Revista Brasileira de Ciências Ambientais
Brazilian Journal of Environmental Sciences

$PM_{2.5}$ removal by urban trees in areas with different forestry conditions in São Paulo using a big-leaf modeling approach

Remoção de $MP_{2,5}$ por árvores urbanas em áreas com diferentes condições de arborização em São Paulo, utilizando um modelo big-leaf

Christianne Nascimento Brito[1], *Luciana Varanda Rizzo*[1]

ABSTRACT

Air pollution is one of the main environmental problems in megacities, such as the metropolitan area of São Paulo (MASP), in Brazil. Urban forests can alleviate air pollution by providing a surface for the dry deposition of particles and trace gases. To benefit from this environmental service and design future green structures, it is crucial to estimate the removal rate of air pollutants by trees. The removal rates of fine particulate matter ($PM_{2.5}$) by urban trees were quantitatively assessed for the first time in Brazil. A big-leaf modeling approach was adopted, using the i-Tree Eco software. In situ dendrometric data, hourly $PM_{2.5}$ concentrations, and meteorological variables were used as inputs to the model. $PM_{2.5}$ removal fluxes ranged between 0.06 and 0.21 g/m^2/year in three study areas with contrasting urban forestry conditions. The neighborhood with the greatest canopy cover and tree diversity had the highest removal rates. The evergreen character of the urban forest in the MASP possibly contributed to the relatively high $PM_{2.5}$ removal fluxes, as compared to other cities around the world. Removal rates were higher in the austral summer, when high precipitation rates restricted the resuspension of deposited particles back to the atmosphere. When extrapolated to the whole metropolitan area, assuming homogeneous forestry conditions, the estimated $PM_{2.5}$ removal rates were comparable to the magnitude of vehicular emissions, showing that air pollution removal by trees can be substantial in the MASP. The results demonstrate the contribution of urban trees to the improvement of air quality and can boost the development of public policies on urban afforestation in the MASP.

Keywords: air quality; ecosystem services; fine particulate matter; green infrastructure; urban forestry.

RESUMO

A poluição do ar é um dos problemas ambientais mais proeminentes em megacidades como a área metropolitana de São Paulo (AMSP). Árvores podem contribuir para a mitigação da poluição do ar proporcionando superfície para a deposição de partículas e gases traço. Para melhor aproveitar esse serviço ambiental e planejar futuras infraestruturas verdes, é fundamental estimar as taxas de remoção de poluentes por árvores. Pela primeira vez em uma cidade brasileira, foi quantificada a taxa de remoção anual de material particulado fino ($MP_{2,5}$) por árvores urbanas. Para isso, foi utilizado o modelo i-Tree Eco, do tipo "folha grande". Como entrada, foram utilizados dados dendrométricos locais, de concentração de $MP_{2,5}$ e de variáveis meteorológicas. As taxas de remoção de $MP_{2,5}$ variaram entre 0,06 e 0,21 g/m^2/ano em três áreas de estudo com condições de arborização contrastantes. A vizinhança com maior cobertura de dossel e diversidade de espécies arbóreas apresentou a maior taxa de remoção. O caráter perene da floresta urbana na AMSP pode ter contribuído para as taxas de remoção relativamente altas em comparação com outras cidades do mundo. A remoção foi maior no verão; a precipitação restringiu a ressuspensão de partículas para a atmosfera. Extrapolando-se os resultados para toda a área metropolitana, supondo condições de arborização homogêneas, verificou-se que a remoção de $MP_{2,5}$ pela vegetação poderia compensar as emissões veiculares desse poluente, demonstrando o potencial de remoção de poluentes pela floresta urbana na AMSP. Os resultados ilustram a contribuição das árvores urbanas para a melhoria da qualidade do ar e podem impulsionar políticas públicas de arborização na AMSP.

Palavras-chave: qualidade do ar; serviços ecossistêmicos; material particulado fino; infraestrutura verde; arborização urbana.

[1]Departamento de Ciências Ambientais, Universidade Federal de São Paulo – São Paulo (SP), Brazil.
Correspondence address: Luciana Varanda Rizzo – Rua São Nicolau, 210 – Centro – CEP: 09913030 – Diadema (SP), Brazil. E-mail: lrizzo@unifesp.br

Conflicts of interest: the authors declare no conflicts of interest.
Funding: none.
Received on: 09/16/2022. Accepted on: 11/09/2022.
https://doi.org/10.5327/Z2176-94781458

Introduction

Air pollution is one of the most important environmental problems in megacities (Gómez Peláez et al., 2020), along with water, waste and sanitation problems, and heat island effects (Li et al., 2019). The metropolitan area of Sao Paulo (MASP), in Brazil, is not an exception. With 21 million inhabitants, the MASP is a node in the global system of finance and trade, being considered a global city (Parnreiter, 2019). Economic development associated with insufficient policies on public transportation, habitation, and urban planning resulted in the depletion of green spaces and chronic traffic jams, leading to air quality deterioration. Vehicles are the main source of air pollutants in the MASP (Andrade et al., 2017), accounting for 73% of hydrocarbon emissions and 37% of fine particulate matter ($PM_{2.5}$) emissions (CETESB, 2020). The vehicle fleet in the MASP is fueled by a blend of gasoline and biofuels, resulting in peculiar atmospheric chemistry conditions that favor the production of secondary particulate matter from hydrocarbons (Salvo et al., 2017). Annual averages of $PM_{2.5}$ concentrations in the MASP typically range between 15 and 23 μg/m^3, above the air quality guideline of the World Health Organization of 10 μg/m^3 (Gómez Peláez et al., 2020). The health impacts of $PM_{2.5}$ are demonstrated in the literature, being associated with respiratory and cardiovascular diseases (Pope & Dockery, 2006; Liu et al., 2019).

Urban forestry can be useful to mitigate air pollution by $PM_{2.5}$, providing surface area for dry deposition of particles over leaves, branches, and stems. The physical process of PM dry deposition depends strongly on particle size. Gravitational settling is the dominant process for the deposition of supermicrometer particles, while fine mode particles are removed from the atmosphere mostly by turbulent diffusion (Seinfeld and Pandis, 2006). The process of dry deposition includes the following three steps:

- particles are transported to the vicinity of the leaves' surface, enduring the so-called aerodynamic resistance;
- particles cut across the laminar layer adjacent to the surface;
- particles adhere to the leaves' surface depending on particle physical and chemical properties and leaf morphology (Janhäll, 2015).

Morphological attributes of tree leaves and crown influence PM removal. The presence of trichomes and cuticle waxes is associated with a higher $PM_{2.5}$ removal capacity (Gaglio et al., 2022).

Green infrastructures including street trees, vegetation barriers, and green roofs have been used as a potential solution for air quality improvement in many cities across the world (Abhijith et al., 2017; Han et al., 2020). For example, a study in 86 Canadian cities evaluated air quality improvement and avoided incidences of health effects associated with $PM_{2.5}$ removal by urban trees (Nowak et al., 2018). Different configurations of roadside green infrastructure have shown reductions in $PM_{2.5}$ concentrations in the range of 15–20% (Abhijith and Kumar, 2019; Donateo et al., 2021). Wind tunnel experiments have shown that selected tree species efficiently remove ultrafine particles from diesel exhaust (Wang et al., 2019).

The design of green interventions in urban areas must consider the built environment geometry, wind flow patterns, and vegetation characteristics like plant height, crown porosity, and proximity to air pollution sources, particularly in street canyons (Janhäll, 2015; Kumar et al., 2019). Particularly, it is important to avoid large trees in street canyons, since they restrict air pollution dispersion and may lead to an unsought concentration increase (Abhijith et al., 2017). In addition to air pollution abatement, urban vegetation can provide other ecosystem services, like urban heat island mitigation, flooding mitigation, and improvement of people's quality of life (Livesley et al., 2016; Moreira et al., 2020).

Changes in air pollution exposure associated with green interventions in urban areas have been assessed by field measurements, wind tunnel laboratory experiments, and model studies (Abhijith et al., 2017). Two modeling approaches have been widely used in the literature to estimate PM removal rates by trees: big-leaf models, which are based on a simplified one-dimensional deposition process representing the vegetation by a single leaf surface, and computational fluid dynamics (CFD), which are based on the fundamental laws of fluid mechanics and thermodynamics (Lin et al., 2019). Recently, coupled modeling frameworks using regional atmospheric transport models and big-leaf models have been applied to estimate dry deposition of air pollutants onto urban trees (Cabaraban et al., 2013). While field, laboratory, and CFD modeling studies provide a detailed picture of air pollutant and vegetation interactions in the microscale, the big-leaf modeling approach is suitable to assess air pollution removal rates by urban forests on a regional scale. In such models, dry deposition rates are estimated based on observations of tree cover, vegetation characteristics like leaf area index (LAI), surface meteorological conditions, and air pollutant concentrations, assuming typical or parameterized dry deposition velocities (Hirabayashi et al., 2012). The big-leaf models do not account for the combined effects of vegetation and urban structures on wind flow and atmospheric dispersion. Even though, model estimates are a valuable tool to assess differences in the air pollution removal between cities (Hirabayashi and Nowak, 2016) and between neighborhoods within a city (Yang et al., 2005; Escobedo and Nowak, 2009). They are also useful to identify scenarios in which increased vegetation cover and multiple green infrastructure designs could improve the air quality (Jayasooriya et al., 2017; Wu et al., 2019).

Most studies on the relationships between air quality and urban vegetation were conducted in North America and Asia (Arantes et al., 2019; Lin et al., 2019). In Brazil, the few existent studies on the subject investigated eco-toxicological effects of particulate matter on urban vegetation and biomonitoring (Locosselli et al., 2018, 2019; Ramon et al., 2022), without providing a quantitative assessment of air pollution removal rates. The main contribution of this study is to provide the first quantitative estimate of air pollution removal rates by the urban vegetation in a Brazilian megacity. South American cities are underrepresented in the literature (Arantes et al., 2019; Lin et al., 2019), even though the predominance of evergreen tree species in tropical and subtropical cities may result in substantial air pollution removal. MASP is a singular urban area to investigate air pollution removal by vegetation, since it combines remnants of the Atlantic rainforest, subtropical humid conditions, and peculiar atmospheric chemistry conditions associated with the broad use of biofuels, influencing air pollution production and emission.

The main objective of the this study was to estimate the $PM_{2.5}$ removal by urban trees in three neighborhoods with contrasting tree cover and similar air pollution burden in the MASP using a modeling approach. The comparison of areas within the same metropolitan region is innovative, since most previous studies have provided air pollution removal rates for entire cities (e.g., Hirabayashi and Nowak, 2016; Parsa et al., 2019), disregarding the spatial heterogeneity of urban forestry conditions. The removal rates estimated for a gradient of tree cover can be interpreted as lower and upper limits for air pollution removal at the MASP. The relevance of $PM_{2.5}$ removal rates was assessed through a comparison with other cities in the world and with vehicular emission rates. To the best of our knowledge, this is the first quantitative estimate of air pollution removal by urban trees in a Brazilian city. The results of this study can support the design of future urban green infrastructures in cities where evergreen species predominate.

Materials and Methods

Study areas and sample design

The MASP spreads through 8047 km^2 and sits in the southeast of Brazil, in a 760 m plateau region, 70 km distant from the Brazilian South Atlantic coast (Figure 1). According to Koppen's classification, the MASP's climate can be classified as subtropical humid (Cwa type) (Alvares et al., 2013). Winter is characterized by dry and mild cold conditions, with monthly mean temperatures around 15°C and mean precipitation of 50 mm/month in July. The summer in the MASP is typically wet and warm, with monthly mean temperatures around 22°C and precipitation in the range 223–237 mm/month in January (Piñero Sánchez et al., 2020).

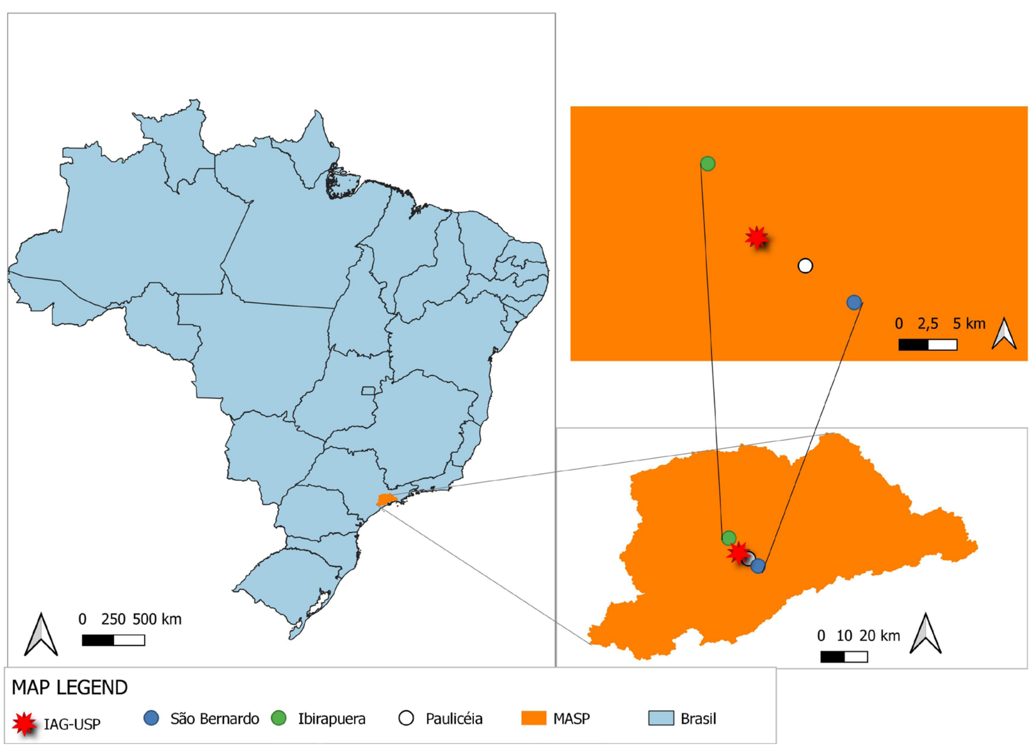

Figure 1 – Limits of the metropolitan area of São Paulo (MASP) in Brazil, location of the three study areas (Ibirapuera, São Bernardo, and Paulicéia) and the IAG-USP meteorological station. The distance between the sites is in the range of 5–17 km.

Three study areas with contrasting urban forestry conditions were selected in the MASP. The Ibirapuera study area (Figure 2A) has 76% of its domain inside the homonymous inner city park, surrounded by a residential area. The São Bernardo study area is a mosaic of residential and commercial zones, containing street trees, public squares, and recreational areas (Figure 2B). The Paulicéia study area (Figure 2C) is mostly residential, with isolated street trees, a few gardens, and a great proportion of impervious surfaces. The distance between the study areas, which are located in the center and southeast of the metropolis, ranges between 5 and 17 km (Figure 1). Therefore, they are subjected to the same climate conditions. All study areas are impacted by vehicular emissions, with similar air pollution burdens, as reported in previous studies (Silva et al., 2021). The MASP fleet reached 7.3 million vehicles in 2019 (CETESB, 2020).

The study areas had 78 ha each and were designed as a 500-m-radius circle around air quality monitoring stations managed by the CETESB state environmental agency (Figure 2). Because of this design, the in situ dendrometric measurements were conducted within the footprint of the air quality monitoring stations. This is important to prevent spatial biases related to the usage of air pollution data that are not representative of the tree's immediate environment (Szkop, 2020). It is important to point out that the three study areas are not intended to represent the whole metropolitan area.

A sample inventory was chosen to characterize the urban forest in each study area, with plots randomly picked. The i-Tree Eco standard plot area of 404.68 m^2 was adopted (Hirabayashi et al., 2015). The sampling effort was determined based on the rarefaction curve method with bootstrap resampling (Engemann et al., 2015). Rarefaction curves with an increasing number of plots were built for the variables canopy cover and leaf area. Stabilization of the rarefaction curves determined the sufficient number of plots in each study area: 55 plots in Ibirapuera, 60 plots in São Bernardo, and 55 plots in Paulicéia. This resulted in sampling intensities in the range of 2.8–3.1%.

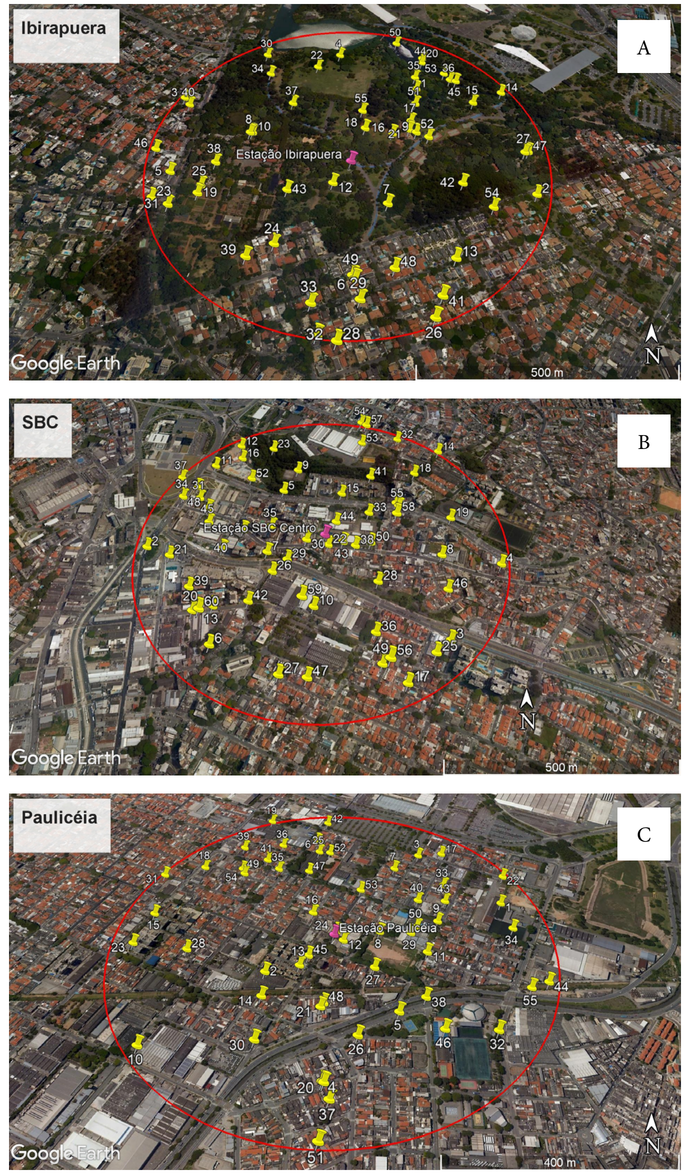

Figure 2 – Limits of the three study areas within the MASP (red circles): (A) Ibirapuera (23°35'14"S, 46°39'27"W), (B) São Bernardo (23°41'54"S, 46°32'46"W), and (C) Paulicéia (23°40'13"S, 46°35'04"W). The red pin shows the location of the CETESB air quality monitoring station. The yellow pins show the location of random plots where dendrometric field data were collected.

Field observations and third-party data

A modeling approach was used to estimate the $PM_{2.5}$ removal rates in the study areas, using the software i-Tree Eco. As input, the software requires data on the urban forest characteristics, air pollutant concentrations, and meteorological conditions (Table 1). This was provided by a combination of in situ observations and third-party data, as described in the following.

Field data collection was performed between June 2020 and April 2021. Most tree species are evergreen, without relevant seasonal variations on leaf area. A smartphone equipped with a GPS (Global Positioning System) and the i-Tree Eco Mobile app was used to register dendrometric parameters for each sampled tree. Only trees and wooden shrubs were considered. Three classes of information were collected in the field: study area, plot area, and individual tree information (Table 1). Tree information included species identification, crown geometry, diameter at breast height (DBH), tree light exposure, and crown conditions related to dieback and pruning.

Third-party data on atmospheric conditions were acquired for the year 2016. This year was chosen because it was the most recent in the i-Tree Eco database. We assume that the overall characteristics of the urban forest did not change significantly from 2016 to 2020, when dendrometric data were collected. In situ dendrometric data, air pollution data, and precipitation data must be submitted to the software developers in advance, so that all the input data are ultimately dependent on the i-Tree Eco database. Hourly data on $PM_{2.5}$ concentrations were acquired from the air quality data platform Qualar (CETESB, 2022), maintained by the CETESB state environmental agency. The typical $PM_{2.5}/PM_{10}$ ratio of 60% in the MASP (CETESB, 2008) was assumed in the case of the Paulicéia study area, since only PM_{10} measurements were available. Recent data from the CETESB air quality monitoring stations at Parque Dom Pedro and São Caetano in the year 2019 confirm that the 60% ratio of $PM_{2.5}/PM_{10}$ remained constant over time and in different parts of the MASP. Hourly precipitation data were provided by the IAG/USP meteorological station at the Universidade de São Paulo (23.6 S, 46.6 W). The distance between the sites and the IAG/USP weather station ranged from 5 to 10 km. Previous studies have shown the homogeneity of precipitation records at the IAG/USP station on the spatial scale so that they are representative of the whole MASP (Sugahara et al., 2012). Data on atmospheric conditions were sent to the i-Tree Eco database 6 months prior to the model runs. Data submission is necessary only for countries outside the USA and Canada.

i-Tree Eco model calculations

The removal rates of $PM_{2.5}$ by the urban trees were calculated using the i-Tree Eco version 6.0 software. The model estimates hourly dry deposition of $PM_{2.5}$ and other atmospheric pollutants like O_3, SO_2, NO_2, and CO. In addition, the software can evaluate many other ecosystem services provided by urban trees, such as carbon sequestration and avoided runoff (Hirabayashi et al., 2012). Considering the availability of air pollution data in the study areas, this research focused on the evaluation of $PM_{2.5}$ removal by urban trees.

As input, the software uses hourly data of in situ observations of air pollutant concentrations and meteorological conditions. In the case of projects located outside the USA and Canada, atmospheric data must be submitted to the i-Tree Eco team in advance. The i-Tree Eco also requires information about the urban forest at each site, such as individual tree properties and land use. A sampling inventory was performed to gather the necessary information about the urban forest at the three study areas. Based on dendrometric data collected at random plots, the software upscales the information of the whole study area by averaging the plots. With that, the software is able to estimate average properties of the urban forest like canopy cover and leaf area (Table 1).

The dry deposition flux of $PM_{2.5}$ (f) is calculated as the product between deposition velocity (V_d) and concentration (C) at each hourly time step (t) (Equation 1):

$$f(t) = V_d\,(t).\,C(t) \qquad (1)$$

in units of g/m²/h. $PM_{2.5}$ concentration was measured in situ, while the deposition velocity was based on the average of reference values for 17 tree species, considering classes of wind speed between 1 and 10 m/s and the LAI derived from field observations (Hirabayashi et al., 2015). Therefore, the information on tree species is used in combination with crown geometry solely to derive the LAI at each site. This is a limitation of the model, since particle deposition velocity may vary with tree species (Gaglio et al., 2022). The model assumes that a percentage of the material deposited on the leaves can be resuspended back into the atmosphere by the action of winds. The flux of resuspended $PM_{2.5}$ (R) is calculated in units of g/m²/h as follows (Equation 2):

$$R(t) = [A(t-1) + f(t)].\frac{rr(t)}{100} \qquad (2)$$

Where:
$A(t-1)$: flux of PM_{25} accumulated on leaves at the previous time step;
$rr(t)$: the percentage resuspension rate at time t.

The resuspension rate is a function of wind speed, ranging between 0 and 23%. Finally, the net removal flux of $PM_{2.5}$ (F_{net}), accounting for dry deposition and resuspension processes, is calculated as follows (Equation 3):

$$F_{net}\,(t) = f(t) - R(t) \qquad (3)$$

Instantaneous values of the net removal flux are usually positive ($f > R$) so that deposition overcomes resuspension. Occasionally, when the wind speed is high, resuspension can exceed the dry deposition flux, so that F_{net} can be momentaneously assumed to be negative values. In addition to the winds, precipitation also plays an important role in the model estimates.

Table 1 – List of field observations collected for the entire study areas, for each plot and tree. Atmospheric conditions were provided by the CETESB environmental agency and the meteorological station of IAG/USP. Based on the in situ observations, the i-Tree Eco model estimated the mean characteristics of the urban forest at each study area.

Information type	Field observations	Third-party data	Estimated quantities (i-Tree Eco)
Study area information	Location. Land use. Evergreen conditions.	–	Canopy cover. Leaf area. Leaf area index. Number of trees. Density of trees. $PM_{2.5}$ net removal rates.
Plot information	Location. Land use. Tree cover. Number of trees. % of impervious surface.	–	Canopy cover. Leaf area.
Tree information	Species. DBH. Height. Crown dimensions. % of missing crown. % of crown dieback. Light exposure.	–	Crown volume.
Air pollution conditions	–	Hourly $PM_{2.5}$ concentrations	–
Meteorological conditions	–	Hourly wind velocity and precipitation	–

The software assumes that $PM_{2.5}$ gradually accumulates on leaves and is washed off by precipitation. That is when the particulates are effectively removed from the atmosphere and are carried to the ground. During drought periods, the deposited particles are subjected to resuspension, going back and forth between atmosphere and leaves, resulting in low values of F_{net}. A recent study has shown that the i-Tree Eco estimates for the net deposition flux of particles are compatible with micrometeorological in situ observations at an urban Mediterranean forest (Pace et al., 2021).

One of the limitations of the big-leaf modeling approach is that the model does not account for the spatial distribution of the urban green structures relative to the location of the air pollution emission sources. In addition, it does not consider the impacts of the vegetation and of the urban structures on the local scale of wind circulation. Tall vegetation with closed canopies can reduce air pollutant dispersion, leading to air quality deterioration, especially in street canyons (Abhijith et al., 2017). Another limitation is that air pollutant removal by bushes and grasses was not accounted for in this study, so that the calculated $PM_{2.5}$ removal rates can be underestimated.

Results and Discussion

Structure of the urban forest in the study areas

Table 2 summarizes the main characteristics of the urban forest in each study area. There is a clear gradient of canopy cover, from 12.6% at Paulicéia to 64.2% at Ibirapuera. The latter has 76% of its domain inside a park, with a density of 111 trees per hectare and a relatively closed canopy. Considering that 59% of the Ibirapuera study area is located within the park, the estimated canopy cover (64.2%) and the estimated number of trees (5,079) are compatible with the Forestry Inventory of the Ibirapuera Park (70% and 5,650 trees, respectively) (Kabashima et al., 2019).

Among the three study areas, the Ibirapuera area has the most heterogeneous urban forest, with a relatively large amplitude of DBH values (Figure 3). Ibirapuera has trees in all DBH and succession classes, similar to natural forests. On the contrary, large trees predominate at Paulicéia, with 50% of the trees having a DBH greater than 45 cm. In this way, the low tree density at Paulicéia is somewhat compensated by large crown volumes. DBH distribution at São Bernardo is concentrated in the range of 15–45 cm (50% of the trees), with only 10% of trees having DBH above 60 cm.

The urban forest at the study areas comprised native and exotic trees. South American native trees comprised 46, 39, and 74% of tree species, respectively, at Ibirapuera, São Bernardo, and Paulicéia. Most exotic tree species have the Asian continent as their origin. A limited number of species were identified, when compared to the Atlantic rainforest in the state of São Paulo (Caiafa and Martins, 2010): 54, 30, and 14 tree species at Ibirapuera, São Bernardo, and Paulicéia, respectively. Increasing the diversity of trees in urban areas can mitigate the impacts of plagues and diseases (Raupp et al., 2006). However, the introduction of exotic species characterized as invasive plants threatens the conservation of native plants, competing for space and resources. Exotic invasive plants usually do not have natural competitors, so that they spread and dominate the environment, threatening the reproductive success of native plant species, endangering plant-animal interactions, and ultimately spoiling the maintenance of biodiversity (Zenni and Ziller, 2011; Silva et al., 2020).

Table 3 lists the four most frequent tree species observed in each study area, as well as their contribution to the total leaf area. Ibirapuera showed the greatest diversity of species, with *Ligustrum japonicum* and *Tipuana tipu* being the most frequent, contributing to 26% of the total leaf area. At São Bernardo, the predominant tree species were *Caesalpinia peltophoroides* (15.1%) and *L. japonicum* (12.1%), comprising 34% of the total leaf area. The urban forest at Paulicéia showed the lowest diversity, with 34.8% of trees of a single species, *T. tipu*, comprising 42.2% of the total leaf area.

Table 2 – Main characteristics of the urban forest at the three study areas, estimated by the i-Tree Eco software based on field observations.

	Ibirapuera	São Bernardo	Paulicéia
Area (ha)	78	78	78
Number of plots	55	60	55
Plots without trees (%)	7.3	33.0	56
Estimated number of trees	8,608	3,756	811
Estimated tree density (trees/ha)	111	48	10
Estimated canopy cover (%)	64.2	20.4	12.6
Estimated canopy cover (ha)	50.11	15.94	9.82
Estimated leaf area (ha)	82.69	17.27	6.94

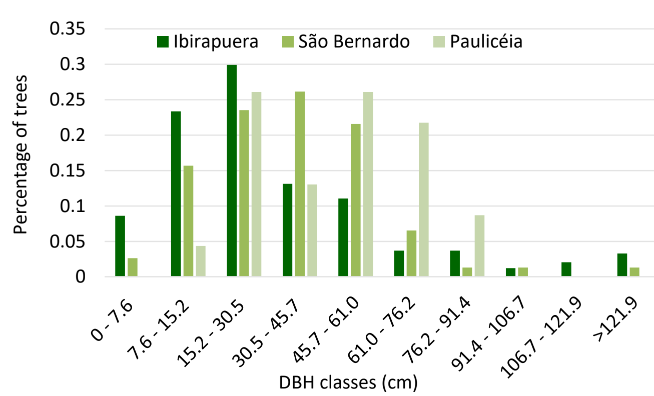

Figure 3 – Distribution of trees by DBH classes for each study area.

Table 3 – Dominant tree species at each study area and corresponding percentage contribution to the tree population and leaf area.

Study area	Species	Family	Leaf area (%)	Population (%)
Ibirapuera	*Tipuana tipu* (Benth.) Kuntze	Fabaceae/Faboideae	16.5	6.1
	Ligustrum japonicum Thunb.	Oleaceae	9.5	10.2
	Ficus sp. (gênero)	Moraceae	7.5	0.4
	Eucalyptus globulus Labill.	Myrtaceae	5.8	1.6
São Bernardo	*Caesalpinia pluviosa* variedade *peltophoroides*	Fabaceae/Caesalpinioideae	21.1	15.1
	Pinus elliottii Engelm.	Pinaceae	19.0	8.3
	Ficus macrocarpa L.f. 1782	Moraceae	18.7	7.3
	L. japonicum Thunb.	Oleaceae	12.9	12.5
Paulicéia	*T. tipu* (Benth.) Kuntze	Fabaceae/Faboideae	42.2	34.8
	C. pluviosa variedade *peltophoroides*	Fabaceae/Caesalpinioideae	18.5	13.0
	Ceiba pentandra (L.) Gaertn.	Malvaceae	15.3	8.7
	L. japonicum Thunb.	Oleaceae	11.0	4.3

Removal of $PM_{2.5}$ by the urban forest

Based on dendrometric field data, air pollution, and meteorological conditions, the i-Tree Eco model calculated the hourly $PM_{2.5}$ removal flux by trees at the three study areas. Hourly removal data were integrated over the year 2016 and over the 78 ha of each study area, resulting in 165, 112, and 51 kg/year of $PM_{2.5}$ removed by the trees at Ibirapuera, São Bernardo, and Paulicéia, respectively (Table 4). Table 4 shows that $PM_{2.5}$ concentrations were similar at the three study areas. Considering that the meteorological conditions are similar because the stations sit relatively close to each other (distances in the range of 5–17 km), differences in the removal rates may be attributed to the contrasting characteristics of the urban forest in each location (Table 2). The greatest $PM_{2.5}$ removal rate was obtained for Ibirapuera, which had the greatest canopy cover, leaf area, tree density, and tree diversity.

Direct observations of $PM_{2.5}$ removal by urban trees are very scarce in the literature (Pace et al., 2021). Since there are no direct observations available for the MASP, the reasonability of the estimated removal fluxes can be evaluated through comparison to previous estimates in other urban forests across the world. For comparison with other urban forests around the world, it is necessary to consider the $PM_{2.5}$ annual removal flux, which is normalized by the area of interest, which could be either a neighborhood or an entire city. Air pollution removal fluxes rely not only on the urban forest properties but also on the magnitude of air pollutant concentrations, so that this factor should be considered.

Table 5 shows a comparison of $PM_{2.5}$ removal fluxes in different cities using a similar methodology and the same model. Paulicéia and Tabriz have comparable values of tree cover and $PM_{2.5}$ removal fluxes. Although the density of trees at Paulicéia is very low, 96% of trees have DBH above 15.2 cm, compared to 22% at Tabriz (Parsa et al., 2019), and that explains the relatively high removal efficiency of the urban forest at Paulicéia. São Bernardo's tree cover is comparable to the cities of Edinburgh and Mérida, but its $PM_{2.5}$ removal fluxes are greater by a factor between 2 and 3. Differences in the DBH distribution and tree species explain the relatively high efficiency of $PM_{2.5}$ removal by the urban forest at São Bernardo. Trees at São Bernardo have a higher DBH compared to those in Edinburgh and Mérida, and most species are evergreen. The low $PM_{2.5}$ concentrations at Edinburgh may also contribute to the relatively low removal rates since the deposition flux is proportional to the concentration (Equation 1). Finally, Ibirapuera and green municipal spaces at Strasbourg can be directly compared, since both studies focused on urban parks and green areas, with a tree cover of more than 60%, and had similar $PM_{2.5}$ concentrations. The $PM_{2.5}$ removal fluxes are comparable in Ibirapuera and Strasbourg. The smaller tree density at Ibirapuera is somewhat compensated by the evergreen character of the vegetation. In contrast, deciduous trees predominate at Strasbourg, with a leaf-off season lasting almost 6 months (Selmi et al., 2016).

Table 4 – Annual mean and standard deviation of $PM_{2.5}$ concentrations observed at the three study areas. $PM_{2.5}$ removal rates estimated by the i-Tree Eco model.

	Ibirapuera	São Bernardo	Paulicéia
$PM_{2.5}$ mean concentration (μg/m³)	16 ± 14	17 ± 12	15 ± 11
$PM_{2.5}$ removal flux (g/m²/year)	0.210	0.148	0.065
$PM_{2.5}$ removal rate (kg/year)	165	112	51

Overall, results indicate a higher removal capacity of the urban vegetation in the MASP compared to other cities. We argue that this could be explained by the evergreen nature of the vegetation in São Paulo, as well as by differences in the DBH distribution toward larger trees. However, since the i-Tree Eco model relies on a number of assumptions and simplifications, as described in the methods section, it is possible that the estimated removal rates could be overestimated. It is noteworthy that an eventual source of the overestimation was not

Table 5 – Comparison between urban forest characteristics, $PM_{2.5}$ annual mean concentrations, and $PM_{2.5}$ removal by trees in different urban areas across the world, using the i-Tree Eco software.

City or urban area and country	Tree cover (%)	Trees per ha	Trees with DBH < 15.2 cm (%)	$PM_{2.5}$ concentration (µg/m³)	$PM_{2.5}$ removal (g/m²/year)	References
Tabriz, Iran	9	79	78	22.9	0.050	Parsa et al. (2019) Barzeghar et al. (2020)
Paulicéia, Brazil	**13**	**10**	**4**	**15.1**	**0.065**	**This study**
Edinburgh, UK	17	62	59	6.4	0.060	Doick et al. (2017) UK-AIR (2022)
São Bernardo, Brazil	**20**	**48**	**18**	**16.7**	**0.148**	**This study**
Merida, Mexico	21	96	64	15	0.049	Concha et al. (2017) INECC (2019)
Ibirapuera, Brazil	**64**	**111**	**32**	**15.9**	**0.210**	**This study**
Green spaces in Strasbourg, France	68	271	44	17.5	0.208	Selmi et al. (2016) Vaudrey et al. (2020)

clearly detected in the analysis. Estimated parameters of the urban forest at Ibirapuera were compatible with the Ibirapuera Park Inventory. The simplification of the model by assuming dry deposition velocities that are not dependent on the tree species typically results in an underestimation of removal rates (Gaglio et al., 2022). The lack of direct field measurements of $PM_{2.5}$ removal by urban trees in São Paulo hinders a complete validation of the results.

The relevance of the $PM_{2.5}$ removal rates by the urban forest at MASP can be assessed through a comparison with vehicular emission rates in the metropolis, estimated at 1,220 tons of PM per year (CETESB, 2020). Extrapolation of the annual removal rate obtained for the São Bernardo area (0.78 km²) to the entire metropolitan area (8,047 km²) leads to 1,191 tons of $PM_{2.5}$ removed by trees per year (Figure 4). In other words, if the MASP as a whole had an urban forest similar to the São Bernardo study area, the $PM_{2.5}$ removal by trees could balance the vehicle emissions. Despite the huge simplification of this reasoning, it is suggested that the contribution of the urban forest to air pollution removal can be substantial in the MASP.

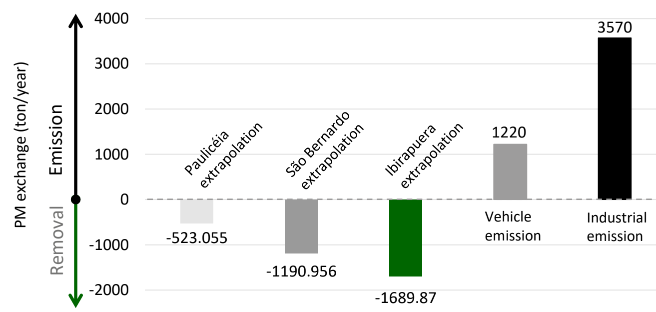

Figure 4 – Extrapolation of the $PM_{2.5}$ annual removal fluxes from the three study areas to the entire metropolitan area. Estimates of PM annual emission rates in the MASP considering vehicle and industrial emissions, according to CETESB (2020).

Seasonality of $PM_{2.5}$ removal

Although the three study areas are located in a subtropical region, with a predominance of evergreen tree species, the removal of $PM_{2.5}$ by the vegetation showed a marked seasonality, which was attributed to climatic conditions, especially the precipitation patterns. The i-Tree Eco model assumes that the particles deposited onto the vegetation are effectively removed from the atmosphere when the leaves are washed by the rain. In the absence of rain, the deposited particles are prone to be resuspended by the wind back to the atmosphere, resulting in a low net removal of $PM_{2.5}$ by the vegetation. Accordingly, the driest months of 2016, April and July (Figure 5A), had the lowest $PM_{2.5}$ removal rates (Figure 6B), with a similar behavior in the three study areas. The influence of wind on $PM_{2.5}$ removal rates was less clear, possibly because its seasonal variation is weaker compared to precipitation (Figure 5B). Therefore, precipitation was a key meteorological factor in the determination of $PM_{2.5}$ removal rates in the study areas.

$PM_{2.5}$ concentrations also responded to the dry conditions, with peak concentrations in April and in the austral winter (June–August) of 2016 (Figure 6A). In addition to the lower precipitation rates, the winter at MASP typically shows unfavorable conditions for air pollution dispersion, resulting in relatively high concentrations of primary pollutants (Carvalho et al., 2015; Silva et al., 2021; Oliveira et al., 2022). The seasonal behavior and concentration range of $PM_{2.5}$ were very similar in all three study areas (Figure 6A), showing that they are subjected to the same regional-scale climate forcing and have comparable air pollution burdens.

Conversely, higher $PM_{2.5}$ removal rates were observed during the austral summer when $PM_{2.5}$ concentrations were lower (Figure 6). The differences in the magnitude of $PM_{2.5}$ removal among the study areas were accentuated during the summer (January–March), ranging from 5 kg/month at Paulicéia to 20 kg/month at Ibirapuera. Considering that the sites have a similar air pollution burden and climatic conditions, the differences in $PM_{2.5}$ removal may be partially attributed to the characteristics of the urban forest at each study area.

RBCIAMB | v.57 | n.4 | Dez 2022 | 606-617 - ISSN 2176-9478

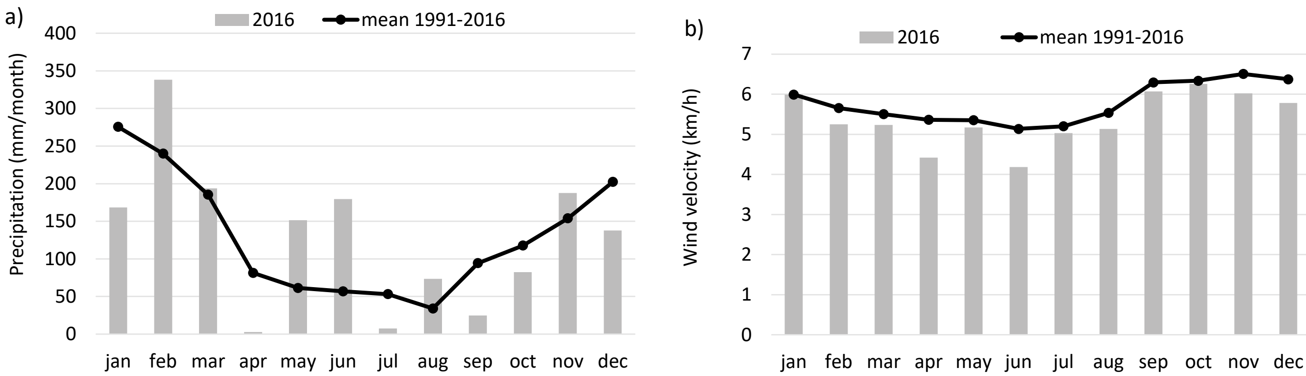

Figure 5 – (A) Monthly precipitation and (B) wind velocity monthly means in 2016 and respective climatological means for the period 1991–2016. The data were provided by the meteorological station of IAG/USP.

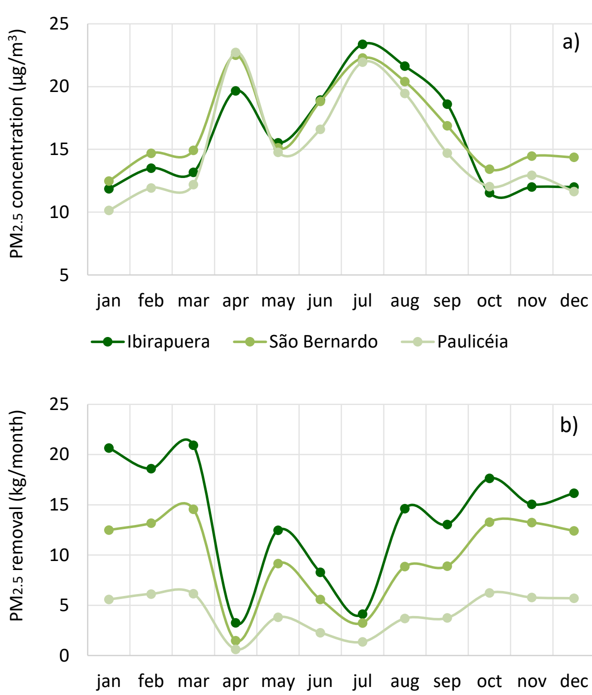

Figure 6 – (A) Monthly means of $PM_{2.5}$ concentrations and (B) monthly removal rates of $PM_{2.5}$ by the urban forest in 2016. The three study areas have 78 ha each so that the removal rates are directly comparable.

Other characteristics of the study area, like local topography and the proximity between trees and $PM_{2.5}$ emission sources, could also contribute to the differences in the removal rates.

The seasonal behavior of PM removal by the urban forest in the MASP was similar to that in Beijing and Strasbourg (Yang et al., 2005; Selmi et al., 2016), with smaller removal rates during the winter. However, the reasoning is distinct. In the MASP, PM removal by the evergreen vegetation is smaller during the winter because of climate conditions, while at Beijing and Strasbourg, it is explained by the leaf-out season.

Conclusion

$PM_{2.5}$ removal by urban trees was estimated for the first time in a Brazilian megacity, with annual removal rates ranging between 0.06 and 0.21 g/m²/year. South American cities are underrepresented in the literature about air pollutant removal by trees, so that the this study contributes to fill this gap. Compared to other cities around the world, the urban forest in the MASP showed great potential for $PM_{2.5}$ removal, with relatively high removal efficiencies. Climate conditions in the MASP favor the development of evergreen tree species, with relatively high DBH and crown volume, resulting in a high efficiency of $PM_{2.5}$ removal per m² of green area. It is important to publicize these results, since they can support the design of future urban green infrastructures for air pollution mitigation in cities where evergreen species predominate.

Another innovation of this study is the comparison of neighborhoods with different urban forestry conditions within the metropolis. The study area with the highest canopy cover and diversity in tree species and DBH classes (Ibirapuera) showed the greatest $PM_{2.5}$ removal rates. Extrapolating the characteristics of the urban forest in the study areas to the whole MASP area, the estimated $PM_{2.5}$ annual removal fluxes are similar in magnitude to the vehicular emission rates. This result suggests that the contribution of the urban forest to air pollution removal can be substantial in the MASP, supporting the development of public policies toward the use of green infrastructure to mitigate air pollution.

It is important to recognize that the big-leaf modeling approach does not consider the location of air pollution emission sources and green structures. For example, a concentrated urban forest massif like the Ibirapuera study area may not be effective in removing air pollutants emitted in other downwind neighborhoods. Because of that, the spatial distribution and the choice of species must be carefully considered in the design of green infrastructure toward the abatement of air pollution. Proximity of green infrastructure to $PM_{2.5}$ emission sources is advised to improve the removal by dry deposition. Another limitation of the model is the assumption that dry deposition velocities are not dependent on the tree species. It is possible that the simplifications of a big-leaf model resulted in the overestimation of removal rates, although the cause of an eventual overestimation was not clearly detected. The lack of direct field measurements of $PM_{2.5}$ removal by urban trees in São Paulo hinders a complete validation of the results. For a complete picture of the urban forest services related to air pollution removal in the MASP, further studies should expand the study areas, assess the removal of gaseous air pollutants, and combine modeling with in situ field observations of dry deposition.

Acknowledgments

We would like to thank the São Paulo state environmental agency (CETESB — Companhia Ambiental do Estado de São Paulo) for providing data on air pollutant concentrations. We also thank the meteorological station of the Atmospheric Sciences Department at the University of São Paulo (IAG/USP) for providing data on surface weather variables.

Contribution of authors:

BRITO, C.N.: Conceptualization; Formal Analysis; Methodology; Writing — Original Draft. RIZZO, L.V.: Conceptualization; Data Curation; Supervision; Validation; Writing — Original Draft.

References

Abhijith, K.V.; Kumar, P., 2019. Field investigations for evaluating green infrastructure effects on air quality in open-road conditions. Atmospheric Environment, v. 201, 132-147. https://doi.org/10.1016/j.atmosenv.2018.12.036.

Abhijith, K.V.; Kumar, P.; Gallagher, J.; McNabola, A.; Baldauf, R.; Pilla, F.; Broderick, B.; Di Sabatino, S.; Pulvirenti, B., 2017. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review. Atmospheric Environment, v. 162, 71-86. https://doi.org/10.1016/j.atmosenv.2017.05.014.

Alvares, C.A.; Stape, J.L., Sentelhas, P.C.; Moraes Gonçalves, J.L.; Sparovek, G., 2013. Köppen's climate classification map for Brazil. Meteorologische Zeitschrift, v. 22, (6), 711-728. https://doi.org/10.1127/0941-2948/2013/0507.

Andrade, M.F.; Kumar, P.; Freitas, E.D.; Ynoue, R.Y.; Martins, J.; Martins, L.D.; Nogueira, T.; Perez-Martinez, P.; Miranda, R.M.; Albuquerque, T.; Gonçalves, F.L.T.; Oyama, B.; Zhang, Y., 2017. Air quality in the megacity of São Paulo: Evolution over the last 30 years and future perspectives. Atmospheric Environment, v. 159, 66-82. https://doi.org/10.1016/j.atmosenv.2017.03.051.

Arantes, B.L.; Mauad, T.; Silva Filho, D.F.D., 2019. Urban forests, air quality and health: a systematic review. International Forestry Review, v. 21, (2), 167-181. https://doi.org/10.1505/146554819826606559.

Barzeghar, V.; Sarbakhsh, P.; Hassanvand, M.S.; Faridi, S.; Gholampour, A., 2020. Long-term trend of ambient air PM10, PM2.5, and O3 and their health effects in Tabriz city, Iran, during 2006–2017, Sustainable Cities and Society, v. 54, 101988. https://doi.org/10.1016/j.scs.2019.101988

Cabaraban, M.T.I.; Kroll, C.N.; Hirabayashi, S.; Nowak, D.J. 2013. Modeling of air pollutant removal by dry deposition to urban trees using a WRF/CMAQ/i-Tree Eco coupled system. Environmental Pollution, v. 176, 123-133. https://doi.org/10.1016/j.envpol.2013.01.006.

Caiafa, A.N.; Martins, F.R., 2010. Forms of rarity of tree species in the southern Brazilian Atlantic rainforest. Biodiversity and Conservation, v. 19, (9), 2597-2618. https://doi.org/10.1007/s10531-010-9861-6.

Carvalho, V.S.B.; Freitas, E.D.; Martins, L.D.; Martins, J.A.; Mazzoli, C.R.; Andrade, M.F., 2015. Air quality status and trends over the Metropolitan Area of São Paulo, Brazil as a result of emission control policies. Environmental Science & Policy, v. 47, 68-79. https://doi.org/10.1016/j.envsci.2014.11.001.

Companhia Ambiental do Estado de São Paulo (CETESB), 2008. Material Particulado inalável fino (MP2,5) e grosso (MP2,5 – 10) na atmosfera da Região Metropolitana de São Paulo (2000 – 2006). (Accessed Nov 15, 2021) at:. https://cetesb.sp.gov.br/qualidade-ar/wp-content/uploads/sites/28/2013/12/Relatorio_MP2_5.zip.

Companhia Ambiental do Estado de São Paulo (CETESB), 2020. Qualidade do ar no Estado de São Paulo em 2019. (Accessed Dec 5, 2020) at:. https://cetesb.sp.gov.br/ar/wp-content/uploads/sites/28/2020/07/Relatório-de-Qualidade-do-Ar-2019.pdf.

Companhia Ambiental do Estado de São Paulo (CETESB), 2022. Qualar - Sistema de Informações da Qualidade do Ar. (Accessed Dec 1 2020) at:. https://cetesb.sp.gov.br/ar/qualar/.

Concha, H. de la; Cano, L.R.; Burgos, A.G., 2017. Inventario del arbolado urbano de la Ciudad de Mérida, Mérida, México. (Accessed Jan 31 2022) at:. http://www.merida.gob.mx/municipio/sitiosphp/sustentable/contenidos/doc/inventario_arbolado_merida.pdf.

Doick, K.J.; Handley, P.; Ashwood, F.; Vaz Monteiro, M.; Frediani, K.; Rogers, K., 2017. Valuing Edinburgh's Urban Trees. An update to the 2011 i-Tree Eco survey – a report of Edinburgh City Council and Forestry Commission Scotland, Edinburgh, UK. (Accessed Mar 13 2021) at:. https://www.forestresearch.gov.uk/documents/7876/FR_Doick_Edinburgh_iTree_Full_Report_2017_OJfWakl.pdf.

Donateo, A.; Rinaldi, M.; Paglione, M.; Villani, M.G.; Russo, F.; Carbone, C.; Zanca, N.; Pappaccogli, G.; Grasso, F.M.; Busetto, M.; Sänger, P.; Ciancarella, L.; Decesari, S., 2021. An evaluation of the performance of a green panel in improving air quality, the case study in a street canyon in Modena, Italy. Atmospheric Environment, v. 247, 118189. https://doi.org/10.1016/j.atmosenv.2021.118189.

Engemann, K.; Enquist, B.J.; Sandel, B.; Boyle, B.; Jørgensen, P.M.; Morueta-Holme, N.; Peet, R.K.; Violle, C.; Svenning, J., 2015. Limited sampling hampers "big data" estimation of species richness in a tropical biodiversity hotspot. Ecology and Evolution, v. 5, (3), 807-820. https://doi.org/10.1002/ece3.1405.

Escobedo, F.J.; Nowak, D.J., 2009. Spatial heterogeneity and air pollution removal by an urban forest. Landscape and Urban Planning, v. 90, (3-4), 102-110. https://doi.org/10.1016/j.landurbplan.2008.10.021.

Gaglio, M.; Pace, R.; Muresan, A.N.; Grote, R.; Castaldelli, G.; Calfapietra, C.; Fano, E.A., 2022. Species-specific efficiency in PM2.5 removal by urban trees: From leaf measurements to improved modeling estimates. Science of The Total Environment, v. 844, 157131. https://doi.org/10.1016/j.scitotenv.2022.157131.

Gómez Peláez, L.M.; Santos, J.M.,; Almeida Albuquerque, T.T.; Reis, N.C.; Andreão, W.L.; Fátima Andrade, M., 2020. Air quality status and trends over large cities in South America. Environmental Science and Policy, v. 114, 422-435. https://doi.org/10.1016/j.envsci.2020.09.009.

Han, D.; Shen, H.; Duan, W.; Chen, L., 2020. A review on particulate matter removal capacity by urban forests at different scales. Urban Forestry and Urban Greening, v. 48, 126565. https://doi.org/10.1016/j.ufug.2019.126565.

Hirabayashi, S.; Kroll, C.N.; Nowak, D.J., 2012. Development of a distributed air pollutant dry deposition modeling framework. Environmental Pollution, v. 171, 9-17. https://doi.org/10.1016/j.envpol.2012.07.002.

Hirabayashi, S.; Kroll, C.N.; Nowak, D.J.; Endreny, T.A., 2015. i-Tree Eco Dry Deposition Model Descriptions. 34. (Accessed Jun 5, 2020) at:. http://www.itreetools.org/eco/resources/iTree_Eco_Dry_Deposition_Model_Descriptions.pdf.

Hirabayashi, S.; Nowak, D.J., 2016. Comprehensive national database of tree effects on air quality and human health in the United States. Environmental Pollution, v. 215, 48-57. https://doi.org/10.1016/j.envpol.2016.04.068.

Informe Nacional de Calidad del Aire (INECC), 2019. México, Ciudad de México, 2021. (Accessed Jul 31, 2021) at:. http://189.240.101.244:8080/xmlui/handle/publicaciones/349.

Janhäll, S., 2015. Review on urban vegetation and particle air pollution - Deposition and dispersion. Atmospheric Environment, v. 105, 130-137. https://doi.org/10.1016/j.atmosenv.2015.01.052.

Jayasooriya, V.M.; Ng, A.W.M.; Muthukumaran, S.; Perera, B.J.C., 2017. Green infrastructure practices for improvement of urban air quality. Urban Forestry and Urban Greening, v. 21, 34-47. https://doi.org/10.1016/j.ufug.2016.11.007.

Kabashima, Y.; Andrade, M.L.F.; Gandara, F.B.; Tomas, F.L.; Polizel, J.L.; Velasco, G.D.N.; Silva, L.F.; Dozzo, A.D.P.; Moura, R.G.; Ferreira da Silva Filho, D., 2019. Histórico da composição da vegetação arbórea do parque do Ibirapuera e sua contribuição para a conservação da biodiversidade. Revista da Sociedade Brasileira de Arborização Urbana, v. 6, (4), 125-144. https://doi.org/10.5380/revsbau.v6i4.66492.

Kumar, P.; Druckman, A.; Gallagher, J.; Gatersleben, B.; Allison, S.; Eisenman, T.S.; Hoang, U.; Hama, S.; Tiwari, A.; Sharma, A.; Abhijith, K.V.; Adlakha, D.; McNabola, A.; Astell-Burt, T.; Feng, X.; Skeldon, A.C.; Lusignan, S.; Morawska, L., 2019. The nexus between air pollution, green infrastructure and human health. Environment International, 133, (part A), 105181. https://doi.org/10.1016/j.envint.2019.105181.

Li, D.; Ma, J.; Cheng, T.; van Genderen, J.L.; Shao, Z., 2019. Challenges and opportunities for the development of MEGACITIES. International Journal of Digital Earth, v. 12, (12), 1382-1395. https://doi.org/10.1080/17538947.2018.1512662.

Lin, J.; Kroll, C.N.; Nowak, D.J.; Greenfield, E.J., 2019. A review of urban forest modeling: Implications for management and future research. Urban Forestry and Urban Greening, v. 43, 126366. https://doi.org/10.1016/j.ufug.2019.126366.

Liu, C.; Chen, R.; Sera, F.; Vicedo-Cabrera, A.M.; Guo, Y.; Tong, S.; Coelho, M.S.Z.S.; Saldiva, P.H.N.; Lavigne, E.; Matus, P.; Valdes Ortega, N.; Osorio Garcia, S.; Pascal, M.; Stafoggia, M.; Scortichini, M.; Hashizume, M.; Honda, Y.; Hurtado-Díaz, M.; Cruz, J., … Kan, H., 2019. Ambient particulate air pollution and daily mortality in 652 cities. New England Journal of Medicine, v. 381, (8), 705-715. https://doi.org/10.1056/NEJMoa1817364.

Livesley, S.J.; McPherson, E.G.; Calfapietra, C., 2016. The urban forest and ecosystem services: impacts on urban water, heat, and pollution cycles at the tree, street, and city scale. Journal of Environmental Quality, v. 45, (1), 119-124. https://doi.org/10.2134/jeq2015.11.0567.

Locosselli, G.M.; Camargo, E.P.; Moreira, T.C.L.; Todesco, E.; Andrade, M.F.; André, C.D.S.; André, P.A.; Singer, J.M.; Ferreira, L.S.; Saldiva, P.H.N.; Buckeridge, M.S., 2019. The role of air pollution and climate on the growth of urban trees. Science of the Total Environment, v. 666, 652-661. https://doi.org/10.1016/j.scitotenv.2019.02.291.

Locosselli, G.M.; Chacón-Madrid, K.; Zezzi Arruda, M.A.; Pereira de Camargo, E.; Lopes Moreira, T.C.; Saldiva de André, C.D.; Afonso de André, P.; Singer, J.M.; Nascimento Saldiva, P.H.; Buckeridge, M.S., 2018. Tree rings reveal the reduction of Cd, Cu, Ni and Pb pollution in the central region of São Paulo, Brazil. Environmental Pollution, v. 242, (part A), 320-328. https://doi.org/10.1016/j.envpol.2018.06.098.

Moreira, T.C.L.; Polizel, J.L.; Santos, I.S.; Silva Filho, D.F.; Bensenor, I.; Lotufo, P.A.; Mauad, T., 2020. Green spaces, land cover, street trees and hypertension in the megacity of São Paulo. International Journal of Environmental Research and Public Health, v. 17, (3), 725. https://doi.org/10.3390/ijerph17030725.

Nowak, D.J.; Hirabayashi, S.; Doyle, M.; McGovern, M.; Pasher, J., 2018. Air pollution removal by urban forests in Canada and its effect on air quality and human health. Urban Forestry and Urban Greening, v. 29, 40-48. https://doi.org/10.1016/j.ufug.2017.10.019.

Oliveira, M.C.Q.D.; Drumond, A.; Rizzo, L.V., 2022. Air pollution persistent exceedance events in the Brazilian metropolis of Sao Paulo and associated surface weather patterns. International Journal of Environmental Science and Technology, v. 19, 9495-9506. https://doi.org/10.1007/s13762-021-03778-1.

Pace, R.; Guidolotti, G.; Baldacchini, C.; Pallozzi, E.; Grote, R.; Nowak, D.J.; Calfapietra, C., 2021. Comparing i-Tree Eco Estimates of Particulate Matter Deposition with Leaf and Canopy Measurements in an Urban Mediterranean Holm Oak Forest. Environmental Science and Technology, v. 55, (10), 6613-6622. https://doi.org/10.1021/acs.est.0c07679.

Parnreiter, C., 2019. Global cities and the geographical transfer of value. Urban Studies, v. 56, (1), 81-96. https://doi.org/10.1177/0042098017722739.

Parsa, V.A.; Salehi, E.; Yavari, A.R.; van Bodegom, P.M., 2019. Analyzing temporal changes in urban forest structure and the effect on air quality improvement. Sustainable Cities and Society, v. 48, 101548. https://doi.org/10.1016/j.scs.2019.101548.

Piñero Sánchez, M.; Oliveira, A.P.; Varona, R.P.; Tito, J.V.; Codato, G.; Ribeiro, F.N.D.; Marques Filho, E.P.; Silveira, L.C., 2020. Rawinsonde-Based Analysis of the Urban Boundary Layer in the Metropolitan Region of São Paulo, Brazil. Earth and Space Science, v. 7, (2), e2019EA000781. https://doi.org/10.1029/2019EA000781.

Pope, C.A.; Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. Journal of the Air & Waste Management Association, v. 56, (6), 709-742. https://doi.org/10.1080/10473289.2006.10464485

Ramon, M.; Ribeiro, A.P.; Theophilo, C.Y.S.; Moreira, E.G.; Camargo, P.B.; Bragança Pereira, C.A.; Saraiva, E.F.; Reis Tavares, A.; Dias, A.G.; Nowak, D.; Ferreira, M.L., 2022. Assessment of four urban forest as environmental indicator of air quality: a study in a Brazilian megacity. Urban Ecosystems. https://doi.org/10.1007/s11252-022-01296-7.

Raupp, M.J.; Cumming, A.B.; Raupp, E.C., 2006. Street tree diversity in eastern North America and its potential for tree loss to exotic borers. Arboriculture & Urban Forestry, v. 32, (6), 297-304. https://doi.org/10.48044/jauf.2006.038.

Salvo, A.; Brito, J.; Artaxo, P.; Geiger, F.M., 2017. Reduced ultrafine particle levels in São Paulo's atmosphere during shifts from gasoline to ethanol use. Nature Communications, v. 8, (1), 77. https://doi.org/10.1038/s41467-017-00041-5.

Seinfeld, J.H.; Pandis, S.N., 2006. Atmospheric chemistry and physics: from air pollution to climate change (2nd ed.). Wiley.

Selmi, W.; Weber, C.; Rivière, E.; Blond, N.; Mehdi, L.; Nowak, D., 2016. Air pollution removal by trees in public green spaces in Strasbourg city, France. Urban Forestry and Urban Greening, v. 17, 192-201. https://doi.org/10.1016/j.ufug.2016.04.010.

Silva, J.L.S.; Oliveira, M.T.P.; Oliveira, W.; Borges, L.A.; Cruz-Neto, O.; Lopes, A.V., 2020. High richness of exotic trees in tropical urban green spaces: Reproductive systems, fruiting and associated risks to native species. Urban Forestry & Urban Greening, v. 50, 126659. https://doi.org/10.1016/j.ufug.2020.126659.

Silva, M.D.; Oliveira, M.C.Q.D.; Drumond, A.; Rizz, L.V. (2021). Air pollutants associated with surface meteorological conditions in São Paulo's ABC region. Brazilian Journal of Environmental Sciences, v. 56, (3), 459-469. https://doi.org/10.5327/Z21769478917.

Sugahara, S.; Rocha, R.P.; Ynoue, R.Y.; Silveira, R.B., 2012. Homogeneity assessment of a station climate series (1933-2005) in the Metropolitan Area of São Paulo: Instruments change and urbanization effects. Theoretical and Applied Climatology, v. 107, (3-4), 361-374. https://doi.org/10.1007/s00704-011-0485-x.

Szkop, Z., 2020. Evaluating the sensitivity of the i-Tree Eco pollution model to different pollution data inputs: A case study from Warsaw, Poland. Urban Forestry and Urban Greening, v. 55, 126859. https://doi.org/10.1016/j.ufug.2020.126859.

UK-AIR, 2022. PM2.5 annual mean at Edinburgh St Leonards air quality monitoring station in 2016. Air Inf. Resource. (Accessed February 3, 2022) at:. https://uk-air.defra.gov.uk/data/data_selector_service#mid.

Vaudrey, B.; Mielcarek, M.; Sauleau, E.; Meyer, N.; Marchandot, B.; Moitry, M.; Robellet, P.; Reeb, T.; Jesel, L.; Ohlmann, P.; Bourdrel, T.; Morel, O., 2020. Short-Term Effects of Air Pollution on Coronary Events in Strasbourg, France—Importance of Seasonal Variations. Medical Sciences, v. 8, (3), 31. https://doi.org/10.3390/medsci8030031.

Wang, H.; Maher, B.A.; Ahmed, I.A.M.; Davison, B., 2019. Efficient removal of ultrafine particles from diesel exhaust by selected tree species: implications for roadside planting for improving the quality of urban air. Environmental Science and Technology, v. 53, (12), 6906-6916. https://doi.org/10.1021/acs.est.8b06629.

Wu, J.; Wang, Y.; Qiu, S.; Peng, J., 2019. Using the modified i-Tree Eco model to quantify air pollution removal by urban vegetation. Science of the Total Environment, v. 688, 673-683. https://doi.org/10.1016/j.scitotenv.2019.05.437.

Yang, J.; McBride, J.; Zhou, J.; Sun, Z., 2005. The urban forest in Beijing and its role in air pollution reduction. Urban Forestry and Urban Greening, v. 3, (2), 65-78. https://doi.org/10.1016/j.ufug.2004.09.001.

Zenni, R.D.; Ziller, S.R., 2011. An overview of invasive plants in Brazil. Revista Brasileira de Botânica, v. 34, (3), 431-446. https://doi.org/10.1590/S0100-84042011000300016.