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Neotropical urban forest allergenicity and ecosystem disservices can affect vulnerable neighborhoods in Bogota, Colombia

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ABSTRACT

Tree allergenicity has been documented as a relevant ecosystem disservice, a tradeoff to the many co-benefits of urban trees. However, information on the allergenic tree dynamics in Neotropical urban environments is scarce. We used species-level Allergenic Potential Value (APV) and pollen-emission capacity as well as data on treestructure and diversity to explore the spatial dynamics of tree allergenicity in Bogota Colombia's public urban forest. We then statistically and spatially analyzed this data along with socioeconomic and vulnerability information to better understand tree allergenicity dynamics and its role as a tropical urban ecosystem disservice. Results show that most of high APV species were present in the lowest socioeconomic strata. Hierarchical cluster analyses indicates that trees with higher APVs trend towards specific sectors in the city. Vulnerable neighborhoods were also identified according to public health access and age-related sociodemographic and used to discuss allergenicity-related ecosystem disservices. Findings show a paucity of tree cover in some vulnerable neighborhoods indicating not only an absence of allergy-related ecosystem disservices, but of overall ecosystem services as well. This approach using information sources can be used to better select functional traits, tree species, and planting strategies to reduce allergy and ecosystem disservice hotpots in tropical urban cities.

1. Introduction

Forests and trees via allergenic pollen production in urban and peri-urban settings have been documented adversely impact human well-being, or ecosystem disservices, via health outcomes related to allergic rhinitis or hay fever (Cariñanos & Marinangeli, 2021; Nowak & Ogren, 2021). Studies have found that different vegetation composition and structure characteristics such as species, functional traits, size, and pollination strategy can affect rates of allergenic pollen production (Grote et al., 2016; Jochner-Oette et al., 2018). Additionally other socio-ecological factors such as land use-land cover, plant selection practices, socio-demographics (i.e., age, employment, sex), geography (latitude, topography), weather, exposure/risk factors, and even climate change influence allergenic pollen production as well as allergies in people (Caraballo et al., 2016; Sarmiento, 2014). Most of these studies in urban contexts are primarily from high income countries with temperate and Mediterranean climates and biomes (Cariñanos et al., 2016; Cepeda & Villalba, 2008; Hurtado et al., 1989) and a well-established body of epidemiological research and information (Caraballo et al., 2016; Dennis et al., 2004; Gernes et al., 2019).

However, the effects of Neotropical urban and peri-urban forests on allergenic production and their possible effects on human well-being have been much less studied. Allergies, primarily resulting from outdoor pollen, have been reported in the tropics but much less so than in countries with temperate climates (Caraballo et al., 2016). This could be due to a lack of exposure, limited information regarding prevalence, and risk factors (Caraballo et al., 2016), or due to the misconceptions that allergies only prevail in high income, temperate countries (Dennis et al., 2004 and 2012). Relevant studies from Latin America have found that hay fever prevalence is 21% in children 13–14 years old and 16% in children 6–7; while the change in the prevalence of hay fever is higher in the tropics relative to temperate areas for children 13–14 years old

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(Caraballo et al., 2016). In the case of Colombia, studies indicate that 16% of the population suffers from allergy-related symptoms (Dennis et al., 2004), while other more recent studies such as Peñaranda et al. (2012) have estimated that it can be up to 30%, particularly in the case of children and adolescents. Despite these studies, the causal factors behind this high allergy incidence and people' vulnerability towards allergies is still not well understood in the Neotropics.

One issue is that vulnerability is a multifaceted condition that can encompass several socioeconomic, demographic, environmental, and health dimensions (Adger, 2006). In the United States and Europe, social vulnerability is defined in terms of the potential negative effects on communities that result from external stressors (e.g., natural disasters) on human well-being and people's ability to avoid, cope and adapt to these effects, and is often measured using socioeconomic status, demographics such as age, housing condition, and access to health care (Flanagan et al., 2018; Kaÿmierczak, 2018). In the Global South and countries like Colombia, vulnerable populations are defined by government health institutions according to not only sociodemographic factors, but also ethnicity, resource access, power dynamics, and being victims of armed conflict (Toro et al., 2012).

In terms of the potential effects of allergies on vulnerable population in the Global South, a study by Peñaranda et al. (2016) found that socioeconomic status is one vulnerability factor that influences the magnitude of allergic rhinitis incidence in Bogotá, Colombia where occurrences of allergenic rhinitis are lower in more affluent populations. Dennis et al. (2012) documented that allergy was a significant problem in Colombian cities, particularly those with more vulnerable populations by showing that the prevalence of allergenic rhinitis in Bogota during 2009–2012 for persons 1 – 59 years old was 32% and 28% for children 5–17 years old. As a results of this, 33% of persons reported absence days from work and school for period of up to 6 months due to allergy-related symptoms. Although several environmental factors in Latin America have been documented to be linked with incidences of allergic reactions in humans (e.g., indoor air quality); fewer studies have focused on outdoor environmental quality and its effects on allergies (García et al., 2008; Peñaranda et al., 2016)

Another influencing factor may be the limited knowledge of tropical flora and its relationship with the emission of allergenic pollen. For example, there is a notable lack of studies characterizing pollination strategies for tropical trees and palms and subsequent pollen emissions and their associated problems (Alzate Guarín et al., 2015). In addition, tropical climates and their increased precipitation and humidity can affect pollen production and concentrations due to frequent atmospheric washing (Lewis, 1986). Similarly, contexts with greater biodiversity - both in numbers of species and ecosystems - could also lead to an immune-protective effect against human inhalation of allergens (Haahtela et al., 2019; Hanski et al., 2012). However, aerobiology studies from the tropics have shown that the pollen spectrum can be highly diverse and dynamic (Cepeda & Villalba, 2008; Hurtado et al., 1989).

In terms of plant functionality, allergenic bioaerosol control analyses studies in tropical Latin America are not as common as in Europe or the United States; despite the climate, vegetation productivity, and diversity of the tropics (Caraballo et al., 2016). Moreover, many aerobiology studies rarely account for the effect of topography, local emission sources, building densities, and microclimatic conditions (Katelaris et al., 2004), as well as inadequate pollen sampling sites and monitors (García-Mozo et al., 2004; Rodriguez-Rajo et al., 2010). In Bogota, the first aerobiology studies were from Sánchez-Medina and Fernández (1966) and more recently by Díaz Carmelo (2017), who characterized atmospheric-level allergenic pollen intensity and dynamics of species such as: *Cupressus lusitanica*, Poaceae, *Cecropia telenitida, Quercus, Eucalyptus Alnus acuminata*, Urticaceae, *Fraxinus chinensis, Pinus* spp., *Juglans neotropica* and *Morus* spp., among others. The perceived impacts, or ecosystem disservices, of vegetation-related allergies to humans have also been studied. For example, a survey of 500 users of Bogota's wetlands, parks, and natural areas found that 17%, 23% and 3%, respectively, reported allergies as a specific ecosystem disservice related to these 3 types of green spaces (Pineda-Guerrero et al., 2021). Despite the above studies, there is little information on how the structure and composition of Neotropical urban forests influence allergenicity and subsequent ecosystem disservices impacts to human well-being (Escobedo et al., 2015). As such, studies documenting the potential allergenicity of trees, shrub and palms and their possible effects on vulnerable populations are needed in Neotropical urban forests.

Given this lack of information, the aim of this study is to better understand how Neotropical urban forests structure (e.g., tree size, crown area) and composition (tree diversity and taxonomy) and spatial distribution influence allergenicity characteristics across a city. Using Bogota, Colombia's public urban forests as a case study, we first analyze their structural and compositional characteristics as related to allergenicity. Second, we explore the spatial distribution of tree allergenicity and its impact on vulnerable populations in representative localities and neighborhoods. Finally, we discuss how the ecosystem disservices framework, knowledge of species composition and plant traits as related to allergenicity, and urban ecology can be used to better inform the management and planning of low allergenicity, environmentally just tropical urban forests; particularly in the Global South.

2. Materials and methods

2.1. Study area

Bogota and its peripheries have been characterized by historical and anthropogenic changes including pre-Hispanic human settlements and land use conversion even before its founding as a Capital in the mid-1500s (Andrade et al., 2013). The study area is located on a high elevation plain in the eastern Andes at an elevation of 2600 m above sea level and has a tropical climate characterized by an average annual temperature of 14 °C and annual precipitation of almost 800 mm. This region is highly biodiverse (Myers et al., 2000) and this diversity is reflected in its urban forest (Escobedo et al., 2015). The study area has also experienced rapid economic development and population increases in recent years. Its peri-urban areas are characterized by agricultural and industrial land uses as well as Andean secondary forests consisting of genera such as *Weinmannia, Cavendishia, Miconia* and *Myrcianthes* (Escobedo et al., 2015).

The 2020 human population of Bogota was almost 8.4 million inhabitants distributed over an urbanized area of approximately 37,972 ha. (DANE, 2018). Approximately 52% of its population is female and the median age is 33 years old and there are 1.3 million children between 5 and 17 years old. The city is classified into 6 administratively designated strata types based on the prevailing socioeconomic condition; with strata 1 being the lowest income and 6 being the most affluent (Fig. 1). The lower a stratum's designation (i.e., strata 1–3) will determine the amount of utilities such as gas, water and electricity that are subsidized. Conversely, residents in upper strata (i.e., 5–6) pay the full costs of utilities; thereby offsetting the costs for lower strata Thibert & Osorio, 2013). As such, these strata provide a fairly accurate representation of socioeconomic differences in the city. Approximately 95% of Bogota's residents live in strata 1–4 (Secretaría Distrital de Planeación, 2018).

2.2. Urban forest data

We used Bogota's public urban forest full inventory from 2006 which consisted of 1.1 million measured trees, palms and shrubs representing 228 different species, of which 50.1% (114 species) were native. Measured individual were distributed throughout the city's different land uses including: parks, wetlands, green areas, transportation right of way, as well as its residential areas across different localities and socioeconomic strata. Although the data are from 2006, they are to our

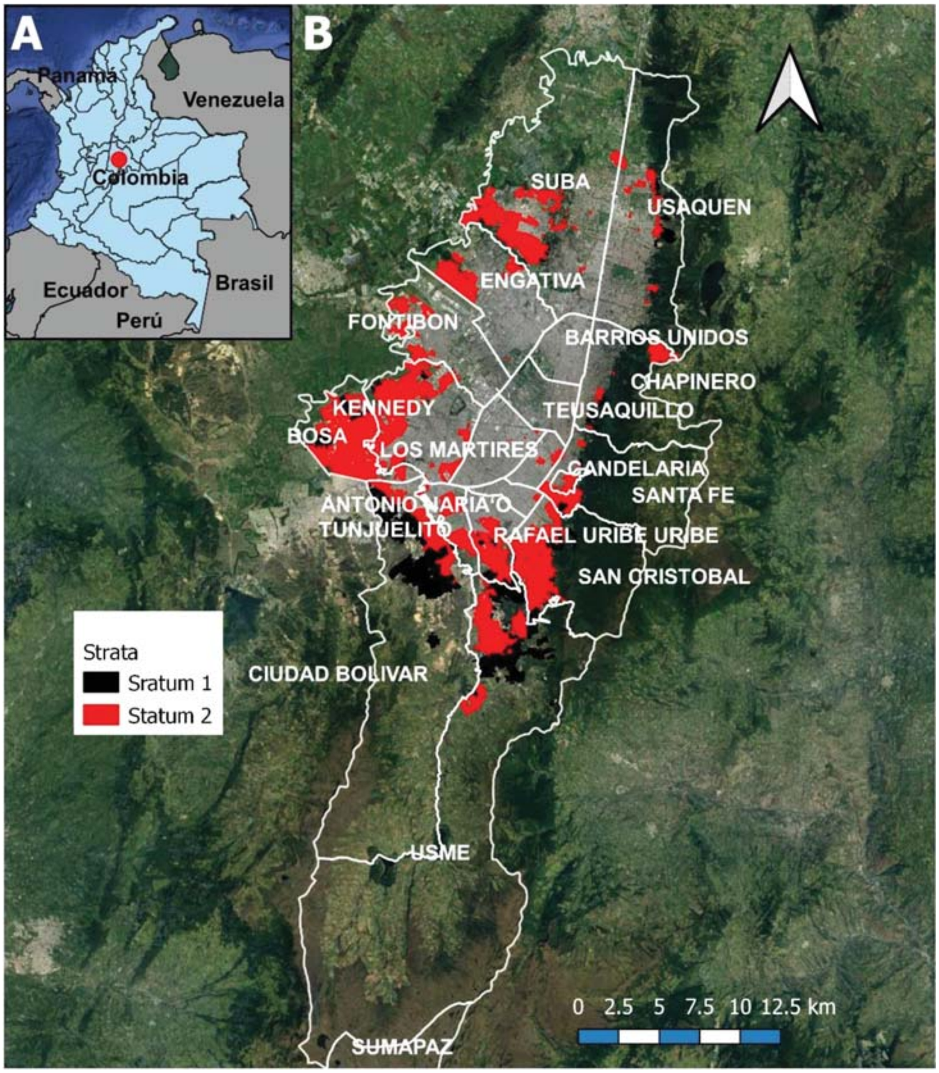

Fig. 1. The Bogota, Colombia study area, its 20 localities, and the locations of socioeconomic strata 1 and 2 throughout the city.

knowledge the only comprehensive, statistically robust, spatially heterogenous, and publicly available data set that is accessible to researchers in the Neotropics (DANE-JBB, 2007). Indeed the data has also been used in other more recent studies of urban forest inequities and tree and crime relationships in Bogota (Escobedo et al., 2015 and 2018). The specific inventory data and metrics analyzed in this study included: taxa, diameter at breast height (DBH; cm), height (m) and crown area (m^2) for all individual trees, palms and tall shrubs regardless of size in all public spaces. However, we eliminated smaller sized individuals and subsequently only analyzed larger trees that will likely have the most influence on allergenicity, specifically those individuals in the database with a DBH greater than 2.5 cm and height greater that 2.0 m. Appendix A lists the structural characteristics for these 445,121 trees and palms meeting these size criteria and that were located across the 20 localities and 6 strata.

Given the high diversity of species and size ranges in the inventory, median and mean: DBH, height, and crown area as well as total individual numbers were analyzed according to socioeconomic strata and locality. Since a tree's allergenic potential is not only a function of its taxa, but its size (Cariñanos et al., 2014), we also used the following approach to identify the most abundant trees and their species and structural metrics in an area of interest (i.e., locality or neighborhood). We first identified the most abundant species per locality in terms of their frequency by calculating the occurrence of species in each locality and then sorted species by most to least occurring individuals of that species. Using this occurrence and sorting of individuals by species, we then calculated each species' percent frequency in an area of interest. Then, individuals from species representing 50–55% of an area of interest's tree population – or the most common tree species per area of interest - were identified and individual tree crown areas were summed to represent the percent tree cover for the most common species. We subsequently use "% Public tree Cover" and "Tree crown area (m^2)" as metrics to characterize the most abundant public tree species in a locality or neighborhood, respectively. All analyses were performed using the *Tapply* and *Sort* functions in RStudio Version 3.65 (RStudio Team, 2020).

2.3. Estimating allergenic potential value

Since studies on allergenic pollen emission and concentration in Bogota are scarce (Díaz Carmelo, 2017; Sánchez-Medina & Fernández, 1966), the allergenic characteristics of Bogotá's public urban trees were determined using a method proposed by Cariñanos et al. (2014). Specifically, every tree species was assigned an Allergenic Potential Value (APV) based on a series of biological attributes such as: type of pollination, duration of the pollination period, and a species' intrinsic allergenic capacity for pollen emissions. Reference databases for many of these allergenicity characteristics are commonly available for

Mediterranean and temperate climate species (Cariñanos & Marinangeli, 2021; Cariñanos et al., 2014, 2016). However, there is a lack of information for tropical and sub-tropical species, which comprise 80% of the public trees in Bogotá. Therefore, a species level APV had to be developed and estimated for each inventoried species based on: 1) type of pollination strategy, 2) duration and date of its pollination period, and 3) its overall allergenic capacity (Cariñanos & Marinangeli, 2021; Cariñanos et al., 2014; 2016).

Pollination strategy, as used in this study, refers to the mechanisms used by most plants to carry out pollination processes such as by: insects or other fauna (zoophilous or entomophilous pollination), wind (anemophilous pollination) or a combination of both (ambophilous pollination). Plants produce excess pollen as a pollination strategy, sometimes in excess amounts that end up contributing to atmospheric bioaerosol concentrations. For plants that use wind as a pollination agent (i.e., anemophilous), excess pollen levels are usually very high; therefore species utilizing this strategy are often the main source of allergens. Accordingly, following Cariñanos et al. (2014) approach, a value between 1 and 3 was assigned to each species, where 1 represents species pollinated by insects or other groups of fauna, 2 for species with mixed strategy, and 3 for anemophilous species.

The pollination dates and duration for all inventoried tree species were then assigned based on a literature review using Scopus, Web of Science, and Google Scholar (Cepeda et al., 2008; Hurtado et al., 1989; Lewis, 1986; Sánchez-Medina & Fernández, 1966; Alzate Guarín et al., 2015; Cepeda & Villalba, 2008; Díaz-Carmelo, 2017; Tovar-Corzo, 2013; Wiesner, 2000). Pollination period refers to the time, generally in weeks, in which the species has the capacity to emit pollen into the atmosphere and therefore when the pollen is potentially available for human inhalation. This period can last from just 1–3 weeks to more than 6 weeks, and therefore we assigned a value of: 1 to species with flowering times of less than three weeks, 2 for periods between 3 and 6 weeks, and 3 when flowering lasts for more than 6 weeks (Cariñanos et al., 2014). In Bogota, the highest atmospheric pollen content has been recorded during the less intense rainfall periods, between the months of January to March and from June to September (Díaz-Carmelo, 2017; Sánchez-Medina & Fernández, 1966). However, high humidity can also exert an atmospheric washing effect by accelerating pollen deposition (Chen et al., 2019). Therefore, for most species a flowering period of less than 6 weeks was assumed.

Thus, the allergenic capacity for a given species was established using allergenicity lists and indices for common urban plant species (Cariñanos et al., 2011, 2014, 2016; Hruska, 2003; Ogren, 2000; 2003). This value ranges from 0 for non-allergenic species to 4 for species with a very high referenced allergenic potency (for example, olive pollen in the Mediterranean region). The Allergome database (Mari et al., 2009) was also used for species with no available or published information (e.g., allergenic molecule emissions, presence of pan-allergens in the exine of the pollen grains). The combination of values for these three characteristics result in allergenic potential values (APV) ranging between 0 and 36; thereby allowing for each species analyzed to be assigned one of the following allergenicity classes: null (when the APV is 0), Low (APV between 1 and 6), Moderate (APV between 8 and 12), High (APV between 16 and 24) and Very High (APV between 27 and 36) as previously done by Cariñanos et al. (2014) and Cariñanos & Marinangeli (2021).

2.4. Spatially analyzing tree allergenicity patterns and vulnerability hotspots

We then analyzed for spatial patterns in the APV of Bogota's urban forest and to identify specific vulnerable populations as defined in the following "Ecosystem disservices, susceptibility to allergenicity and vulnerability" section. First, we tested if the distribution of allergenic urban trees in Bogota was randomly distributed via Moran's I (Anselin, 1995) and if clustering occurred in areas of interest with vulnerable populations. We then mapped the spatial distribution of Bogota's urban trees according to the following four most relevant APV classes: High, Moderate, Low, and Non-allergenic.

We also analyzed whether the clustering of highly allergenic trees was related to sociodemographic conditions in vulnerable neighborhoods; please refer to the following section for methods used to determine vulnerability. We tested this relationship based on the abundance of highly allergenic trees present within each socioeconomic stratum. Data were standardized to the highest abundance for the Cluster analysis, a multivariate technique for identifying groupings of similar conditions into mutually exclusive classes (McGarigal et al., 2000). Specifically, we used a hierarchical cluster analysis with a Ward's method to minimize heterogeneity within a cluster while maximizing heterogeneity between clusters. This method is commonly used in ecology since it allows for better classification of groups based on socio-ecological features (Steenberg et al., 2015). We also used a Generalized Linear Model (GLM, with a binomial family and logit link function) to test if any sociodemographic variables were related to a higher abundance of allergenic tree. We used the number of individuals classified as highly allergenic as the dependent variable while the independent variables were level of education, age, and socioeconomic strata. In addition, we used Multivariate Analysis of Variance (MANOVA) to test for the effects of tree cover and the strata and locality-level abundance of allergenic species. All statistical analyses were done in RStudio Version 3.3 as well as its '*ape*', '*cluster*' and '*nmle*' packages (RStudio Team 2020).

2.5. Ecosystem disservices, susceptibility to allergenicity and vulnerability

We then used findings from our first two objectives to further explore the impacts of allergenic trees and ecosystem disservices on vulnerable populations. Specifically, we focused on the following vulnerability factors based on Adger (2006), Flanagan et al. (2018), Kaÿmierczak (2018), and Toro et al. (2012): socioeconomic strata, resident's age, locality, and health access in the general area (Dennis et al., 2012). District-level population information from Secretaria de Integración Social (2018) and available spatial information from SDP (2022) was used to delineate socioeconomic strata and localities. Since no neighborhood-level public health or morbidity data was publicly available for our study, we used district level data from DANE (2018) to obtain age ranges for the population. Based on this, we defined district-level, vulnerable populations in Bogota as those: residing in strata 1 and 2, that were less than 9 years of age and older than 60 years of age, and with limited access to health care centers (Secretaria de Integración Social, 2018; Toro et al., 2012). Finally, we identified localities and *Unidad de Planification Zonal* districts (i.e., neighborhoods) with vulnerable sociodemographic groups and a presence of moderate and high APV trees as measured using number of trees (i.e., high frequency) and tree cover (% tree cover).

3. Results

3.1. Tree structure, composition and allergenicity

Overall, trees had greater DBH in the localities of Teusaquillo and Barrios Unidos. Tree crown area was greatest in Teusaquillo and Chapinero and tree height was greatest in Usme and Barrios Unidos; Santa Fe had taller trees with lower DBHs. In terms of socioeconomic strata, Tree DBH and crown area was greatest in Strata 6 and 4 while height and DBH were lowest in strata 1 and 2 (Table 1; Appendix A).

In terms of composition, we found that approximately 41% of Bogota's 228 species had no allergenicity rating information available (Appendix C). Results show that of the total number of species, 17%, 18%, and 25% had an APV value of high, moderate, and low, respectively (Appendix C), while approximately 41% of species were classified as being non-allergenic. In terms of pollination strategy, 67% were

Table 1
Allergenicity relevant structural characteristics for public urban trees, according to socioeconomic strata, in Bogota, Colombia with a Diameter at Breast Height greater than 2.5 cm and 2.0 m in height.

Socioeconomic strata	Diameter at Breast height (cm)		Height (m)		Crown area (m^2)		number
	Median	Mean	Median	Mean	Median	Mean	n
1	7.9	12.7	4.2	6.3	7	15.6	10,421
2	10.8	15.7	4.9	6.8	9.6	19.7	70,874
3	14.1	19.6	5.2	6.8	13.2	24.7	99,501
4	16.2	22.9	5.6	7.4	16.1	31.3	37,974
5	13.7	20.8	5.9	7.7	15.8	30.3	29,948
6	15.9	23.6	6.2	8.1	18.1	34.4	25,166
Missing strata designation	12.4	18.2	6.0	7.9	12.6	24.6	171,237

entomophyllic, 16% zoophyllic (i.e., birds, bats, primates), 14.5% anemophyllic, and 3% were a mix (i.e., ambiphyllic). The species *Acacia melanoxylon, Acacia decurrens, Cupressaceae, Fraxinus chinensis* and *Eucalytpus globolus* were the most common highly allergenic public urban trees in Bogota (Table 2). The localities of Suba and Usme had the greatest numbers of high and moderate APV trees, however, this is in part due to the large areal extent of these two localities (Fig. 1).

3.2. Spatial and socioeconomic dynamics of urban tree allergenicity

Given the distribution of tree sizes across the study area's localities, the wide range in numbers of public trees per unit area, and structural metrics across the different localities (Table 1); we explored spatial and socioeconomic dynamics at a neighborhood scale called *Unidad de Planification Zonal* district (UPZ hereafter) using Moran's I. The Moran's I analysis found that there was spatial autocorrelation of the trees according to the 3 allergenicity classes, specifically high (p-value 0.026), moderate (p-value 0.01) and no APV (p-value 0.019); thereby corroborating our use of the hierarchical clustering technique in our analyses.

Accordingly, the hierarchical cluster analysis identified 3 distinct clusters and that the distribution of high APV trees followed a trend towards specific UPZs (Fig. 2; Appendix D and E). Cluster 1 included the least number of UPZs ($n = 7$) and was characterized by the highest abundance of allergenic trees (more than 20,000 individuals). This same cluster had less than 2% of its population in the most affluent Strata 6, and nearly 25% of its population corresponded to vulnerable population (i.e., less than 9 years of age and older than 60 years of age). The second cluster included 18 UPZs with a moderate abundance of highly allergenic urban trees (20,000 and 2000 individuals). Cluster 2 had between 20 and 30% of its populations as vulnerable and 3% of its population belonging to Strata 6 ($n = 22$ UPZs). Finally, cluster 3 was the most numerous ($n = 79$ UPZs), however there were no discernable spatial trends regarding the UPZ's sociodemographic characteristics. A description of the UPZs can be found in https://osgis.co/cual_es_mi_upz/). Our GLM results found no significantly statistical relationships between the sociodemographic characteristics of the UPZs and the abundance of highly allergenic trees.

Table 2
The ten most common public urban trees and their Allergenic Potential Value (APV) in Bogota, Colombia.

Species	APV	Number of Trees	Relative to the total public tree population
Sambucus nigra	Low	82,068	18.0%
Acacia decurrens	Moderate	53,479	12.0%
Pittosporum spp.	Low	50,758	11.0%
Acacia melanoxylon	Moderate	41,779	9.0%
Fraxinus chinensis	High	40,225	9.0%
Cupressus sempervirens	High	36,114	8.0%
Eucaliptus globulus	Moderate	34,734	7.8%
Paraserianthe lophanta	NA	28,952	6.5%
Cotoneaster multiflorus	Low	28,662	6.4%
Tecoma stans	Low	26,922	6.0%

*NA refers to No Available information and that APV could not be assigned to the species because of lack studies reporting its pollination type or allergenicity of its pollen. We note that many of these species are entomophiles and might vary the range from non-allergenic to high APVs.

3.3. Allergy related ecosystem disservices to vulnerable communities

The localities of Engativa, Santa Fe, Suba, and Bosa had the greatest amount of highly allergenic% tree cover (Fig. 3). Engativa had more than 10% of its public tree cover assigned as higher APV values. The localities of Usme, Fontibon, Chapinero, San Cristobal, and Ciudad Bolivar were the localities with the greatest amount of moderate APV public tree cover (Fig. 3). Fontibon and Usme have more than 70% of its trees in this allergy category, thus indicate a higher level of ecosystem disservices for this vulnerable community. Chapinero had a slightly better situation with 40% of its tree cover in the moderate APV category. The locality of Kennedy shows improved conditions for its vulnerable communities since less than 5% of the tree cover is classified as High or Moderate APV (Fig. 3).

We analyzed the effects of allergenic urban forests to vulnerable communities by focusing on 11 of the localities from Fig. 3 based on: (1) the abundance of high and moderately allergenic tree species, (2) their frequency in terms of total population at the locality-level and (3) the% of public tree cover in that locality (Table 1; Appendix B). We found that many of the peri-urban trees in the localities of: Bosa, Ciudad Bolivar, San Cristobal, Suba and Tunjuelito consisted of non-native *Acacia* spp., *Eucalyptus spp*., and *Cupressus* spp.; trees that were classified with high APVs and thus highly allergenic (Table 3). More inner urban areas such as Kennedy and Engativa had different and more diverse species assemblages including: *Alnus* spp., *Salix* spp., *Schinus spp,* and *Szygium spp*. (Table 3). As shown in Fig. 3, Engativa had a lower abundance of lower allergenic tree species. In addition, our MANOVA found that the socioeconomic strata had no effects in relation to the abundance of either moderate or high allergenicity species. However, we found that there was a statistically significant relationship between the abundance of allergenic trees and public tree cover (p-value <0.001). There was only a moderate difference (p-value 0.01) regarding the abundance of moderate allergenicity trees.

Finally, we also selected the locality of Engativa for a neighborhood-scale case study to explore the effects on vulnerable populations from allergy-related urban tree ecosystem disservices. For this analysis we selected neighborhoods based on the amount of allergenic tree frequency and our vulnerability factors. Overall, Engativa had 9.8% of its population composed of children and adolescents and 13% of individuals older than 60 years old (Secretaría de Integración Social, 2018). There were also only 3 neighborhoods with health clinics, but these same areas had a notable absence of trees: Engativa zona urbana (4 trees), Bolivia (30 trees), and Ciudad Bachue (5 trees). Other neighborhoods without clinics did have greater public tree cover (m^2) with high and moderate levels of allergenicities (Table 4). Thus, vulnerable residents living near high and moderate APV trees in the neighborhoods

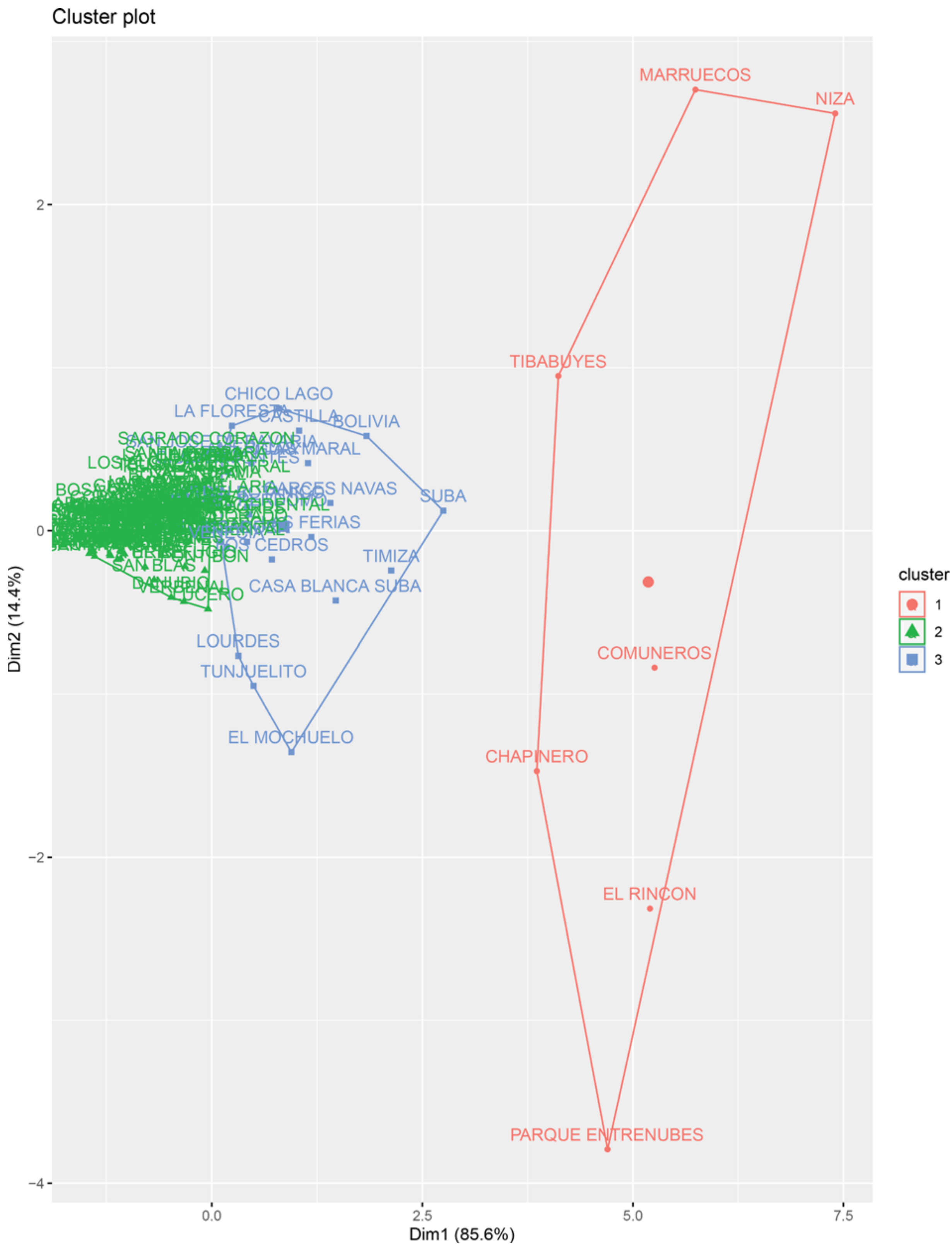

Fig. 2. Ordination indicating the clustering and relative similarity of different *Unidad de Planification Zonal* districts (UPZ) according to the abundance of highly allergenic urban trees in Bogota, Colombia. The x and y axes represent how much of the data variability is explained by their ordination in the orthogonal space.

(e.g., La Faena), might be negatively affected by this ecosystem disservice (Table 4). However, and most notably, the lack of public tree cover – and likely lack of tree cover in private residential and commercial areas as well- in these neighborhoods such as Villas de Alcala indicate not only an absence of this ecosystem disservice (i.e., allergies) but also other ecosystem services that could improve well-being in these neighborhoods.

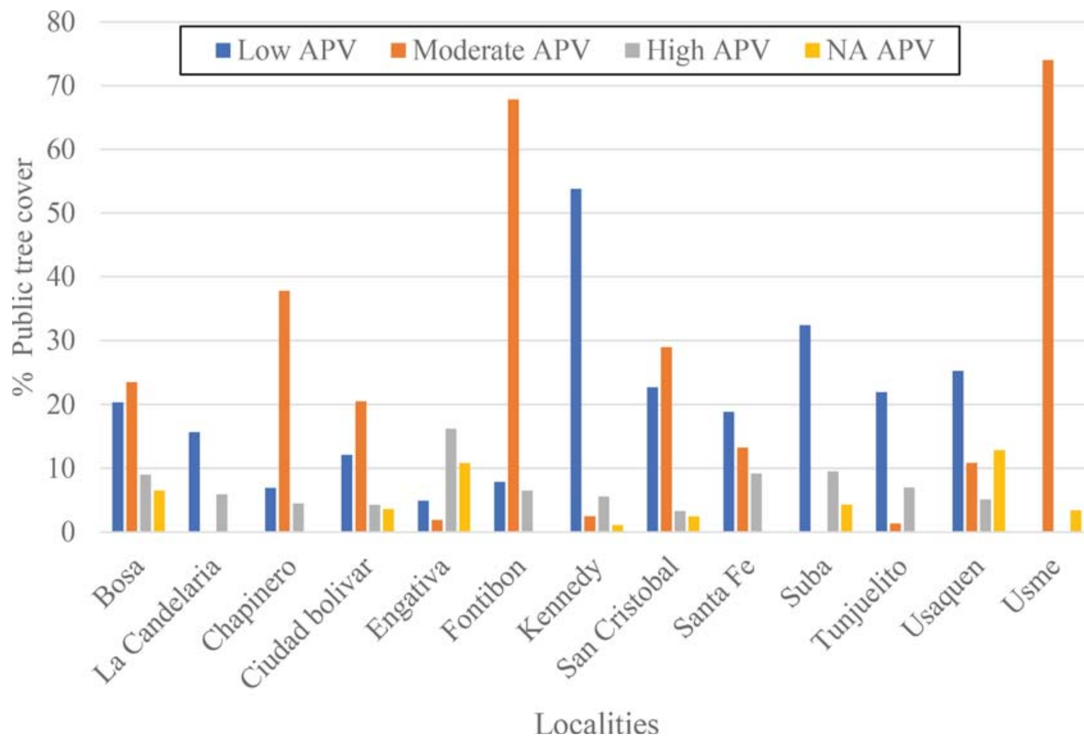

Fig. 3. Percent public tree cover for the most abundant species (i.e., 50–55% of the localities' tree population) with high, moderate, low, and unclassified allergenicity (NA) Allergenicity Potential Values (APV) in localities with a high occurrence of low-income Strata 1 and 2 neighborhoods in Bogota Colombia.

4. Discussion

This study analyzed the structure, composition, and allergenicity of a Neotropical urban forest in the Global South; a context that is little studied in comparison to urban forests from temperate high-income countries (Dobbs et al., 2018; Escobedo et al., 2015). Our approach shows how an ecosystem disservice such as allergies can be estimated using available data and information to assess how communities and individuals can be potentially impacted using relevant measures of vulnerability. As such, this study is a first step in improving our knowledge on the ecosystem disservices of tropical urban forests and the allergenic potential of tree species in the Neotropics.

4.1. Tree structure, composition and allergenicity

We found that tree structure and composition and related APVs were inequitably distributed across our study area (Tables 1 and 2; Fig. 1). Specifically, results on APVs show that of Bogota's 228 public tree species, 45% have high to moderate allergenic potential, and 16.7% have attributes that highly contribute to allergenicity, in particular: a wind pollination strategy, flowering periods of more than 6 weeks, and a reference indicating its allergenicity (Table 2; Appendix C). In terms of the tree species composition, 17% of the most abundant species are highly allergenic and corresponding to only two species, while moderate allergenic potential corresponds to 28% of the most abundant trees comprised of three species (Table 3). The distribution, abundance, and composition of tree species across a city influences the pollen emissions and concentrations in specific areas, given that species composition is one of the main strategies in minimizing the allergenic impact and ecosystem disservices of green areas (Cariñanos & Casares-Porcel, 2011). Species distribution is not only important at the city scale but also at finer scale, where distribution should also be accounted for, since higher socioeconomic strata tend to show greater tree diversity than lower socioeconomic strata (Escobedo et al., 2015). Our findings also corroborate other studies from regions in the Global North such as North American where less than 10% of the urban forests are reported to be composed of low allergenic trees (Nowak & Ogren, 2021); thus, emphasizing the need to improve tree selection in urban plantings to promote healthier cities.

Our results also show that the introduction of non-native species is one of the main contributors to the presence of allergenic trees. Species such as *Acacia japonica* (*A. melanoxylon*) and the black acacia (*A. decurrens*), which were introduced for reforestation objectives, are characterized by moderately invasive traits (Díaz Espinosa et al., 2012) and are largely abundant in the city. Further, *Acacia* pollen is reported to strongly induce rhinitis and asthma, and even dermatitis and "pollen toxemia" (Woodehuse, 1971). The species also has a moderate cross-allergenicity with pollen from *Prosopis juliflora* and grasses from the Poaceae family (Shamsbiranvand et al., 2014); the latter having about 52 different species present throughout urban and peri-urban Bogotá. Similarly, the invasive nature of other species, also needs to be considered as these can become established over large areas of Bogota (Álvarez-Gómez, 2018) and its peri-urban areas (Saavedra Ramírez, 2014). *Schinus molle*, in particular, is a species native to the Central Andes with a wide distribution in tropical and subtropical areas of South America, with sometimes invasive traits. Its pollen is cited as one of the most relevant allergens in Mexico (Rosas-Alvarado et al., 2011) and presents cross-allergenicity with other species of the Anacardiaceae family such as *Anacardium occidentale* and *Mangifera indica* (Funes et al., 1999).

Fraxinus chinensis comprised 3.7% (40,225 trees) of all public trees in Bogotá. It was introduced to Colombia in the 1960s for use in afforestation projects (Saavedra-Ramírez, 2014). The species is considered one of the most successful exotic species in urban areas due to its rapid growth and regeneration capacity (Tovar-Corzo, 2007), being frequently found in parks and streets throughout the city. Thus *Fraxinus chinensis* pollen and its cross-reactivity with other highly allergenic Genera such as *Olea* spp. and *Ligustrum* spp. (Cariñanos et al., 2002) and other native and exotic species (e.g., *Chionanthus* spp.) needs to be considered in long term urban forest planning (Cariñanos & Casares-Porcel, 2011). The trade-offs between short term (e.g., increase canopy cover, reforestation and aesthetics) versus long-term objectives (biodiversity and allergies)

Table 3
Most frequent trees with a High (H) and Moderate (M) Allergenic Potential Value (APV) in localities with a high occurrence of low-income Strata 1 and 2 neighborhoods in Bogota Colombia.

Locality	Species	APV	Species frequency (%)	Public tree cover (%)
Bosa	*Cupressus sempervirens*	H	5.8	8.9
	Syzygium paniculatum	M	4.9	2.0
	Tuja spp	H	4.2	<1
	Eucalyptus sp. *globulus*	M	3.0	21.4
	Total	H	10	9
		M	7.9	23
Chapinero	*Pinus patula*	M	22.4	25.6
	Acacia decurrens	M	11.6	12.2
	Alnus acuminata	H	4.7	4.5
	Total	H	4.7	4.5
		M	34	37.8
Ciudad Bolivar	*Acacia melanoxyon*	M	10.1	8.4
	Dodonea viscosa	H	7.2	<1
	Ligustum lucidum	M	5.1	1.8
	Acacia decurrens	M	3.8	10.2
	Schinus molle	H	3.4	3.4
	Total	H	10.6	4
		M	11	20.8
Engativa	*Tuja spp*	H	8.2	<1
	Alnus acuminata	H	7.6	11.2
	Syzygium paniculatum	M	7.5	1.9
	Salix humboldtiana	H	3.5	5.0
	Total	H	19.3	17.2
		M	7.5	1.9
Fontibon	*Syzygium paniculatum*	M	17.7	1.8
	Eucalyptus sp. *Globulus*	M	8.5	66.0
	Schinus molle	H	7.1	6.5
	Total	H	7.1	6.5
		M	26.2	72.5
Kennedy	*Tuja spp*	H	11.0	<1
	Syzygium paniculatum	M	6.4	2.5
	Schinus molle	H	4.3	3.5
	Cupressus sempervirens	H	3.3	1.9
	Total	H	18.6	6.4
		M	6.4	2.5
Usme	*Eucalyptus* sp. *Globulus*	M	28.5	65.0
	Pinus patula	M	6.1	8.6
	Myrsine guianensis	M	3.8	<1
	Total	M	38.4	74.6
San Cristóbal	*Eucalyptus* sp. *Globulus*	M	4.8	28.9
	Cupressus sempervirens	H	3.2	3.3
Santa Fe	*Platanus acerifolia*	H	21.2	9.2
	Acacia decurrens	M	8.4	13.3
Suba	*Cupressus sempervirens*	H	7.8	7.0
	Araucaria excelsa	H	3.0	2.5
Tunjuelito	*Ligustum lucidum*	M	9.2	1.4
	Cupressus sempervirens	H	5.7	7.0

shed a light on the potential tradeoffs between ecosystem services and disservices when planning for the maximization of urban forest benefits for sustainable and resilient cities (Pineda-Guerrero et al., 2021). Accounting for plant traits other than allergies and aesthetics is also important for accounting for these trade-offs. For example, trees in the Sapindaceae family in Bogota are common but have been reported to contribute little to overall carbon stocks (Escobedo et al., 2015) and

Table 4
Tree cover for the most abundant species (50–55% of the locality's tree population) with high and moderate Allergenic Potential Values (APV) in Neighborhoods lacking health clinics in the locality of Engativa, Colombia.

Neighborhood (Area km^2)	Tree cover (m^2) High APV	Moderate APV	Total APV (High and moderate)
Villas de Alcala (0.5)	7.9	63.8	71.7
La Faena (0.3)	1222.5	46.7	1269.2
La Riviera (0.3)	386.9	0.1	387.1
El Gaco (1.5)	547.8	0	547.8

therefore indicate the low potential of certain species for providing regulating ecosystems services (Predergast & Pearman, 2001).

Cupressus sempervirens, is also recognized as one of the largest contributors of atmospheric pollen (Díaz-Carmelo, 2017) and comprised 3.2% (36,114 trees) of Bogota's public urban tree population. The role of this species on allergenicity has been discussed in other studies (Pacini & Hese, 2012; Sánchez-Medina & Fernández, 1966). However, the high relative humidity characterizing Neotropical cities can be considered an influential factor in *Cupressus'* pollen allergenicity. Particularly, since the protein shortage of the pollen wall, facilitates grain rupture while airborne (Pacini & Hese, 2012), thus yielding a higher allergenic potency as reported in the Mediterranean region (Charpin et al., 2005).

Other species might also have unknown allergy potential. For example, *Dodonaea viscosa* (25,946 trees, 2.35% of the total trees in the city of Bogotá), is a species with unknown information regarding pollination mechanisms. However, the species has recently been determined to be an important source of allergenic pollen in its native range (Jones et al., 2021) and in tropical climate zones of India (Bai & Reddi, 1982). Other studies also indicate possible changes in the pollination strategy as an adaptation to climate change (e.g., increased aridity and temperatures; Harrington, 2008) and its poorly understood dioecy, since the same plant can present both male and female unisexual flowers (Rani et al., 2009). This corroborates our assigning this specie a high APV value and its relevance as a local allergen.

4.2. Spatial patterns in tree allergenicity and vulnerability

Our findings on tree species abundance and distribution patterns and trends at the city-level are highly relevant for better understanding the allergy potential across Neotropical cities. Our hierarchical cluster analyses indicates that trees with higher APVs trend towards specific districts in the city (Fig. 2). Accordingly, 30% of Bogota's public trees were in northern extreme of the city (Fig. 1; Table 1; Appendix A). Although these northern-most localities have traditionally been recognized as being more affluent, there are also disparities in terms of socioeconomic strata (Scopelliti et al., 2016). Conversely another 30% of all public trees were in southern localities with a predominance of people living in strata 1, 2 and 3 (Fig. 1). In general, strata 5 and 6 and the northern localities had greater tree heights, DBHs and crown areas, relative to Strata 1 and 2 and southern localities (Table 1). We noted that median and mean DBHs in strata 3 and 4 were greater than those in Strata 5. But we found that socioeconomic strata had no effects in relation to the abundance of highly allergenic tree species. That said, there were statistically significant relationships between the abundance of allergenic trees and public tree cover and a moderate difference regarding the abundance of moderate allergenicity trees. Escobedo et al. (2015) using the available data from this same inventory data, and Dobbs et al. (2018) using remote sensing, found similar patterns in the distribution of the urban forest. Therefore, in addition to an inequitable distribution of ecosystem services in Bogota, we are also finding inequities in the distribution of ecosystem disservices via urban forest allergenicity.

Indeed, we found that strata 1 and 2 had a higher frequency of high-moderate APV trees relative to other strata (Fig. 3 and Table 3). Furthermore, in our UPZ-level case study, we found that certain vulnerable neighborhoods without clinics and with vulnerable population, had a noticeable absence of overall total tree cover (e.g., Villas de Alcala; Table 4); but of that tree cover a high percentage was of high and moderate APV. This lack of urban forests present a conundrum that is probably common in many urban forests of the Global South, specifically a lack of not only ecosystem services (e.g., carbon stock, fruit production, air quality improvement; Escobedo et al., 2015), but ecosystem disservices as well.

4.3. Allergy related ecosystem disservices in vulnerable communities

Our findings show that information and knowledge on taxa, pollen-related plant traits, and urban ecology can be used to better inform the management and planning of low allergenicity tropical urban forests in the Global South. In terms of spatial distribution, three of the localities with some of the lowest socioeconomic strata in the city - Ciudad Bolivar, Usme and Tunjuelito - had the lowest tree diversity in the city; a phenomenon typical of cities (Fig. 3; Dobbs et al., 2018). Ciudad Bolivar is one of the localities in which there is a greater number of species with moderate and high allergenicity (Table 3), including *Acacia melanoxylon* and *Dodonaea viscosa* which are notable in their frequency with 10.1% and 7.2% respectively, as well as the prevalence of *D. viscosa* and *Schinus molle;* species with high allergenicity.

Overall, peri-urban areas indicate a greater presence of native and invasive species that have generally been used for timber plantations and reforestation purposes such as *Eucalyptus* spp. *Cuppresus* spp., and *Acacias spp* (Table 2). Conversely more inner urban and core areas had other types of non-native trees such as *Schinus spp, Szygium spp*., and *Salix spp* (Tables 2 and 3). Similarly, findings showing locality-level species distribution, indicate that the greatest number of allergenic species in the same localities that have an overall lack of tree diversity. For example, Fontibon and Usme have close to 70% of their already low levels of tree cover, comprised of moderate to high APV tree species. Such environmental justice situations present an opportunity for a more equitable and sustainable improvement for new plantings and tree replacements with non-allergenic species to decrease impacts to these vulnerability communities. The largest number of *Cupressus* spp. trees are in the localities of Bosa (5.8%), Kennedy (3.3%), San Cristóbal (3.2%), Suba (7.8%) and Tunjuelito (5.7%). These same localities have greater populations of people living in Strata 1 and 2, thus vulnerable populations in these localities might have a greater exposure to pollen and, therefore, a greater symptomatic response. Studies have documented the association between socioeconomic strata and a more frequent diagnosis treatment of allergic rhinitis (Peñaranda et al., 2016; Stewart et al., 2001).

Previous studies show that allergies from urban vegetation are as frequent in the tropics as they are in temperate regions; however, their prevalence, risk factors, sensitizers and triggers are likely different (Alzate Guarín et al., 2015). Similarly, more equatorial areas in Colombia show a higher prevalence of allergies in children as they get older (Caraballo et al., 2016). Sensitivity to outdoor allergens in the tropics is also tempered by lower levels of seasonal asthma and allergic rhinitis relative to temperate climates (Dennis et al., 2012). Indeed, information on local flora – as shown in this study - provides insights for more resilient cities. Specifically, mitigating public health concerns such as allergic rhinitis in vulnerable populations- a disease burden recognized as highly prevalent in many Latin American countries - that has been largely overlooked in national health strategies (Dennis et al., 2012). The results discussed above can also be applied to gain a better understanding of the environmental justice implications of tropical urban forests and their ecosystem disservices (Escobedo et al., 2015; Pineda-Guerrero et al., 2021) as well as the importance of proper tree species selection as a low-cost Nature-Based Solution that can improve public health and well-being in the Global South.

We do however recognize some limitations in our study. First, we recognize that the 2006 (DANE-JBB, 2007) data that we used was rather dated and limited to only public spaces and land tenures. However, to our knowledge, Bogota's urban forest inventory is the only publicly available database with complete inventory of all public trees, shrubs, and palms Neotropical Latin America. Although other data do exist and have been used in the study area, they are often only partial inventories, have low sample sizes, are not heterogeneously distributed throughout the city; and most importantly they are simply not publicly available (Barona et al., 2020; Sierra-Guerrero & Amarillo-Suárez, 2017). That said, the 2006 database is still used for policy formulation and decision making and the data has also been used for other more recent studies dealing with issues such as urban inequities and crime in Bogota (Escobedo et al., 2015 and 2018).

Second, strata-level census sociodemographic and vulnerability data were not available for most areas in Bogota. Thus, including public health data in addition to the approach we laid out in this study, could better inform the public and decision makers on the link between ecosystem disservices and impacts to public health outcomes such as asthma related diseases. Third, we also recognize that the causal links between ecosystem disservices and vulnerable populations in Bogota were not directly measured in this study; despite the importance of the perception of citizens towards the socioeconomic and environmental (i.e., allergies) costs related to green spaces in Bogota (Pineda-Guerrero et al., 2021; Scopelliti et al., 2016). That said, in this study we present one of the first attempts to relate the role of allergies as an ecosystem disservice in tropical forests of the Global South.

Accordingly, future research could use our approach and other methods to better account for the effects of weather (i.e., wind speed and direction) and climate change on pollen production. In particular, both temperature and precipitation are known to be primary drivers of the daily emission, dispersion, and concertation of airborne pollen (Haberle et al., 2014) and could therefore be included by other researchers as part of more advanced analyses and studies. Clinical trials and longitudinal studies measuring the effects of pollen production and concentrations on respiratory infections in people living near allergenic trees could also be further investigated. Furthermore, ambient air pollutants such as ozone and particulate matter could also be modeled to estimate effects on pollen production, emissions, concentrations, and dose responses from the existing urban forest (Luschkova et al., 2022; Sarmiento, 2014). The seasonality of pollen production is also affected by the growing season, thus climate change can also be studied by accounting for the effects of induced early pollen onset and the introduction of pollen diversity resulting from plant assembly shifts due to increased temperatures (Luschkova et al., 2022).

5. Conclusions

Out study contributes to the growing need to better understand and quantify the ecosystem disservices and environmental injustices in cities; particularly those in the Neotropics. The ecosystem disservice resulting from allergenic trees in a tropical city in the Global South corroborates similar findings from urban forests in the Global North, particularly in terms of inequities in tree cover and diversity of the urban forest according to socioeconomic realities. Similarly, the role of introduced trees and their short and long-term effects on not only native flora, but human well-being via allergies, highlights the need to regulate and restrict the use of invasive species. Most importantly it shows the need to also promote the use of tree with low to no allergenicity as this could lead to an improvement of public health, especially in vulnerable communities.

Our study can also be used as a basis for future epidemiological research in the tropics. Particularly, to better understand the mechanisms in likely future increase in pollen that can exacerbate the impact on respiratory infections by increasing the severity of allergy sufferers' symptoms and their acquisition of new sensitization, especially for vulnerable populations that have less access to urgent hospital care. Indeed, these additional allergenicity impacts add to the need for information on how increased climate change burdens will be experienced by vulnerable populations in the Global South. Also, the improvement of spatially explicit monitoring systems for respiratory diseases and ongoing tree and plant pollen monitoring can be incorporated as part of public health systems to better help identify allergy hot spots in highly vulnerable areas. Such data can also be used to understand the spatial variation in allergenicity according to the phenological period for a wide range of plants. In addition, the support of understudied pollen frequency and abundance from tropical species can have important implications for decision making in cities located in these biomes, which tend to also concentrate vulnerable communities. This is especially relevant under climate change that will have implications for pollen productions as well as increased health and adaptation burdens in cities.

The role of tree allergies and ecosystem disservices in environmental justice issues warrants further attention. Indeed, information on allergen emission sources and areas of greater allergenic risk to vulnerable populations could lead to opportunities for management and planning guidelines to reduce the allergenic potential of tree allergenic and appropriate tree species selection criteria. A more integrated and transdisciplinary approach using urban forest structural and diversity data along with socioeconomic and demographic characteristics, as well as public health outcome data and systems modeling could offer novel insights into tree allergenicity dynamics. Such information is key for improving human well-being in resource limited environments and could also be used to better understand the role of ecosystem disservices in Neotropical cities.

Declaration of Competing Interest

The authors certify that there is no actual or potential conflict of interest in relation to this article.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2022.104343.

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