

CASE REPORT

Removal of atmospheric pollutants by the urban forest in the Aburrá Valley

Maria del Pilar Arroyave-Maya^{1*}, Martha Isabel Posada-Posada¹, David J Nowak², Robert E Hoehn²

¹ Universidad EIA, Envigado, Colombia. E-mail: maria.arroyave@eia.edu.co

² Usda Forest Service Northeastern Research Station 5 Moon Library, Syracuse, NY 13210, USA.

ABSTRACT

Urban forests provide different ecosystem services, such as the removal of atmospheric pollutants, carbon sequestration, water and microclimate regulation, and habitat for wildlife. This improves environmental quality and the well-being of the population. In this study, the structure of the urban forest of the Aburrá Valley was analyzed and its contribution to the removal of atmospheric pollutants was estimated and valued using the i-Tree Eco software. For this purpose, 398 forest sampling plots were established and secondary information on climatic and pollution conditions was used. A 23% tree cover was found in the study area and a removal of 228 tons of pollutants per year (approximate value of 2.1 million USD). Finally, strategies are recommended for the optimization of this service and the creation of mechanisms to compensate for the loss of tree cover.

Keywords: Air Quality; Ecosystem Services; Urban Forestry

ARTICLE INFO

Received: 9 August 2020
Accepted: 16 October 2020
Available online: 23 October 2020

COPYRIGHT

Copyright © 2020 Maria del Pilar Arroyave-Maya, *et al.*
EnPress Publisher LLC. This work is licensed under the Creative Commons Attribution-NonCommercial 4.0 International License (CC BY-NC 4.0).
<https://creativecommons.org/licenses/by-nc/4.0/>

1. Introduction

Currently 54% of the world's population lives in urban areas and it is expected to reach 66% by 2050^[1]. In Latin America, approximately 80% of the population lived in urban areas in 2010, making it the most urbanized region in the developing world^[2]. In the case of Colombia, the urban population represents 76% and according to projections, it is estimated that by 2050 the population will reach 52.6 million inhabitants, equivalent to 86% of the total population^[3].

In order to meet the needs of this growing population, infrastructure is required for housing, basic services, industry and transportation. Similarly, increasing urbanization results in a number of environmental problems that negatively affect human health and well-being. Cities are sources of particulate matter emissions and polluting gases, carbon monoxide, ozone, nitrogen and sulfur dioxides, which affect air quality, as well as greenhouse gases that affect the Earth's climate, carbon dioxide and others^[4].

Air pollution is a major risk to human health. In 2016, 91% of the world's population lived in places where the maximum concentration limits for air pollutants defined by the World Health Organization^[5] were not met. This situation leads to an increase in heart disease, respiratory diseases and lung cancer^[6,7]. An estimated three million people die each year from urban outdoor air pollution, more than half in developing countries, according to WHO^[8]. Approximately 3% of deaths from cardiopulmonary disorders and 5% of deaths from lung

cancer are attributable to particulate matter^[9].

In many Colombian cities there are high levels of pollution that deteriorate public health and the quality of life of its citizens^[10]. In the Aburrá Valley, specifically, air quality levels have been shown to be detrimental to metropolitan inhabitants^[11]. The records of the air quality monitoring network (Redaire) report that particles smaller than 2.5 micrometers (PM_{2.5}) and ozone (O₃) are the main pollutants responsible for generating an increasing number of acute episodes of air pollution in the metropolitan region of the Aburrá Valley^[12].

During several days in 2016, 2017 and 2018, critical episodes of air pollution were generated in the Aburrá Valley, mainly associated with high concentrations of PM_{2.5} (**Figure 1**), which caused orange and red alerts phase I^[13,14]. For this reason, the authorities had to take measures, such as restricting the mobility of vehicles, in order to reduce pollutant emissions and thus avoid severe impacts to the health of the population, following the protocol of the Operational Plan to face Critical Air Pollution Episodes^[13]. It is important, therefore,

to propose different strategies to contribute to the improvement of air quality conditions.

According to Baró *et al.*^[15] and Willis and Petrokofsky^[16], increasing tree cover in cities can improve environmental quality and thus the well-being of the urban population. However, trees must be planted and managed strategically to achieve these goals^[17].

The urban forest is defined as the network or system comprising the woodland, groups of trees and individual trees located in urban and peri-urban areas^[18]. As an ecosystem, it has the potential to offer different types of services (cultural, provisioning, regulating, supporting and habitat) that increase the well-being of the population and the resilience of cities^[19]. Among them, the following can be highlighted: improvement of air quality^[20], reduction of solar radiation and temperature^[21], carbon sequestration^[22] and biodiversity conservation^[23]. Urban forest services have been quantified and valued in different cities around the world^[15,24-27].

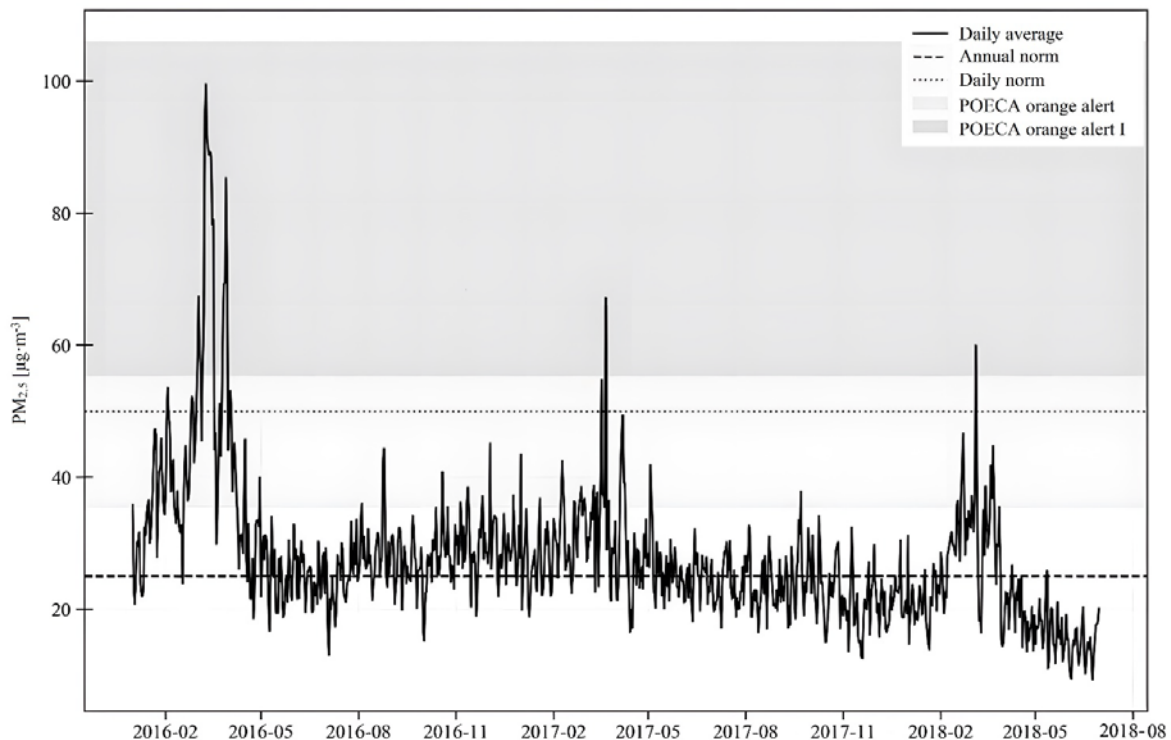


Figure 1. Behavior of daily averages of PM_{2.5} concentrations in the Aburrá valley in the period between January 2016 and June 2018, with reference to the maximum permissible level of PM_{2.5} daily (24 hours) and annual at the national level according to Resolution 2254 of 2017^[28] and the ranges established in the Protocol of the Operational Plan to Confront Critical Air Pollution Episodes in the jurisdiction of the Metropolitan Area of the Aburrá valley^[13]. Source: own elaboration with data taken from SIATA^[14].

However, in Colombia, and even in Latin America, there are very few studies that evaluate these ecosystem services^[22,30]. The objective of this research was to estimate and value the removal of atmospheric pollutants by the urban forest in the Aburrá Valley, Colombia, and to provide management strategies to optimize this service. The methodology used and the results obtained in this study can be applied in other Latin American cities, which will contribute to increase the adaptation of cities to global environmental change.

2. Materials and methods

2.1 Study area

The study was conducted in the urban area of the Aburrá Valley (**Figure 2**), which has an extension of 192.7 km² and a population that reaches more than 3.5 million inhabitants^[30]. It includes 10 municipalities, one of them Medellín, the second largest city in Colombia. It is located in the central Andean mountain range between 1,300 and 1,800 m altitude, at 6°15'N, 75°36'W; the average annual temperature is 17 °C in the upper parts of the slopes and between 20 °C and 24 °C in the lower parts of the valley; precipitation fluctuates between 1,400 mm·year⁻¹ in the central part and 2,800 mm·year⁻¹ in the northern part^[31].

2.2 Establishment and measurement of sample plots

For the estimation of pollutant removal, it was necessary to analyze some variables of the trees that are part of the urban forest. For this purpose, a random sampling of the forest component was used using a land cover map generated with a supervised classification process on a satellite image with a resolution of 50 cm of the urban area of the Aburrá Valley. The plots were located in the tree cover information layer, that is, the existing tree vegetation in the urban area associated with parks, squares, roads, water bodies, hills, among others, as illustrated in **Figure 2**. 398 circular plots of 400 m each were distributed over this information layer, using a random coordinate generator by means of a geographic information system. Subsequently, maps were obtained with the spatial location of each of

the plots. Field work was carried out between September and November 2015. The plots were located using a GPS and the maps containing the exact position of the center of the plots.

Generally speaking, the number of plots for i-Tree Eco projects is 200^[32]. This value was almost doubled in the project due to the large size of the valley. The plots were located in both public and private areas. In the process of characterizing the plots and the existing vegetation in each plot, the protocol described in the i-Tree Eco Manual^[32] was followed. The information collected in the field for each plot was the following: address; geographic coordinates of the plot center; reference object (a fixed element on the territory that allows the subsequent location of the plot) and distance from the plot center to it; land uses within the plot and its percentage; percentage of tree cover, percentage of shrub cover; percentage of potentially plantable space (that has the possibility of planting trees) and soil cover (hard ground, grass, water).

The information recorded in the field for each of the tree individuals located within the plot was as follows: species, diameter at breast height (DBH), total height, height to live crown, height to base of crown, crown width, percentage of the crown with dry or dead branches, percentage of impervious surface under the crown, and mechanical and phytosanitary damage. If the species was not found in the model, secondary information available in the literature on growth rate, leaf permanence (evergreen, semi-deciduous, deciduous), longevity and continent of origin was compiled. This information was sent to the Forest Service to be incorporated into the model.

Based on the information recorded in the plots, the most abundant species were identified and the importance value index (IVI, sum of the abundance, basal area and relative frequency of each species), the diameter structure and the percentage of individuals with crown deterioration greater than 20% were estimated.

2.3 Removal of contaminants

The estimation of pollutant removal was performed using the i-Tree Eco v 5.0.9 model^[32],

which requires tree, air quality and climate information for a full year of the study area. Pollution data were provided by the air quality network in the Aburrá Valley (Redaire). Hourly concentration data for carbon monoxide (CO), ozone (O₃), nitrogen dioxide (NO₂), particulate matter less than 2.5 µm (PM_{2.5}) and particulate matter less than 10 µm (PM₁₀) during 2014 were used. Since the Aburrá Valley has different air quality conditions between the northern, middle and southern regions, three projects were evaluated separately, each with information from the most representative station in each zone. Subsequently, the results from the three zones were aggregated to obtain the results for the entire valley.

Precipitation data for 2014 was provided by IDEAM from the Olaya Herrera airport station in the city of Medellín. Air temperature, wind direction and wind speed data for 2014 were provided by Redaire.

Once the field information was collected, it was entered into the online platform of the U.S. Forest Service and sent for processing. The report with the results was then received.

The i-Tree Eco model estimates the capture of pollutants and their associated monetary value, as well as the improvement of air quality by the urban forest. The pollutant flux (F , in $\text{g}\cdot\text{m}^{-2}\text{s}^{-1}$) is estimated as $F = V_d * C$, where V_d is the deposition velocity in ms^{-1} and C is the pollutant concentration (in $\text{g}\cdot\text{m}^{-3}$)¹. The associated monetary value is estimated based on the average values of externalities in the U.S. for each ton of pollutant.

To determine the relative contribution of the urban forest to the improvement of air quality, the values of pollutant emissions were compared with those of removal by urban trees. Emissions were obtained from the reports of the Metropolitan Area Authority^[33] which corresponded to the year 2015, because those of 2014 were not available.

2.4 Management strategies

In order to propose management strategies to optimize the removal of pollutants by the urban forest, the information reported in different studies

on the subject was compiled and analyzed. Subsequently, the most relevant options for the Aburrá Valley were discussed.

3. Results

3.1 Structural characteristics of the urban forest

It was found that tree cover represented 23.3% of the urban area, with a density of 133 trees·ha⁻¹ and an approximate number of 688,000 trees. The species with the highest IVI were eucalyptus (*Eucalyptus saligna* Sm.), urapan (*Fraxinus uhdei* (Wenz.) Lingelsh.) and mango (*Mangifera indica* L.). The diameter structure had an inverted “J” shape, with a higher percentage of individuals in the smaller diameter classes, a percentage that decreases as the diameter increases, until only a few individuals remain in the larger classes. In relation to the evaluation of the phytosanitary condition, it was found that 5.1% of the total number of trees presented a percentage of crown deterioration greater than 20%.

3.2 Contaminant removal

A total annual removal of 228 t of air pollutants was estimated, where 12.3 t corresponds to carbon monoxide (CO), 49.1 t to nitrogen dioxides (NO₂), 32.1 t to PM_{2.5}, 60.4 t to PM₁₀ and 74.3 t to ozone (O₃). However, the data for CO and PM_{2.5} may be underestimated, since no reports of these pollutants were obtained from the station in the north of the Aburrá Valley.

Pollutant emissions in the Aburrá valley reported by the Metropolitan Area authority^[33] during 2015 are presented in **Table 1**, which also differentiates the emissions from each source (mobile and stationary) and the proportion of the removal of each pollutant by the urban forest. This table does not include ozone, because, although its removal was estimated, the emissions were not reported in the reports of the environmental authority of the Aburrá Valley. The monetary values corresponding to the elimination of pollutants are presented in **Table 2**.

¹ For more details on the model calculations, see Nowak and Crane^[26], Nowak^[34] and Nowak *et al.*^[20].

4. Discussion

The contribution of the urban forest in the Aburrá Valley to the elimination of particulate matter emissions is higher than that of gaseous pollutants (NO₂ and CO). If only industrial emissions of PM_{2.5} are considered, the removal by

the urban forest is equivalent to 9.3%, a significant value, especially because this pollutant has highly deleterious effects on human health. Similarly, for PM₁₀, the removal of 5.18% of emissions from stationary sources can be considered a significant contribution.

Table 1. Proportion of pollutant removal by the urban forest compared to emissions in the Aburrá Valley in 2015

Variable	Contaminant			
	CO	NO ₂	PM _{2.5}	PM ₁₀
Urban forest removal (t·yr. ⁻¹)	12.3	49.1	32.1	60.40
Emissions from mobile sources (t·yr. ⁻¹)	145,552	14,293	1,508	*
Contribution to urban forest removal (%)	0.01	0.34	2.13	*
Emissions from stationary sources (t·yr. ⁻¹)	3,213	2,979	345	1166
Contribution to urban forest removal (%)	0.38	1.65	9.30	5.18
Total emissions (t·yr. ⁻¹)	148,766	17,272	1,852	1,166
Contribution to urban forest removal over total emissions (%)	0.01	0.28	1.73	5.18

*Data not available. Emissions data were obtained from AMVA.

Table 2. Monetary value of pollutant removal by the urban forest for 2015

Contaminant	Value/ton * (US\$)	Total value (US\$)	Percentage of total economic value (%)
CO	1,619	19,914	0.9%
NO ₂	11,397	559,593	26.3%
O ₃	11,397	846,797	39.8%
PM _{2.5}	7,609	244,249	11.5%
PM ₁₀	7,609	459,584	21.6%
Total		2,130,136	100%

*The monetary value is estimated in i-Tree Eco based on the average values of externalities for each ton of pollutant.

Table 3 shows a comparison of the number of trees and the removal of atmospheric pollutants from the urban forest in different cities around the world in which the i-Tree Eco model was applied. In contrast to the Aburrá valley, some similar values are found, for example, San Francisco has 668,000 trees and the pollutant removal is 276 t^[20].

In any case, given that there are several factors that affect the removal of pollutants by urban forests, caution should be exercised when analyzing the data. For example, according to the study by Baró *et al.*^[15] Barcelona has 1,419,823 trees (2.1 times more than the Aburrá valley), but the pollution removal is 305 t (1.3 times more than the Aburrá valley). This is probably due to the higher concentration of pollutants in our study area, climatic conditions or tree characteristics such as leaf area and leaf permanence throughout the year. Although the Aburrá valley is located in the tropical zone, where there are no climatic seasons with marked differences in temperature as in temperate

zones, it is necessary to clarify that there are seasons with variations in rainfall regimes and some species are deciduous during the dry season.

However, **Table 3** shows that some cities have lower tree cover and a higher number of trees (London) than others (San Francisco and Edinburgh). This can be explained by the existence of high-density tree stands, which probably correspond to remnants of natural forest. Pollutant removal depends on pollutant concentration, climatic conditions and species characteristics. For this reason, the comparison of removal values between different sites must take these factors into consideration.

Urban forest management has been recognized as a viable option to contribute to air quality improvement^[29,34,35]. In contrast, Setälä, Viippola, Rantalainen, Pennanen, *et al.*^[36] found that the contribution is very marginal for the specific site evaluated in their study (two cities in Finland). Specifically, in the Aburrá Valley, the increase of

green spaces and urban trees, together with strategies such as the control of polluting emissions to vehicles and industries and the use of mass transportation and clean fuels are included in the

Integrated Air Pollution Management Plan^[37]. Even so, some considerations in species selection and vegetation design should be taken into account for that purpose.

Table 3. Comparison of urban forest ecosystem services in different cities of the world

City	Number of trees	Tree cover (%)	Pollutant removal (t-yr. ⁻¹)	Reference
London, UK	8,421,000		2,241	[27]
New York, USA	5,212,000		1,790	[20]
Beijing, China	2,383,000		1,261	[24]
Oakville, Canada	2,000,000	28		[25]
Washington, USA	1,928,000		558	[20]
Barcelona, Spain	1,419,823		305	[15]
Boston, USA	1,183,000		272	[20]
Syracuse, USA	876,000		99	[20]
San Francisco, USA	668,000		276	[20]
Edinburgh, UK	600,000			[27]
Aburrá Valley, Colombia	687,867		228	This study

The first step is the selection of the species with the greatest potential for the removal of atmospheric pollutants. Some morphological and physiological characteristics of plants will allow some species to fulfill this function better than others^[38]. Morphological traits include higher tree crown density and permanence of foliage throughout the year^[38,39], and rough leaf surfaces with presence of waxes and pubescence^[39,40].

It is also important to consider the plants' resistance to pollution and the effectiveness of the leaves' defense mechanisms: if the plants are not healthy, they are less able to provide their benefits. One method used for this purpose is the calculation of the air pollution tolerance index (APTI), which measures chlorophyll, ascorbic acid, water content and leaf pH^[41,42].

In addition to species selection, it is important to consider the floristic design, i.e., the pattern of tree planting in space, so that ecosystem services are optimized^[17,43]. In that sense, some designs will have beneficial effects, while others will be harmful, although this depends on the spatial scale (national, municipal or local). Vos, Maiheu, Vankerkom, *et al.*^[44] give an example at the local scale, they report that urban and tunnel-forming trees along narrow roads can lead to higher pollutant concentration, in particular for pollutants related to vehicular traffic, such as nitrogen dioxide and carbon monoxide. This can occur because of the obstruction of wind flow,

and the consequent reduction in ventilation, which allows pollutants to escape into the outside atmosphere.

On the other hand, the study by Maher, Ahmed, Davison *et al.*^[45] reported that strips of trees along roadways can reduce particulate matter levels inside homes near the roadway by more than 50%. Electron microscopy analyses show that particulate matter captured by leaves is concentrated in clumps around leaf pubescence and within leaf microtopography^[45].

In a review of the state of the art on urban vegetation and particulate matter air pollution, Janhäll^[43] concludes that the establishment of large, dense canopy trees on roadways reduces dispersion to the upper layers of the atmosphere, thereby increasing local air pollution levels, while low vegetation near sources can improve air quality by increasing deposition. Vegetation barriers should be dense enough to provide a greater surface area for deposition and porous enough to allow penetration rather than deflection of the air stream above the barrier.

In terms of environmental policies and regulations, tree planting is not commonly included as one of the strategies to improve air quality in cities. Despite this, there are some good examples that deserve to be mentioned.

As part of a plan to reduce air pollution, the government of Santiago (Chile) defined as an

environmental policy to use urban forests for this purpose. The results reveal that the cost-benefit ratio of urban forest management to reduce PM₁₀ was similar to other control policies such as alternative fuels^[29]. In addition, the U.S. Environmental Protection Agency (EPA) recommends the implementation of emerging measures, such as strategic tree planting, as a means to help meet air quality standards^[39].

In the Aburrá Valley, Agreement 19 of 2017^[46] adopts guidelines and determinations for the management of urban green public space. The agreement takes into account the economic value of the ecosystem services provided by urban trees for the estimation of the compensatory value for tree felling; this proposes as a new compensation option the payment of the monetary value of the trees, in order to create a green fund to be used for the planting and care of the urban forest and green areas. We believe that the monetary value associated with the removal of air pollutants can be used to estimate that value. Of course, several adjustments must be made according to the conditions in Colombia and to estimate the unit value for each tree, which is beyond the scope of this study.

Similarly, community participation and engagement can help maintain, or even increase, tree cover and thus the benefits of the urban forest. One option is to establish environmental service payment schemes to compensate for the footprint of pollutant emissions, either for individuals or for industries. A sample of mechanisms already applied in Colombia in rural areas is the strategy known as BanCO₂, in which landowners (usually peasants) receive money for keeping natural forests intact for carbon sequestration^[47]. Those payments are made by individuals or industries wishing to offset their carbon footprint. For urban areas, it is proposed to establish similar strategies to preserve, establish and maintain urban forests within cities, as a compensation measure to air pollutant emissions.

5. Conclusion

The urban forest in the Aburrá Valley removes approximately 228 t of atmospheric pollutants per

year, which is equivalent to a monetary value of 2,130,136 USD. In order to optimize this ecosystem service, it is necessary to select tree species with characteristics that facilitate removal (dense canopy, permanent foliage, high leaf area, waxy and pubescent leaf surfaces) and floral designs in which a dense and porous lateral barrier is formed, which in turn allows the vertical dispersion of pollutants. It is also important to link urban planning, environmental regulations and public policies with urban forestry in order to provide additional tools to improve environmental quality. These efforts will contribute to the sustainability and resilience of the city, which will improve environmental conditions and the quality of life of the population. It is recommended to advance in the knowledge of species that have the functional traits associated with this service and that, in addition, tolerate air pollution, given that the state of health of the tree has an impact on the fulfillment of its functions.

Acknowledgement

We thank the Administrative Department of Science, Technology and Innovation (COLCIENCIAS) for co-financing the project, the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) and the Air Quality Network (Redaire) for supplying climate and weather information of air quality.

Conflict of interest

The authors declared no conflict of interest.

References

1. UN. World urbanization prospects: The 2014 revision. United Nations Department of Economics and Social Affairs, Population Division: New York, NY, USA; 2015. p. 41.
2. Comisión Económica para América Latina y el Caribe (Cepal). Población, territorio y desarrollo sostenible. Santiago, Chile (Spanish) [Population, territory and sustainable development. Santiago, Chile]. 2012. Available from: https://repositorio.cepal.org/bitstream/handle/11362/22425/1/s2012034_es.pdf.
3. Departamento Nacional de Planeación (DNP). Conpes 3819: Política nacional para consolidar el sistema de ciudades en Colombia (Spanish) [Conpes 3819: National policy to consolidate the system of

- cities in Colombia]. 2014. Available from: <https://colaboracion.dnp.gov.co/cdt/conpes/económicos/3819.pdf>.
4. Grimm NB, Faeth SH, Golubiewski NE, *et al.* Global change and the ecology of cities. *Science* 2008; 319(5864): 756–760. doi: 10.1126/science.1150195.
 5. World Health Organization. Ambient (outdoor) air pollution. WHO; 2018. Available from: [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health).
 6. Kampa M, Castanas E. Human health effects of air pollution. *Environmental Pollution* 2008; 151(2): 362–367. doi: 10.1016/j.envpol.2007.06.012.
 7. Calderón-Garcidueñas L, Villarreal-Ríos R. Living close to heavy traffic roads, air pollution, and dementia. *The Lancet* 2017; 389(10070): 675–677. doi: 10.1016/s0140-6736(16)32596-x.
 8. Prüss-Üstün A, Wolf J, Corvalán C, *et al.* Preventing disease through healthy environments: A global assessment of the burden of disease from environmental risks. World Health Organization; 2016. Available from: https://apps.who.int/iris/bitstream/handle/10665/204585/9789241565196_eng.pdf?sequence=1&isAllow ed=y.
 9. Cohen AJ, Anderson HR, Ostro B, *et al.* Urban air pollution. In: Ezzati E, Lopez AD, Rodgers A, and Murray CJL (editors). *Comparative quantification of health risks: Global and regional burden of disease attributable to selected major risk factors*. Geneva: World Health Organization; 2004. p. 1353–1433.
 10. Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM). Informe del estado de la calidad del aire en Colombia 2011-2015 (Spanish) [Report on the state of air quality in Colombia 2011-2015]. Bogotá; 2018. Available from: http://documentacion.ideam.gov.co/openbiblio/bvirtual/023637/informe_del_estado_de_la_calidad_del_aire_en_colombia_2011-2015_vfinal.pdf.
 11. Gaviria CF, Benavides PC, Tangarife CA. Particulate air pollution (PM_{2.5} and PM₁₀) and medical consultations due to respiratory disease in Medellín (2008–2009). *Revista Facultad Nacional de Salud Pública* 2011; 29(3): 241–250.
 12. Área metropolitana del Valle de Aburrá (AMVA). Desarrollo de una estrategia ambiental integrada para una movilidad sustentable en el área metropolitana del valle de Aburrá (Spanish) [Development of an integrated environmental strategy for sustainable mobility in the metropolitan area of Valle de Aburrá]. Medellín; 2015.
 13. Área metropolitana del Valle de Aburrá (AMVA). Acuerdo Metropolitano n.º 15 (Spanish) [Metropolitan Agreement No.15]. 2016. Available from: <http://www.metropol.gov.co>.
 14. SIATA. Información de calidad del aire (Spanish) [Air quality information]. Medellín: Sistema de Alerta Temprana de Medellín y el valle de Aburrá. 2018. Available from: https://siata.gov.co/descarga_siata/index.php/index2/calidad_aire/.
 15. Baró F, Chaparro L, Gómez E, *et al.* Contribution of ecosystem services to air quality and climate change mitigation policies: The Case of urban forests in Barcelona, Spain. *AMBIO* 2014; 43: 466–479. doi: 10.1007/s13280-014-0507-x.
 16. Willis KJ, Petrokofsky G. The natural capital of city trees. *Science* 2017; 356(6336): 374–376. doi: 10.1126/science.aam9724.
 17. Bodnaruk EW, Kroll CN, Yang Y, *et al.* Where to plant urban trees? A spatially explicit methodology to explore ecosystem service tradeoffs. *Landscape and Urban Planning* 2017; 157: 457–467. doi: 10.1016/j.landurbplan.2016.08.016.
 18. Salbitano F, Borelli S, Conigliaro M, *et al.* Guidelines on urban and peri-urban forestry. FAO Forestry Paper; 2016, No.178. Available from: <http://www.fao.org/3/a-i6210e.pdf>.
 19. Gómez-Baggethun E, Gren Å, Barton DN, *et al.* Urban ecosystem services. Urbanization, biodiversity and ecosystem services: Challenges and opportunities. Springer, Dordrecht; 2013. p. 175–251. doi: 10.1007/978-94-007-7088-1_11.
 20. Nowak DJ, Crane DE, Stevens JC. Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening* 2006; 4(3–4): 115–123. doi: 10.1016/j.ufug.2006.01.007.
 21. Armson D, Rahman MA, Ennos AR. A comparison of the shading effectiveness of five different street tree species in Manchester, UK. *Arboriculture & Urban Forestry* 2013; 39(4): 157–164.
 22. Reynolds CC, Escobedo FJ, Clerici N, *et al.* Does “greening” of neotropical cities considerably mitigate carbon dioxide emissions? The case of Medellín, Colombia. *Sustainability* 2017; 9(5): 785. doi: 10.3390/su9050785.
 23. Dobbs C, Eleuterio AA, Amaya JD, *et al.* The benefits of urban and peri-urban forestry. *Unasylva* 2018; 69(250): 22–29.
 24. Yang J, McBride J, Zhou J, *et al.* The urban forest in Beijing and its role in air pollution reduction. *Urban Forestry & Urban Greening* 2005; 3(2): 65–78. doi: 10.1016/j.ufug.2004.09.001.
 25. McNeil J, Vava C. Oakville’s urban forest: Our solution to our pollution. Canada: Town of Oakville; 2006.
 26. Nowak DJ, Crane DE, Stevens JC, *et al.* A ground-based method of assessing urban forest structure and ecosystem services. *Arboriculture & Urban Forestry* 2008; 34(6): 347–358.
 27. Rogers K, Sacre K, Goodenough J, *et al.* Valuing London’s urban forest: Results of the London i-Tree eco project. 2015. London: Treeconomics London. Available from: https://www.london.gov.uk/sites/default/files/valuin g_londons_urban_forest_i-tree_report_final.pdf.
 28. Ministerio de Ambiente y Desarrollo Sostenible (MADS). Resolución 2254 (Spanish) [Resolution 2254]. Bogotá: MADS; 2017. Available from: http://www.mads.gov.co/descarga_mads/index.php/index2/resolucion_2254/.

- www.minambiente.gov.co/images/normativa/app/resoluciones/96-res2254de2017.pdf.
29. Escobedo FJ, Wagner JE, Nowak DJ, *et al.* Analyzing the cost effectiveness of Santiago, Chile's policy of using urban forests to improve air quality. *Journal of Environmental Management* 2008; 86(1): 148–157. doi: 10.1016/j.jenvman.2006.11.029.
 30. Horbath JE. Tendencias y proyecciones de la población del área metropolitana del valle de Aburrá en Colombia, 2010–2030 (Spanish) [Trends and projections of the population of the Aburrá Valley metropolitan area in Colombia, 2010–2030]. *Notas de Población*; 2016. Available from: <https://www.cepal.org/es/publicaciones/40259-tendencias-proyecciones-la-poblacion-area-metropolitana-valle-aburra-colombia>.
 31. Universidad Nacional de Colombia, Área Metropolitana del valle de Aburrá, Cornare y Corantioquia. Plan de ordenación y manejo de la cuenca del río Aburrá: aspectos principales (Spanish) [Planning and management plan for the Aburrá river basin: Main aspects]. Medellín: Impregon; 2007.
 32. USDA Forest Service. I-Tree Eco User's Manual V 5.0. 2013. Available from: www.itreetools.org.
 33. Área metropolitana del Valle de Aburrá (AMVA). Actualización inventario de emisiones atmosféricas del valle de Aburrá (Spanish) [Updating inventory of atmospheric emissions from the Aburrá Valley]. 2017. Available from: <http://www.metropol.gov.co>.
 34. Nowak DJ. Institutionalizing urban forestry as a “biotechnology” to improve environmental quality. *Urban Forestry & Urban Greening* 2006; 5(2): 93–100. doi: 10.1016/j.ufug.2006.04.002.
 35. Yang J, Chang Y, Yan P. Ranking the suitability of common urban tree species for controlling PM 2.5 pollution. *Atmospheric Pollution Research* 2015; 6(2): 267–277. doi: 10.5094/apr.2015.031.
 36. Setälä H, Viippola V, Rantalainen AL, *et al.* Does urban vegetation mitigate air pollution in northern conditions? *Environmental Pollution* 2013; 183: 104–112. doi: 10.1016/j.envpol.2012.11.010.
 37. Área metropolitana del Valle de Aburrá (AMVA). Plan integral de gestión de contaminación del aire (Spanish) [Comprehensive air pollution management plan]. 2017. Available from: <http://www.calidaddelaire.co/pigeca.php>.
 38. Grote R, Samson R, Alonso R, *et al.* Functional traits of urban trees: air pollution mitigation potential. *Frontiers in Ecology and the Environment* 2016; 14(10): 543–550. doi: 10.1002/fee.1426.
 39. Nowak DJ. I-Tree species selector user's manual. Syracuse, Nueva York: Usda Forest Service; 2008. Available from: <https://www.itreetools.org/resources/manuals/i-treespeciesusers-manual>.
 40. Weerakkody U, Dover JW, Mitchell P, *et al.* Evaluating the impact of individual leaf traits on atmospheric particulate matter accumulation using natural and synthetic leaves. *Urban Forestry & Urban Greening* 2018; 30: 98–107. doi: 10.1016/j.ufug.2018.01.001.
 41. Prajapati SK, Tripathi BD. Anticipated Performance Index of some tree species considered for green belt development in and around an urban area: A case study of Varanasi city, India. *Journal of Environmental Management* 2008; 88(4): 1343–1349. doi: 10.1016/j.jenvman.2007.07.002.
 42. Zhang P, Liu Y, Chen X, *et al.* Pollution resistance assessment of existing landscape plants on Beijing streets based on air pollution tolerance index method. *Ecotoxicology and Environmental Safety* 2016; 132: 212–223. doi: 10.1016/j.ecoenv.2016.06.003.
 43. Janhäll S. Review on urban vegetation and particle air pollution—Deposition and dispersion. *Atmospheric Environment* 2015; 105: 130–137. doi: 10.1016/j.atmosenv.2015.01.052.
 44. Vos PEJ, Maiheu B, Vankerkom J, *et al.* Improving local air quality in cities: to tree or not to tree? *Environmental Pollution* 2013; 183: 113–122. doi: 10.1016/j.envpol.2012.10.021.
 45. Maher BA, Ahmed IAM, Davison B, *et al.* Impact of roadside tree lines on indoor concentrations of traffic-derived particulate matter. *Environmental Science & Technology* 2013; 47(23): 13737–13744. doi: 10.1021/en404363m.
 46. Área metropolitana del Valle de Aburrá (AMVA). Acuerdo Metropolitano n.º 19 (Spanish) [Metropolitan agreement No.19]. 2017. Available from: <http://www.metropol.gov.co>.
 47. BancO2. BancO2 Servicios Ambientales Comunitarios (Spanish) [BancO2 community environmental services]. 2018. Available from: <http://www.banco2.com/>.