wallis) was applied.

To test the effect of the season (dry and rainy) on the variation of air pollution values, regardless of the site of exposure, a non-metric multidimensional (NMD) analysis was conducted, considering stress <0.2 (Kruskal, 1964). To infer the distance between clusters, a similarity analysis (one-way ANOSIM) was performed, considering an alpha of 5 %. Finally, a similarity percentage (SIMPER) analysis was employed to assess the relative contribution of each dependent variable (pollutant concentration) to the homogeneous groups. The analyses were performed using PAST software (Hammer and Harper, 2001).

3. Results

Our assessment of the spatiotemporal relationship between air pollution and urban forests employing the biomonitoring method demonstrated that the concentration of air pollution varies according to the site and season of exposure. With specific reference to the spatial evaluation of plants in the sites of exposure, and regardless of the position of the plants in the exposure lines, *T. usneoides* L. exposed in PIA exhibited higher values of Cd and Pb than in the other two sites of exposure. The highest concentration of Cu was reported in the PAR during the wet season, while the lowest was reported in UFO and PIA. However, this pollutant presented a strong association with seasonality during the temporal evaluation, with lower values recorded in the dry season. Pb was another pollutant that exhibited variations between the rainy and dry seasons, most prominently in PIA (Fig. 3).

The Cd and Pb values revealed an attenuating effect of vegetation in mitigating air pollution along the exposure lines, particularly at PIA and UFO, even considering the presence of outliers in the analyses conducted. The wet season displayed slightly higher values for these

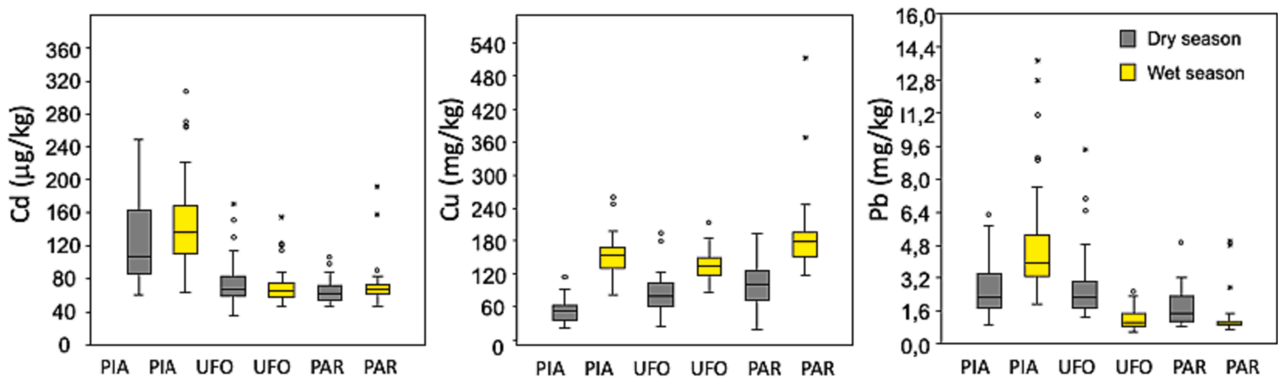

Fig. 3. The concentration of pollutants (Cd, Cu and Pb) on the biomonitor *Tillandsia usneoides* L. at different exposure sites and seasons. PIA – Piaçaguera forest Area (predominantly heavy fleet); UFO – Urban Forest fragment in the city center (mostly cars and vans); PAR – Protected Area (distant from the highway). The circles above the boxplots indicate outliers.

elements compared to the dry season at each exposure site. The concentration of Cu in *T. usneoides* L. did not show an attenuation effect of the vegetation along the lines, demonstrating that regardless of the distance from the main source of the element Cu concentration would not change (Fig. 4).

As demonstrated by the Kruskal-Wallis multivariate analysis, both location and season were important to differentiate the concentration of pollutants in the biomonitor plants. Cu presented a seasonal effect but did not differ along the exposure lines at each site. The location of the forests where the plants were exposed was an important factor to differentiate the concentrations of Cd, Cu and Pb in the plants. The distance of *T. usneoides* L. from the main source of pollutants (streets, avenues, and highways) showed that only Cu was not significantly attenuated (Table 3).

The NMD analysis showed that the joint variability of the data, independently of site and exposure line, separated the concentrations of Cd, Cu and Pb in the two seasons, shaping homogeneous clusters (stress

Table 3
Non-parametric MANOVA (multivariate Kruskal-Wallis) and significance to evaluate the effects of season and forest location on the variation of pollutant concentrations.

	Test	Cd	Cu	Pb
Season	Kruskal-Wallis H Probability (p)	0.902 0.342	92.378 <0.0001*	8.160 <0.0001*
Forest location	Kruskal-Wallis H Probability (p)	80.703 <0.0001*	14.517 <0.0001*	63.060 <0.0001*
Proximity to source	Kruskal-Wallis H Probability (p)	12.296 0.031*	2.338 0.801	28.039 <0.0001*

* Significant at alfa < 0.05. Cd, cadmium, Cu, copper, and Pb, lead.

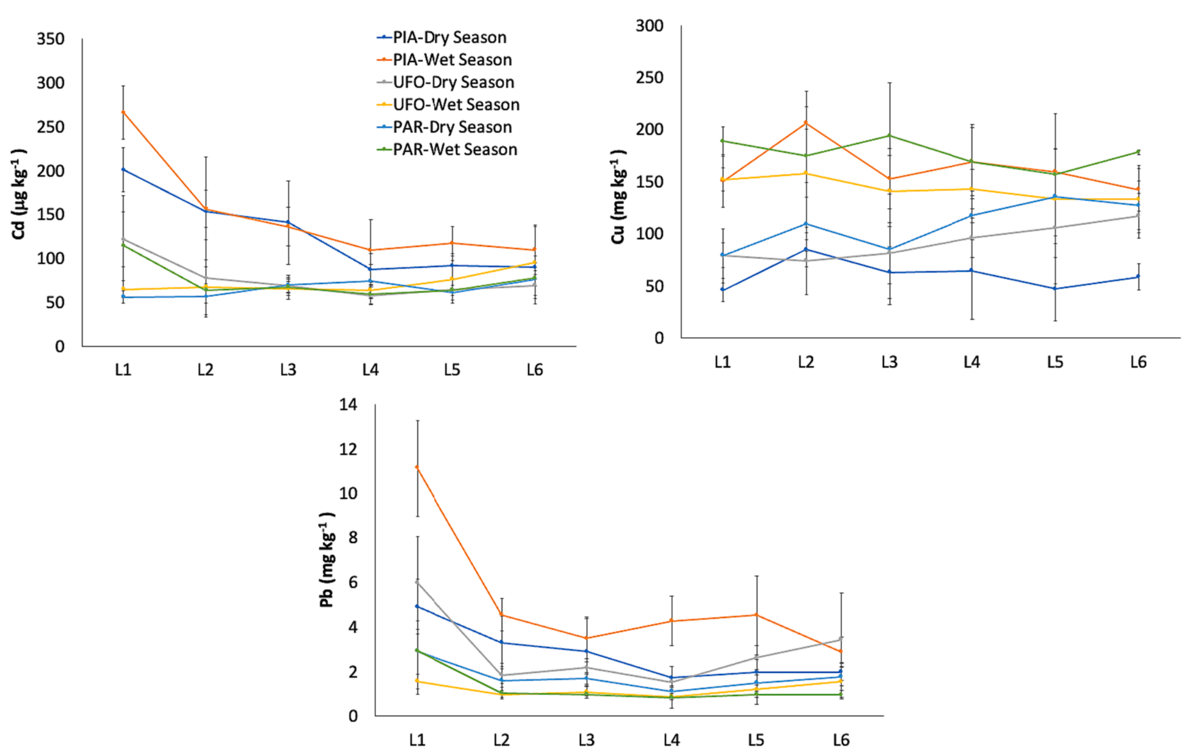

Fig. 4. The concentration of pollutants (Cd, Cu and Pb) on the biomonitor *Tillandsia usneoides* L. at various distances from the source (roads, avenues, and highways). Lines of different colors represent different locations and seasons.

<0.2). The one-way ANOSIM showed that the cluster representing the concentrations of air pollutants deposited during the dry season in *T. usneoides* L. was significantly different from the cluster of pollutants deposited in the plants during the wet season (R = 0.3359; $p < 0.001$) (Fig. 5).

The SIMPER analysis revealed the relative contribution of the main pollutants responsible for the differences observed between the stations, inferred by ANOSIM. Cu accounted for 64.34 % of the seasonal effect, Cd for 34.21 % and the remainder for the relative effect of Pb.

4. Discussion

4.1. Spatial variations of air pollution

The concentrations of the traffic-related elements Cd, Cu and Pb observed at the exposure sites, during both the dry and wet seasons, fall within the values found by other air quality biomonitoring studies with *T. usneoides* L. (Nogueira, 2006; Vianna et al., 2011; Cardoso-Gustavson et al., 2016). Cu is considered as one of the best tracers for the gasoline fleet (Vianna et al., 2011; Cardoso-Gustavson et al., 2016). However, the three study areas presented relevant numbers of light vehicle fleet running on gasoline. No significant difference was observed in Cu content, which could be strongly related to the sampling sites. Therefore, in the case of the city of Guaruja, this element could not be considered as the best tracer of air pollution. In contrast, Cu was the best tracer for the seasonal increment of air pollutants, an expected result as the city is a summer tourist site.

In addition to Cu, other traffic-related elements pose risks in terms of atmospheric pollution, such as Pb. This element has been the focus of numerous policies and actions that regulate the composition of fossil fuels, such as the Clean Air Act of 1970 in the United States (US-EPA, 2023) and the Brazilian Control Program of Air Pollution – PROCONVE (Carvalho et al., 2015). Among the noteworthy results of the latter have been the removal of Pb from gasoline and the reduction of sulfur (S). Since PROCONVE was implemented, from 1986 to 2015, pollutant emissions have been reduced by 70 % (Carvalho et al., 2015). Nevertheless, unleaded gasoline and diesel remain a source of atmospheric Pb (Nogueira, 2006; Cardoso-Gustavson et al., 2016; Chrastný et al., 2018). The presence of Pb may be associated with industrial oil processing and a by-product of fuel combustion (Chrastný et al., 2018). Hence, the quantification of Pb is normally associated with the monitoring of gasoline and diesel quality to enforce local legislation.

Regarding Cd, the results indicated a significant variation in its content when the sampling sites were compared, with the median highest values recorded in PIA (season: dry = 105.25 μg kg^{-1} and rainy = 135.48 μg kg^{-1}). The avenue that borders the PIA also borders the residential area of the Vicente de Carvalho district. Even worse, trucks enter, transit and park on the streets of this district waiting to unload commodities and thus emit tons of air pollutants, annually. Moreover, since Cd is the best marker for diesel (Coufalík et al., 2019), the highest levels of this element in PIA match those in the study of Theophilo et al. (2021). However, in their study, the Cd levels varied from 44 to 3,000 μg kg^{-1}. In our study, the critical sites corresponded to Idalino Pines Street, which is the only street with access to the cargo Port of Santos terminal.

A previous study that also supports our findings was conducted by Nogueira (2006), who analyzed the spatial distribution of Cd in the São Paulo Metropolitan Region. The regions that presented the highest Cd content (~2400 μg kg^{-1}) were Santo Andre and Mauá. Both cities are surrounded by the Mário Covas and Anchieta highways, which make up a complex infrastructure with several large roads that ease the incoming traffic of trucks traveling inland towards the Port of Santos.

For Cd and Pb, the median values of air pollution at PIA were higher than those of the other two sites. Although the medians of Cd at UFO were almost half of those found at PIA for both the dry and wet seasons (67.29 mg kg^{-1} and 63.89 mg kg^{-1}, respectively), the values were still high. Likewise, the high values at UFO may be due to the bus fleet that transits into the city, since the center is the main location for shopping and services.

The chronic situation of air pollutant emissions in important areas of Guaruja represents a risk to public health, especially to the most vulnerable populations such as children, the elderly, and people with respiratory comorbidities (Murray et al., 2020). It can threaten the financial and health management of the City Hall when considering the associated costs within the public health sector, since increased atmospheric pollution is closely related to a higher incidence of respiratory diseases (chronic non-communicable diseases), a fact that is costly to Brazilian public coffers (Nilson et al., 2020). For instance, in a survey carried out in 35 low- and middle-income countries the atmospheric concentration of particulate matter ($PM_{2.5}$) was related to an increased risk of acute respiratory infection in children less than 5 years of age (Odo et al., 2022).

Nevertheless, there are still few studies demonstrating the extent to which $PM_{2.5}$ should be reduced to significantly decrease morbidity and mortality in children of low-income countries (Schraufnagel et al., 2019). A public health dilemma caused by air pollution is the downsizing of gross domestic product of an economically active population. This scenario can be worsened by other sources of pollution, such as fires

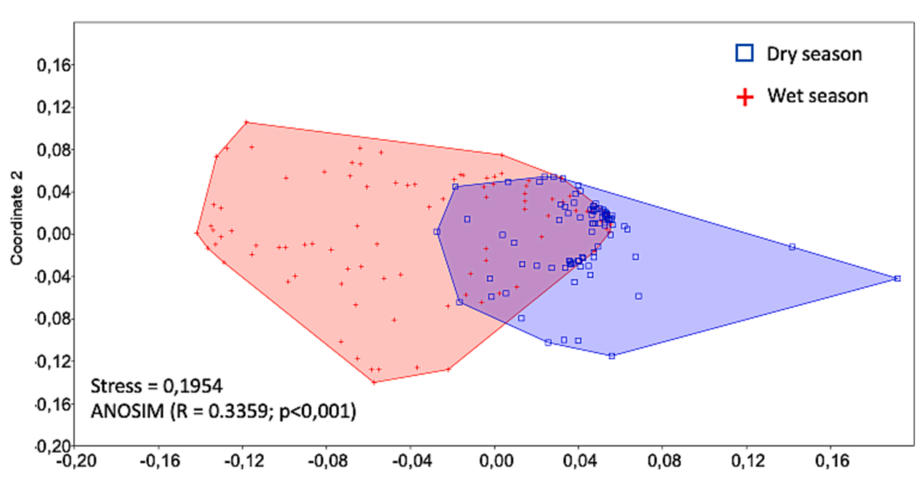

Fig. 5. Non-metric multidimensional analysis and analysis of similarity (one-way ANOSIM) to test the effect of seasons on the concentration of the pollutants Cd, Cu and Pb, independently of site, in the biomonitor plant *Tillandsia usneoides* L.

in urban forests (Ozenen et al., 202), resulting in a barrier to sustainable development (Wild, 2019) and becoming a challenge for future decades. Projections point to an increase of more than 65 % of cancer-related deaths in Latin America between 2020 and 2040 (WHO, 2020).

Furthermore, by thinking systemically about different urban issues, especially from the perspective of the challenging climate scenarios expected for the upcoming decades and SDG 11, natural landscapes with the potential to mitigate air pollution and partially solve the problem of urban drainage can still serve as environments for food production. They could act as financial vectors for economically vulnerable populations and ensure food security in the city, with less logistical problems and low emissions of air pollutants (Caputo et al., 2021). In the case of the city of Guaruja, stakeholders need to be informed about this potential to plan or re-plan public actions that require substantial investment and can result in multiple benefits (Albert et al., 2021).

As previously mentioned, the dataset obtained in this work involve three extremely heterogeneous areas in terms of socioeconomic aspects, vehicular traffic, and environmental conditions in biomonitoring exposure. Although these areas represent, to a great extent, the metropolitan reality in low-income countries, the city of Guaruja is quite large and includes many other social and environmental particularities that impose a limitation to covering the whole territory. However, our results highlight important concentrations of atmospheric pollutants associated with socioeconomic differences in the municipal territory. Such associations have been insistently requested in the context of local actions aimed at reducing social inequalities and promoting adaptive, equitable and sustainable settlements (Yang et al., 2021; Venter et al., 2023).

4.2. Temporal variations of air pollution

The observed values of Cu and Pb in our study pointed to a strong effect of seasons on the concentrations found in *T. usneoides* L study samples. In the UFO, for example, the values of Cu and Pb found during the wet season were 38 % and 52 % higher than during the dry season, respectively. This variation suggests a notable contribution from the light vehicle fleet of tourists in the cities during January and February.

Cu is a trace pollutant of light vehicles and has been widely employed in studies that evaluate the impact of vehicle fleets on air quality (Chaparro et al., 2013; Zheng et al., 2021; Morera-Gómez et al., 2021; Martins et al., 2021b). Ramon et al. (2022) observed a linear decrease of Cu concentration in sites that varied in vehicle fleet from the center to the periphery of the megacity of São Paulo, the center being the site with the highest predominance of vehicles and the periphery with the lowest density and flow of cars. Corroborating this result and the contribution of the light vehicle fleet in this urban gradient, Pereira et al. (2022) demonstrated the same linear trend from the center to the periphery of São Paulo appropriating $\delta^{15}N$ and passive NO_x samples and highlighting Cu as a tracer of light vehicles.

According to the Brazilian Institute of Geography and Statistics (IBGE)-Cidades (IBGE, 2022), the estimated population of Guaruja is 345,977. However, during the summer vacation season, there is a seven-fold increase in number of occasional residents – nearly 2.5 million people – which added to the flow of trucks represents a serious public issue, since the city is not equipped with an infrastructure capable of absorbing the sudden demand for essential services (Theophilo et al., 2021). Running a simple simulation of this total would show that for every four people there is an increase of one light vehicle in the city, resulting in more than half a million cars in Guaruja during the wet season. This abrupt increase in light vehicle fleet traffic, added to more than 3,000 trucks that access the Port of Santos daily (Guaruja. Guaruja City Hall, 2021b), leads to a complexity of urban problems, such as the intensification of air pollution which induces more adverse effects on public health. Therefore, it is noteworthy that in the case of Cu, the seasonal effect is more pronounced compared to the site where *T. usneoides* L. plants were exposed.

In addition, the plants exposed in the PAR, the area supposedly less affected by air pollution, were those that presented the highest medians in the study for Cu both in the dry and wet seasons (88.01 mg kg^{-1} and 141.5 mg kg^{-1}, respectively). This finding can be partially explained by the vehicle emissions and by singular biomonitor attributes. Cu is an essential micronutrient for plants and the values found during the dry season may be in the range of the plant's physiological needs (Abd El-Samad et al., 2017).

Urban settlements are also strongly affected by tropospheric ozone (O_3), a phytotoxic pollutant that undergoes photochemical reactions in its genesis, thus being more pronounced in the summer (wet season) (Ferreira et al., 2012; Souza et al., 2020; Souza et al., 2022a; Souza et al., 2022b). Upon entering the leaves, O_3 reacts with water forming reactive oxygen species, thus upsetting the pro-oxidant/antioxidant balance of plants and demanding greater activity on the part of antioxidant enzymes, such as superoxide dismutase and peroxidases. These defenses use Cu as an enzymatic cofactor, which may mask the effect of atmospheric deposition in the leaf trichomes of *T. usneoides* L., highlighting an indirect seasonal effect of tropospheric O_3 formation.

The NMD analysis and non-parametric MANOVA showed that regardless of the site of plant exposure and the line of plant position (i.e., road, avenue, or highway), the exposure period was fundamental to highlight the differences in concentration of the traffic-related elements in the two seasons. Regardless of the factors that operate in the seasonality of pollutants, especially Cu, the results of this study indicate that the highest concentration of the element was found during the wet season in all study areas, coinciding with the peak tourist season in the city. This finding draws attention to the need for efficient alternative mechanisms of mobility, such as bicycles, at critical times of the year, since the coastal plains have a suitable topography for this transport mode which promotes sustainability. For instance, promoting innovative programs based on smart urban design, such as "The 15-Minute City", offers diverse alternatives of sustainable transport, along with NbS approaches to establish green infrastructure, giving priority to walking and cycling (Niță et al., 2018; Khavarian-Garmsir et al., 2023). Additionally, it is mandatory to consider that such solutions should generate multifaceted benefits across various spatial scales, encompassing all regions within the city.

4.3. Critical areas eligible for NbS

Our assessment of the spatiotemporal relationship between air pollution and urban forests employing biological monitoring demonstrated that TRE contents vary according to the site and season of exposure. With specific reference to the spatial evaluation of plants, having compared the results of TREs with background values as well as considering the three urban forests, the highest concentrations of Cd, Cu and Pb were verified in the *T. usneoides* L. samples exposed in PIA, which is located in Vicente de Carvalho district, the poorest residential area of the city.

Currently, half of the residents of Guaruja live in the Vicente de Carvalho district, which has an estimated population density of 3,804 inhabitants/km^2 (IBGE, 2021). This territory consists of green areas in only 13 % of its extension (Guaruja, 2021a), representing a dramatic and unequal environmental scenario. Whereas the other half of the inhabitants live in an area with a predominance of Atlantic Forest remnants (PAR) in more than 70 % of the territory and a population density of 1,592 inhabitants/km^2 (IBGE, 2021).

According to Rakauskas (2022), who studied the contribution of heavy-duty vehicle emissions to air pollution in Guaruja, trucks using the main street to reach the port account for more than 600 units per hour. The study also indicated that the PM_{10} emitted by the fleet varied between 54 and 211 μg/m^3, which may be classified by Brazilian law as "unhealthy for sensitive groups" such as children, the elderly, and individuals with chronic obstructive pulmonary disease (CONAMA, 2018).

Our results show that the use of plants in measuring the environmental impacts caused by atmospheric pollution proved to be a sound indicator of air quality, highlighting the level of interventions required for the transport sector in the city of Guaruja. However, this environmental tool gains prominence when considering that in some low-income territories of Latin America, Africa and Asia, the coverage of high-precision technological equipment capable of measuring a wide variety of pollutants is not able to provide spatiotemporal resolutions of air pollution. As a result, knowledge of geographic coverage by reliable air quality data remains limited (Yan et al., 2011; Boer et al., 2023). In cities with high social inequality and polluted areas, the poorest population occupies empty spaces and buildings in low-income districts, which are highly vulnerable to the harmful effects of atmospheric pollution (Ferreira et al., 2017b). Thus, the cost-effective biomonitoring approach using *T. usneoides* L. enables this environmental tool to be widely used in places faced with socioeconomic challenges and limitations, providing more robust meteorological stations with reasonable spatiotemporal precision.

Therefore, considering the chemical indicators for TREs, the intense and constant vehicular flow combined with the high population in the PIA surroundings, under conditions of precarious urban infrastructure (Rakauskas, 2022), the Vicente de Carvalho district was considered a priority area for implementing NbS approaches. Hence, the planting of trees to create requalified public green spaces with high potential for urban agriculture, since food production can be an economic tool that promotes food security in urban centers (Hallett et al., 2016; Lafortezza et al., 2018; Bennedetti et al., 2023), and the economic rise of the vulnerable population to minimize social inequalities may constitute an alternative that renders aspects of urban drainage feasible – another potential for NbS approaches to achieve sustainability. The latter would be most appropriate during the wet season in addition to mitigation of air pollution, which is paradoxically more intense in the heaviest wet season of the year.

Certain plant species with specific leaf morphologies are more suitable for afforestation in critical zones with high levels of PM and may be more efficient in attenuating atmospheric pollutants. *Acer campestre* L., Betula pendula Roth, *Carpinus betulus* L. and *Salix alba* L. were used in Dortmund (Germany) and showed high potential for PM removal; i.e., *S. alba* was able to remove up to 3.8±0.4 μg cm^{-2} of leaf unit area of $PM_{0.2–10}$ (Ristorini et al., 2023). These authors showed a similar experimental trend using i-Tree Eco, although the software underestimated the values obtained by scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy. Along this line of investigation, Prigioniero et al. (2021) carried out a broad literature review on the role of NbS as tools for air phytoremediation and presented a database with 413 species belonging to 240 genera and 98 different families. Among the tree species, *Robinia pseudoacacia* L., *Tilia chordata*, Mill., *Ficus* spp and *Quercus* spp were the most employed. The families Moraceae and Fabaceae were the most recurrent in the studies reviewed.

The city of Guaruja is a biodiversity hotspot and presents mega biological diversity, which allows a wide variety of native taxonomic groups to be employed in urban afforestation and partially mitigates vehicle fleet emissions. Native evergreen species with rough leaf types (enabling greater adsorption to atmospheric pollutants) and roots suitable for sidewalk planting, which are easily found in seedling nurseries are: *Clethra scabra* Pers. (Clethraceae); *Pleroma arboreum* Gardner (Melastomataceae); *Pleroma fothergillii* (Schrank et Mat. ex DC.) Triana (Melastomataceae); *Pleroma mutabile* (Vell.) Triana (Melastomataceae); *Pleroma raddianum* (DC.) Gardner (Melastomataceae); *Bathysa australis* (A.St.-Hil.) K.Schum. (Rubiaceae) and *Styrax acuminatus* Pohl (Styracaceae). All these plant taxa can enhance the mitigation of air pollution in Guaruja and, if well distributed throughout the territory, can provide a wide variety of ecosystem services in addition to the air pollution mitigation; i.e., attenuation of urban heat islands, pollination and maintenance of fauna (Marando et al., 2019; Llodra-Llabrés and Carinanos, 2022).

The increase of green areas by specific tree enrichment and the requalification of empty urban spaces through the adequate management of trees with mitigating potential are NbS strategies that promote public health and restore dignity to the inhabitants of the poorest district of Guaruja. The relative low cost of implementing this green infrastructure associated with savings in the health sector is an economic mechanism that justifies the wide use of this NbS in the Vicente de Carvalho district and other economically vulnerable territories. Furthermore, the expansion of urban green areas can increase the city's tourist potential, as well as contribute to thermal comfort (Degerli and Çetin, 2022).

4.4. The benefits of NbS implementation

Although many political decisions are taken in the personal interest of decision-makers, scientific research plays a fundamental role in the construction of effective models that contribute to the improvement of society and the wellbeing of the population. It is noteworthy that Theophilo et al. (2021) and the results of the present study have been providing the public management of Guaruja with information regarding the city's strategic environmental plans and decisions on the direction of public policy. Both scientific studies have informed the municipality of the critical areas in Guaruja regarding urban mobility, vehicle fleet emissions and port activities adjacent to the residential area. Based on Theophilo's (2021) conclusions and our results, a report of the findings was drafted and communicated to policymakers and the Public Prosecutor. The latter required that the City Hall strike an agreement with the administration of the port region whereby both parties are committed to enhancing urban afforestation in the Vicente de Carvalho district, promoting a natural alternative for the mitigation of air pollution and public health issues.

The pilot project for NbS strategy may be considered as a pioneer case in the state of São Paulo, strengthening an area that lacks basic health services and faces serious economic and social challenges. Food security policies aimed at these afforested urban spaces may be applied in the future as a vector for local economic development (Beneddetti et al., 2023). Such actions are aligned with the 2030 Agenda, especially SDGs 3, 11 and 13, which is also a target to be reached by the Municipal Environment Secretariat of Guaruja (SEMAM) and other municipal actors. Target 11.6 of SDG11 advocates for the reduction of negative *per capita* environmental impact of cities, with particular attention to air quality. The city of Guaruja as well as those settlements of signatory countries of the 2030 Agenda with medium or high human density must seek efficient mechanisms to meet this goal. The NbS proposed in this study is an example that can be economically replicated in low-income cities, since the cost-effectiveness of this methodology enables its application.

Another political development arising from these scientific works has been the elaboration of the Atlantic Forest Municipal Plan. This public instrument is aimed at mapping all green spaces in the municipal territory to select priority areas for conservation and points to the creation of ecological corridors crossing the gray matrix of the city. The corridors would serve as urban green spaces to mitigate pollution emitted by the light vehicle fleet that circulates in the city's core areas. Furthermore, PAR is considered a biodiversity hotspot and is home to a vast biological diversity. CNCFlora recently published a report on a newly discovered species of Myrtaceae, *Myrcia guarujana* (Sobral et al., 2016), emphasizing the vocation of forests for conservation and not urban development.

Although the biomonitoring of air quality with *T. usneoides* L. has pointed out strategic places to implement NbS, our results have led to political consequences for the city of Guaruja to minimize its urban contrasts, especially in relation to the democratization of green spaces. The implementation of the above-mentioned policies produced environmental and social benefits, especially in the field of public health. Therefore, combining the cost-effective approach of biomonitoring using *T. usneoides* L. with the enrichment of urban green areas became a relevant NbS for a territory that historically records the worst indicators of poverty. Thus, considering that the political class has taken over the concept of NbS in public management, it can be expected that strategies that combine social, economic, and environmental aspects will be more recurrent in the territory, seeking greater urban equity and resilience for cities.

5. Conclusions

The overarching goal of our study is to demonstrate the spatiotemporal concentration of air pollution and the role urban forests play towards its mitigation. For this purpose, we used an effective low-cost protocol, namely biomonitoring by means of the plant species *Tillandsia usneoides* L., to quantify chemical compounds commonly related to traffic and to assess NbS strategies for public action. The spatial variability of atmospheric pollution was made evident by a high socioeconomic contrast mainly affecting the poorest population inhabiting the least green region of the territory. The study results of the traffic-related elements in Guaruja showed that seasons resulted as the most relevant parameter to be considered for the atmospheric input of Cu, since this element is one of the most efficient tracers of gasoline and is commonly used to evaluate the adverse effects of light vehicle fleet emissions. Lead levels along with quantitative data were determined to contribute to the Brazilian Control Program of Air Pollution, which since 1986 has prohibited the addition of this metal in diesel and gasoline. We demonstrated efforts toward strengthening the socio-environmental governance system, targeting the surroundings of an economically vulnerable population, to strike a critical balance between the two integrated systems – social and ecological.

In terms of advocating for NbS implementation in public policy, the significant value of this study lies in emphasizing the effectiveness of biological monitoring of air pollution and the consequent expansion of urban green areas with mitigation potential. The engagement of the political class to incorporate the concept of NbS in public action is an outstanding measure that highlights the multiplier capacity of this concept in future strategies and policies to be elaborated and/or implemented. Finally, this ambition is in line with the 2030 Agenda established in different spheres of power and falls within the scope of sustainable action and management of the city of Guaruja, which can be replicated in other territories with high social vulnerability and socioeconomic contrasts.

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.

Acknowledgments

Maurício Lamano Ferreira wishes to thank the São Paulo State Foundation (FAPESP) for grant No. 2019/24325-2. Andreza Portella Ribeiro thanks FAPESP for grant No. 2020/05383-9 and the National Council for Scientific and Technological Development (CNPq) for grant CNPq No. 17071/2021-1.

Terminology

NbS – Nature-based Solutions are actions to protect, sustainably manage, and restore natural and modified ecosystems that address societal challenges effectively and adaptively, simultaneously benefiting people and nature. (https://www.iucn.org/our-work/nature-based-solutions)

Income groups (High/Medium/Low-income countries) – Economies are currently divided into four income groupings: low, lower-middle, upper-middle, and high. Income is measured using gross national income (GNI) per capita, in U.S. dollars, converted from local currency using the World Bank Atlas method. Estimates of GNI are obtained from economists in World Bank country units, and population size is estimated by World Bank demographers from a variety of sources, including the UN's biennial World Population Prospects. (https://datahelpdesk.worldbank.org/knowledgebase/articles/378834-how-does-the-world-bank-classify-countries)

Climatic seasons (wet and dry) – The annual precipitation cycle features distinct wet and dry seasons between the equator and 25°S. Many areas within that region receive more (less) than 50 % (5 %) of their total annual precipitation during the austral summer (winter). The peak of the rainy season in southeastern Brazil occurs from December through February (Marengo et al., 2012).

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