Urban Tree Effects on Fine Particulate Matter and Human Health

By David J. Nowak

Overall, city trees reduce particulate matter and provide substantial health benefits; but under certain conditions, they can locally increase particulate matter concentrations. Urban foresters need to understand how trees affect particulate matter so they can select proper species and create appropriate designs to improve air quality. This article details trees' effects on particulate matter and provides recommendations for urban foresters to improve air quality.

Trees in cities can affect air pollution and the health of local residents as a consequence. One pollutant of particular concern is fine particulate matter less than 2.5 microns ($PM_{2.5}$). This pollutant is associated with significant health effects that include premature mortality, pulmonary inflammation, lung cancer, accelerated atherosclerosis, and altered cardiac functions (e.g., Pope et al. 2002; Pope et al. 2004; Sun et al. 2010). A modeling study was recently completed for 10 U.S. cities to help gauge the magnitude of the impact of city trees on fine particulate matter and human health (Nowak et al. 2013).

Trees in cities directly affect particulate matter by removing particles (e.g., Beckett et al. 2000; Freer-Smith et al. 2004) and emitting particles (e.g., pollen) or through resuspension of particles captured on the plant surface. Emission of volatile organic compounds (VOC) by trees can also lead to particulate matter formation (Carlton et al. 2009). In addition, captured particles can adversely affect tree health (e.g., some metals can be toxic to leaves and accumulated particles can block light and affect photosynthesis) (Ziegler 1973; Smith 1990). Some captured particles can be absorbed by the tree, though most particles that are intercepted are retained on the plant surface. Intercepted particles are often resuspended into the atmosphere (i.e., wind can blow particle off the leaf), washed off by rain, or dropped to the ground when leaves and twigs fall. Although vegetation is only a temporary retention site for many atmospheric particles, trees in cities do affect the concentration of $PM_{2.5}$ and consequently human health of city residents.

To help assess the impact of trees on fine particulate matter, field data in each of 10 cities were analyzed using the i-Tree model (Nowak et al. 2008; www.itreetools.org) to estimate: a) daily leaf area, b) the hourly flux and resuspension of $PM_{2.5}$ to and from the leaves based on local hourly pollution and weather conditions for 2010, and c) the effects of hourly $PM_{2.5}$ removal by trees on $PM_{2.5}$ concentration in the atmosphere. The model results were then combined with the U.S. EPA Environmental Benefits Mapping and Analysis Program (BenMAP) model (U.S. EPA 2012) to estimate the health incidence impacts and monetary value of the change in $PM_{2.5}$ concentration.

Research Findings

1. Substantial amounts of fine particulate are removed annually. Total amount of $PM_{2.5}$ removal annually by trees varied from 4.7 tonnes (tonne = metric ton = 2,204.6 pounds) in Syracuse, New York, to 64.5 tonnes in Atlanta, Georgia. The net removal amounts per square meter of canopy cover varied from 0.13 grams per square meter per year ($g/m^2/yr$) in Los Angeles, California, to 0.36 $g/m^2/yr$ in Atlanta (Table 1). Of all the particles intercepted by leaves, on average 34 percent were resuspended, with percent resuspension varying from 26.7 percent in Syracuse to 42.6 percent in San Francisco, California. Removal amounts and rates vary depending upon total amount of tree cover, pollution concentration, and meteorological conditions.
2. Effects on fine particulate matter concentration are small. The average annual percent air quality improvement ranged between 0.05 percent in San Francisco and 0.24 percent in Atlanta (Table 1). Average reduction in $PM_{2.5}$ concentrations ranged between 0.006 micrograms per cubic meter ($\mu g/m^3$) in Philadelphia, Pennsylvania, and San Francisco, to 0.03 $\mu g/m^3$ in Atlanta.
3. Effects on human health are substantial. The value of fine particulate matter reductions due to trees

varied from USD $1.1 million in Syracuse to $60.1 million in New York City (Table 1). Most of these values were dominated by the effects of reducing human mortality. Median mortality reduction was 1.2 persons per year per city, but was as high as 7.6 per year in New York City. The average health benefits value per hectare of tree cover was approximately $1,600, but varied from $500 in Minneapolis, Minnesota, and Atlanta to $3,800 in New York City (Table 1). The value per tonne of $PM_{2.5}$ removed averaged $682,000, but varied from $142,000 in Atlanta to $1,610,000 in New York City. The health benefits value per reduction of one μg/m^3 also varied from $122 million in Syracuse to $6.2 billion in New York City, with an overall average of $1.6 billion per city.

Implications for Urban Forestry

Though there are various limitations to these model estimates (Nowak et al. 2013), the results indicate a first-order approximation of the magnitude of tree effects on $PM_{2.5}$ concentrations, and these findings have implications for urban forestry. While this study investigated overall impacts across a city, local scale effects within a city are also important. Removal rates and health effects vary depending upon local conditions, some of which are impacted by urban forests and urban foresters. Removal rates and health effects are dependent upon:

a. **Local meteorological conditions** – the main meteorological drivers affecting fine particulate matter removal, resuspension, and concentrations are wind and rain. Urban areas can affect rain (e.g., Shepherd 2005) but urban trees have a greater impact on wind. Reduced wind speeds due to trees tend to reduce both particulate removal rates and resuspension, but also tend to increase concentrations due to limiting dispersion (e.g., Vos et al. 2013). In addition, if local sources of $PM_{2.5}$ come from wind-borne soils, tree cover can reduce these particles by reducing wind speeds (Heisler and DeWalle 1988).

   In areas of high pollution concentrations and human populations (e.g., along heavily traveled roadways), forest designs to increase wind-driven dispersion may prove more effective at reducing local pollution concentrations than designs to maximize tree cover. Enhanced tree cover in these areas may increase local pollution concentrations by trapping pollutants beneath the tree canopy (e.g., Gromke and Ruck 2009), even though pollution removal rates may be higher in these areas due to increased canopy cover and pollution concentrations (Figure 1). As pollutant sources on roadways are often near ground level, a key to protecting nearby pedestrians or residents from roadside pollutants is to shield people from high concentrations (e.g., vegetation buffers between road and human) and allow for the dispersion of roadside pollutants to reduce concentrations (e.g., open and wide roadways) (Baldauf and Nowak, *in press*).

b. **Local pollution concentration** – Although it is best to prevent the emission of pollutants, once the pollutant has been emitted, trees can remove pollutants and help reduce pollutant concentrations. As health impacts are greater in more heavily polluted areas, vegetation designs to improve air quality will have greater effects and removal rates in more polluted areas. Urban forest designs could focus in these areas to improve air quality but with consideration to local scale impacts as previously described (e.g., near roadside areas).

c. **Human population density** – Naturally, human health effects are largely dependent upon the

Table 1. Estimated removal of $PM_{2.5}$ by trees and associated value in several U.S. cities (from Nowak et al. 2013).

City	Total (t/year)	Range (t/year)	Value (USD$/year)	Effect[z] (g)	($)	ΔC[y] (μg/m^3)	AQ[x] (%)
Atlanta, GA	64.5	(8.5-140.4)	9,170,000	0.36	0.05	0.030	0.24
Baltimore, MD	14.0	(1.8-29.5)	7,780,000	0.24	0.13	0.010	0.09
Boston, MA	12.7	(2.0-35.6)	9,360,000	0.32	0.23	0.020	0.19
Chicago, IL	27.7	(4.0-68.1)	25,860,000	0.26	0.24	0.011	0.09
Los Angeles, CA	32.2	(4.2-70.3)	23,650,000	0.13	0.09	0.009	0.07
Minneapolis, MN	12.0	(1.6-28.2)	2,610,000	0.23	0.05	0.010	0.08
New York City, NY	37.4	(5.1-97.2)	60,130,000	0.24	0.38	0.010	0.09
Philadelphia, PA	12.3	(1.6-28.1)	9,880,000	0.17	0.14	0.006	0.08
San Francisco, CA	5.5	(0.8-14.4)	4,720,000	0.29	0.25	0.006	0.05
Syracuse, NY	4.7	(0.6-10.8)	1,100,000	0.27	0.06	0.009	0.10

[z] Average effects (grams or dollars) per square meter of tree cover per year.
[y] Average annual reduction in hourly concentration.
[x] Average percent air quality improvement.

▶

presence of human populations. Thus, designs to improve air quality and human health are most beneficial in areas with higher population densities. For example, the greatest effect of trees on reducing health impacts of $PM_{2.5}$ occurred in New York City due to its relatively large human population and moderately high removal rate and reduction in concentration.

d. **Tree cover and species composition** – The amount of tree cover, location of tree cover, species composition, and tree health are attributes of the urban forest that are influenced by the urban forester. Increasing tree cover tends to increase particulate matter removal and improve air quality, but as previously mentioned, could increase concentrations under certain local conditions and designs. Large stands of trees can also reduce pollutant concentrations in the interior of the stand due to increased distance from emission sources and increased pollution removal (e.g., Dasch 1987; Cavanagh et al. 2009).

Evergreen trees offer leaves year-round to intercept particles and often have canopy and leaf structures that are typically best for reducing particulate matter. Generally, dense- and fine-textured crowns and complex, small, and rough leaves are believed to capture and retain more particles than open and coarse crowns and simple, large, smooth leaves (Little 1977; Smith 1990; Beckett et al. 2000). Little (1977) notes that rough or hairy leaf discs collected five micron particles seven times more effectively than smooth leaves, and that leaves of complex shape with a large circumference-to-area ratio could be expected to collect particles most efficiently.

In addition to $PM_{2.5}$ removal, trees also remove other air pollutants (e.g., ozone, sulfur dioxide, nitrogen dioxide) (Nowak et al. 2006) and emit volatile organic compounds that can contribute to ozone, carbon monoxide, and particulate matter formation (e.g., Chameides et al. 1988).

Conclusion

Improving air quality with vegetation can lead to improved human health and substantial health care savings in cities. More research is needed to improve particulate matter removal estimates and to determine local scale effects of vegetation designs. Urban forest designs that consider source-sink relationships of $PM_{2.5}$ and other pollutants can be developed to reduce $PM_{2.5}$ concentrations and minimize human exposure to it in cities across the globe.

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Figure 1. Tree canopies may remove air pollutants, but they can also increase local pollutant concentrations by limiting dispersion and trapping pollutants near ground-level breathing spaces, under certain circumstances.

Urban Forest Strategies to Improve Air Quality

Strategy	Reason
Increase the number of healthy trees	Increases pollution removal
Sustain existing tree cover	Maintains pollution removal levels
Maximize use of low VOC-emitting trees	Reduces ozone, carbon monoxide, and particulate formation
Sustain large, healthy trees	Large trees have the greatest per-tree effects
Use long-lived trees	Reduces long-term pollutant emissions from planting and removal
Use low maintenance trees	Reduces pollutant emissions from maintenance activities
Reduce fossil fuel use in maintaining vegetation	Reduces pollutant emissions
Plant trees in energy conserving locations	Reduces pollutant emissions from power plants
Plant trees to shade parked cars	Reduces vehicular VOC emissions
Supply ample water to vegetation	Enhances pollution removal and temperature reduction
Plant trees in polluted or heavily populated areas	Maximizes tree air quality benefits
Avoid pollutant-sensitive species	Improves tree health
Utilize evergreen trees for particulate matter	Maintains year-round removal of particles

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