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Retention Analysis of Atmospheric Particulate Matter by Urban Road Vegetation

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Abstract

This paper shows an analysis of the retention capacity of atmospheric particulate matter (PM) by existing trees on roads of Bogota city (Colombia). Six tree species and two roads with different pollution degree by PM (PM_{10} and TSP) were considered. Total amount of PM retained by the leaves of each tree species was determined and correlated with TSP concentrations observed in air quality monitoring stations located in the study roads. In this study, the results suggested the monthly timescale as the most suitable to study the PM retention capacity (PMRC) by road vegetation and its possible relationship with air quality in urban areas. The PM amount retained by tree leaves tended to decrease when TSP concentrations tended to increase in the study areas. The results also suggested in order of importance to the species Ligustrum Lucidum, Eucalyptus Ficifolia, and Tecoma Stans as those of greater PMRC. On average, these species had a PMRC 3.99 times greater in relation to the other species considered in this study. These species were probably most appropriate in the context of improving air quality in urban areas. This study will be important to deepen the knowledge about the influence of road vegetation on urban air quality.

Keywords: Urban trees, air quality, road vegetation, total suspended particles.

INTRODUCTION

Air quality was one of the most important factors in determining the life quality index in urban areas (Rojas, 2014). In the Colombian context, Bogota was classified as the city with higher levels of atmospheric pollution (Behrentz, 2009; Zafra et al., 2017); being the atmospheric particulate matter (PM) the pollutant that most often exceeded the permissible legislative levels. According to reports from Bogota Air Quality Monitoring Network (RMCAB), this pollution was found directly related to human activities. Mobile emission sources were an important factor with about 1,572,711 vehicles and 402,657 motorcycles, which emitted about 1,152 ton/year of PM_{10}. On an annual basis, these emissions contributed 40% of PM_{10}, and were responsible for 20% of acute respiratory infections in Bogota city (SDA, 2015).

The constant PM emission by fixed and mobile sources in urban areas favored the sedimentation and permanence of suspended atmospheric solids. Thus, the possibility of PM retention by urban vegetation increased (Jhosi and Bora, 2011). This PM retention referred to the function exerted by trees to act as particulate filters, which was influenced by the leaf morphological characteristics and climatic variables such as rainfall and wind velocity (Alcalá et al., 2010). The role played by trees in mitigation and indication of PM pollution is a study topic to strengthen in Bogota city, because it constitutes a useful, complementary, and alternative tool to evaluate the air quality in urban areas where there are no active monitoring systems.

There were studies aimed at evaluating the role of urban trees as an indicator of atmospheric pollution by PM. The studies of Dalmansson et al. (1997) and Alcalá et al. (2010) were some of the first referents. Most studies were aimed at evaluating the role of urban trees on atmospheric decontamination through studying the PM retention capacity (PMRC) by leaves. For example, Steffens et al. (2012), Hagler et al. (2012), and Ugolinia et al. (2013) studied the PMRC by urban trees. In the Colombian context, these studies were scarce. However, there were descriptive studies carried out by Duran (2008) in Medellin city and Ramos (2012) in Bogota city. It has been demonstrated that urban trees showed a great capacity indicator of air pollution due to their significant relationship with PM concentrations and therefore to its role as an atmospheric particles filter. Atmospheric particles were retained by the tree stem and its leaves due to the action of gravity force and atmospheric stability (Nowak et al., 2006). The amount of retained solids depended on the PM concentrations, size and shape of particles, atmospheric conditions, and leaf surface morphology (Alcalá et al., 2010).

The objective of this paper is to show an analysis of PMRC by road trees of Bogota city (Colombia). We study the possible relationship between the solids amount retained by tree leaves and PM concentrations observed in air quality monitoring stations. The best tree species are also identified in relation to their PMRC. This study will be important to deepen the knowledge about the influence of road vegetation on urban air quality.

MATERIALS AND METHOS

Description of the study area

Two stations of Bogota Air Quality Monitoring Network (RMCAB) were selected, which reported on average the largest and least daily PM_{10} concentrations during the study period (6 months). The monitoring stations selected were Carvajal-Sony (average daily PM_{10} = 81 $\mu g/m^3$) and Simón

Bolívar-IDRD (average daily PM_{10} = 38 μg/m^3). Thus, the roads closest to these 2 monitoring stations were also selected to study the PMRC by existing trees on these urban roads.

The road selected at the Carvajal-Sony station (Zone 1) was located at 36 meters in relation to the air quality monitoring station. The road was on the southern highway of Bogota city, between 45 South Street and 62 South Street. The sampling area had a length of 500 m along the road (250 m to the east and 250 m to the west in relation to the air quality monitoring station) and a width of 67.8 m. The total study area on the road was 33,900 m^2 and it was located on an area with commercial and industrial land use. That is, with a land surface coverage predominantly impervious and without vegetation (SDA, 2015). The road selected at the Simón Bolívar-IDRD station (Zone 2) was located at 360 m in relation to the air quality monitoring station. This study area was located inside a recreational park. The study area had a length of 344 m and 34 m wide, for a total area of 11,696 m^2. This road was located in an area with recreational land use. That is, with a predominantly vegetative land surface coverage (SDA, 2015).

Sample collection

According to the trees inventory in the study areas provided by Bogotá Botanical Garden, the species with a population of more than 10% were selected according to the methodology proposed by Badii et al. (2011). A sample size of 6 species was obtained (Callistemon Citrinus, Eucalyptus Ficifolia, Ligustrum Lucidum, Tecoma Stans, Lafoensia Acuminata, and Quercus Humboldtii) and 143 trees for the 2 study areas. A systematic sampling model was used during the trees selection. In other words, 2 weekly samplings (Sunday and Wednesday) were performed over a period of 6 months. This allowed selecting 2 trees per species for each sampling day, for a total of 12 trees per day: 8 trees in Zone 1 and 4 trees in Zone 2. In order to determine the amount of retained PM, 16 healthy leaves were collected randomly from the most exposed branches in each tree, 4 in each cardinal direction and at a height of 2.0 m. We collected in total 578 samples formed by 9216 leaves, which were stored individually in plastic bags at 4 °C and transferred to the laboratory for subsequent gravimetric analysis.

Laboratory analysis

The leaves were washed with deionized water by using a 750 cm^3 manual pump and a thin and soft bristle brush to detach the PM adhering to the surface. PM dilution was placed in a forced air heater at 80 °C for 72 hours, from which the solid fraction retained on the leaf surface was obtained. A gravimetric test with a 4-digit analytical balance was performed to determine the retained PM. During all the laboratory analyses, the methodologies proposed by Alcalá et al. (2010), Duran (2009), and Bogotá Botanical Garden (2010) were followed.

Information analysis

The information obtained was analyzed using InfoStat (v. 2015) and IBM-SPSS (v. 17.0) software. To study the possible relationship between PM concentrations retained by tree leaves (μg/cm^2) and PM observed by air quality monitoring stations (μg/cm^3) matrices were constructed taking into account 3 timescales: daily, weekly, and monthly. The data had a non-normal distribution (Kolmogorov-Smirnov test, p-value < 0.05). During the information processing, the following non-parametric statistical tests were used: Spearman correlation coefficient (r) and Kruskal-Wallis test.

RESULTS AND DISCUSION

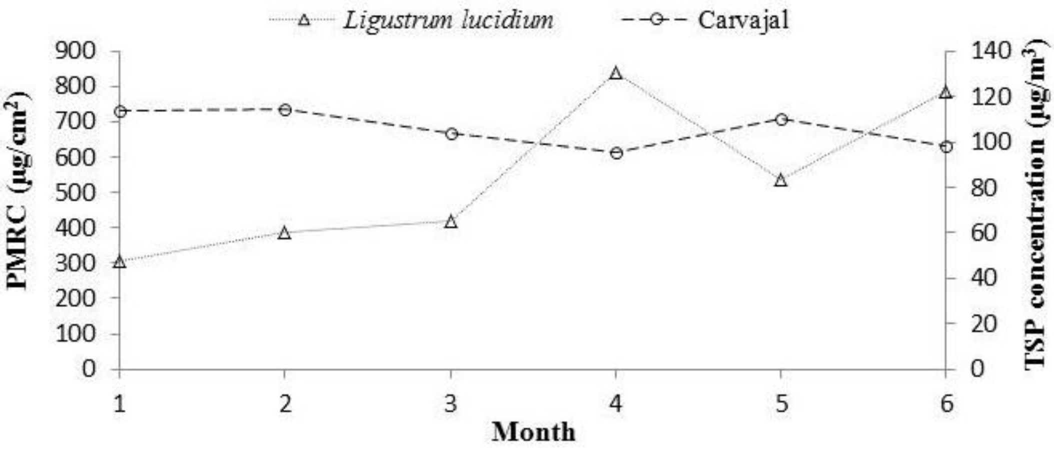
PM concentrations in trees and air quality monitoring stations

The results showed a very strong direct correlation between TSP and PM_{10} concentrations observed in air quality monitoring stations during the study period. In Zone 1 the Spearman correlation coefficient (r) between these variables was 0.86 (p-value < 0.010), and in Zone 2 the r-Spearman was 0.99 (p-value < 0.01). Results suggested that the TSP concentrations could explain the behavior of the PM_{10} concentrations between 86% and 99%, respectively. Toro and Marín (2006) obtained similar results in Medellín city, Colombia (r-Spearman between 0.83 and 0.89).

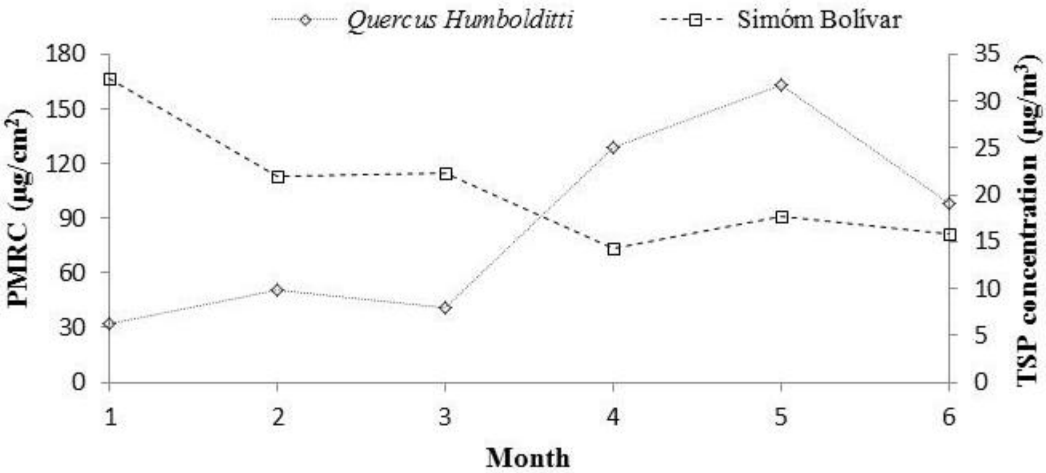
The results also showed that the monthly timescale was best suited to study the relationship between PMRC by tree leaves and TSP concentrations observed in the air quality monitoring stations. The daily and weekly timescales did not allow observing significant correlations (r-Spearman, p-value > 0.050). In this study, the results suggested the monthly timescale as the most suitable to study the PMRC by road vegetation and its possible relationship with air quality in urban areas.

On a monthly basis, the results showed in Zone 1 that Ligustrum Lucidum species showed a strong inverse correlation between the PM amount retained by this species and the TSP concentrations observed in the air quality monitoring station (r-Spearman = -0.82, p-value = 0.040). In other words, the PM amount retained by this species tended to decrease when the TSP concentrations tended to increase in the study area (Figure 1). Tecoma Stans species probably showed a similar trend, despite having obtained a minor statistical significance (r-Spearman = -0.77, p-value = 0.070; p-value < 0.10). The other tree species in study showed no significant correlations. However, comparatively also an inverse relationship was observed between the PM amount retained by Eucalyptus Ficifolia species and the TSP concentrations observed in the air quality monitoring station. On average, the air quality monitoring station in Zone 1 was located at a distance of 122 m in relation to the sampled tree species.

In Zone 2 there were no significant correlations between the PM amount retained by trees and TSP concentrations observed in the air quality monitoring station. However, on a monthly basis was observed comparatively an inverse relationship between these variables for the species Quercus Humboldtii and Lafoensia Acuminata (Figure 1). On average, the air quality monitoring station in Zone 2 was located at a 365 m distance in relation to the trees sampled. The results suggested that increasing the distance between the sampled trees and air quality monitoring station decreased the possibility of obtaining significant correlations between PMRC and TSP concentrations observed, respectively. In Zone 1 we observed significant correlations in Ligustrum Lucidum species for distances less than 122 m. For example, Zafra et al. (2017) reported that the best distance to evidence the previous findings was between 50-100 m in relation to the physical location of the air quality monitoring station.



a)



b)

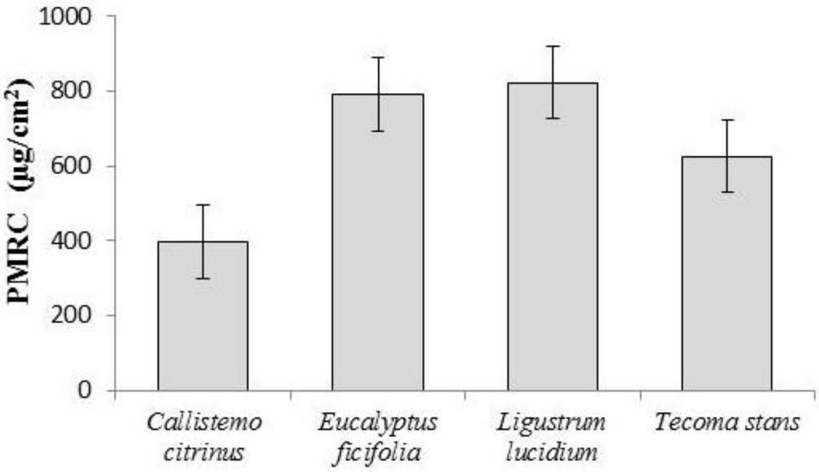
Figure 1. Average monthly variation of PMRC per tree species in relation to TSP concentrations observed in air quality monitoring stations. a) Ligustrum Lucidum (Zone 1) and b) Quercus Humboldtii (Zone 2)

Additionally, an inverse relationship between PMRC by leaves and its location in relation to the study road was displayed in Zone 1. Specifically, when the distance between the road and tree increased the PMRC by leaves tended to decrease. We identified the species Tecoma Stans (r-Spearman = -0.88, p-value < 0.010) and Ligustrum Lucidum (r-Spearman = -0.82, p-value = 0.040) as the best to study this trend. The distances assessed for each tree species were between 16-86 m and 1.0-147 m, respectively. In zone 2 the trend was similar. In this zone, Quercus Humboldtii species was the best to describe the inverse trend between PMRC by leaves and distance to the study road (r-Spearman = -0.81, p-value < 0.050). Distances of up to 340 m were evaluated in this zone. Steffens et al. (2012) and Ugolinia et al. (2013) reported similar results in relation to the distance-of-road effect on the PMRC by urban vegetation.

PMRC by tree species

In Zone 1, PMRC was determined for the 4-tree species under study (Callistemon Citrinus, Eucalyptus Ficifolia, Ligustrum Lucidum, and Tecoma Stans). The results showed significant differences in PMRC of Callistemon Citrinus species in relation to the other species under study (Kruskal-Wallis test, p-value < 0.050). On average, this species showed the least PMRC during the study period (396 µg/cm²). PMRC in order of importance for the species Ligustrum Lucidum, Eucalyptus Ficifolia, and Tecoma Stans was 823 μg/cm^2, 791 μg/cm^2, and 625 μg/cm^2, respectively. These species showed no significant difference in their PMRC (Kruskal-Wallis test, p-value > 0.050). However, Ligustrum Lucidium species showed comparatively the greatest PMRC in relation to the other tree species in Zone 1. On average, this species probably showed a PMRC 2.08, 1.32, and 1.04 times higher in relation to the species Callistemon Citrinus, Tecoma Stans, and Eucalyptus Ficifolia, respectively (Figure 2).

The results showed in Zone 2 that there were no significant differences in PMRC between the species Lafoensia Acuminata (75.1 μg/cm^2) and Quercus Humboldtii (91.3 μg/cm^2). It was observed that Quercus Humboldtii species showed a PMRC 1.22 times greater in relation to Lafoensia Acuminata species (Figure 2).



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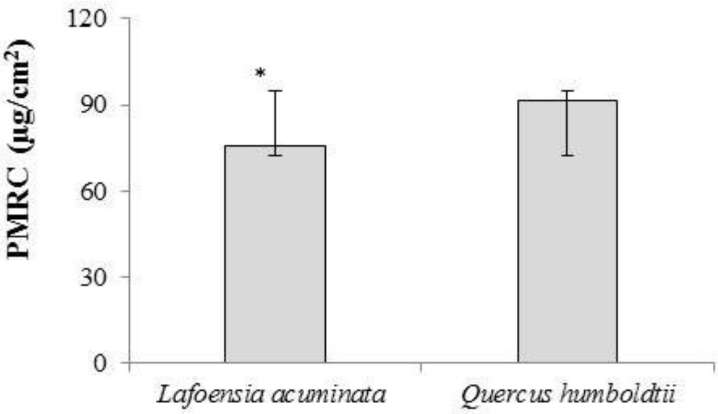

b)

Figure 2. PMRC by tree species. a) Zone 1 (Kennedy) and b) Zone 2 (Simón Bolívar)

A comparison between study zones of PMRC by tree species was done. In this comparison, TSP concentrations observed in air quality monitoring stations were also considered. On average, the results showed that daily TSP concentrations in Zone 1 (106 μg/m^3) were 5.05 times higher in relation to Zone 2 (21 μg/m^3). This factor was used to compare the PMRC of tree species between study zones. It was observed that most of the species studied in Zone 1 had greater PMRC in relation to the tree species of Zone 2 (Table 1). Except Callistemon Citrinus species, this showed less PMRC in relation to Quercus Humboldtii species. The results suggested that Callistemon Citrinus species was the least PMRC. This tree species probably should not be considered a means of retention PM in the study areas.

On the contrary, the results suggested in order of importance to the species Ligustrum Lucidum, Eucalyptus Ficifolia, and Tecoma Stans as those of greater PMRC. These species were probably most appropriate in the context of improving air quality in the study areas. On average, these species had a PMRC 3.99 times greater in relation to the other species considered in this study.

Table 1. Relation between study zones of PMRC by tree species.

Especies	**Zone 2 (Simón Bolívar)**	
	Lafoensia Acuminata (PMRC = 75,1 µg/cm²)	*Quercus Humboldtii* (PMRC = 91,3 µg/cm²)
Zone 1 (Kennedy)		
Callistemon Citrinus (PMRC = 396 µg/cm²)	5.27[a]	4.34
Eucalyptus Ficifolia (PMRC = 791 µg/cm²)	10.5	8.66
Ligustrum Lucidum (PMRC = 823 µg/cm²)	10.9	9.01
Tecoma Stans (PMRC = 625 µg/cm²)	8.32	6.85

Note. [a] PMRC relationship between tree species: 396/75.1 = 5.27.

CONCLUSIONS

In this study, the results suggest to the monthly timescale as the most suitable for analyzing PMRC by road vegetation and its possible relation with the air quality in urban areas (PM_{10} and TSP). The PM amount retained by tree species tends to decrease when TSP concentrations increase in the study areas. The species that best describe this trend are Ligustrum Lucidum (r-Spearman = -0.82) and Tecoma Stans (r-Spearman = -0.77). The other tree species in this study show no significant correlations. The results also show that by increasing distance between the tree and air quality monitoring station decreases the possibility of obtaining significant correlations between the PM amount retained by leaves and TSP concentrations observed in air quality monitoring stations. On average, we observed significant correlations in the species Ligustrum Lucidum and Tecoma stans for distances less than 122 m.

The results show an inverse relationship between the PM amount retained by trees and their location in relation to the study road. Species that best describe this trend are Ligustrum Lucidum (r-Spearman = -0.82), Tecoma Stans (r-Spearman = -0.88), and Quercus Humboldtii (r-Spearman = -0.81). In this study, significant correlations are observed for distances up to 340 m. This distance could be indicative of the maximum limit of trees location in relation to the study road, in order to retain the PM emitted from urban roads.

The results suggest in order of importance to the species Ligustrum Lucidum, Eucalyptus Ficifolia, and Tecoma Stans as those of greater PMRC. These species are probably the most appropriate in the context of improving air quality in the study areas. On average, these species have a PMRC 3.99 times greater in relation to the other species considered in this study. These 3 species do not show significant differences in their PMRC. On average, the results show that the Ligustrum Lucidum species has a PMRC 1.32 and 1.04 times higher in relation to the species Tecoma Stans and Eucalyptus Ficifolia, respectively.

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