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# Tree and forest effects on air quality and human health in the United States

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ABSTRACT

Trees remove air pollution by the interception of particulate matter on plant surfaces and the absorption of gaseous pollutants through the leaf stomata. However, the magnitude and value of the effects of trees and forests on air quality and human health across the United States remains unknown. Computer simulations with local environmental data reveal that trees and forests in the conterminous United States removed 17.4 million tonnes (t) of air pollution in 2010 (range: 9.0–23.2 million t), with human health effects valued at 6.8 billion U.S. dollars (range: $1.5–13.0 billion). This pollution removal equated to an average air quality improvement of less than one percent. Most of the pollution removal occurred in rural areas, while most of the health impacts and values were within urban areas. Health impacts included the avoidance of more than 850 incidences of human mortality and 670,000 incidences of acute respiratory symptoms.

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## 1. Introduction

Air pollution is a significant problem in the United States that affects human health and well-being, ecosystem health, crops, climate, visibility and man-made materials. The Clean Air Act requires the U.S. Environmental Protection Agency (EPA) to set National Ambient Air Quality Standards for six "criteria pollutants" – that are both common throughout the United States and detrimental to human welfare (US EPA, 2013a). These pollutants are: carbon monoxide (CO), nitrogen dioxide ($NO_2$), ozone ($O_3$), lead (Pb), sulfur dioxide ($SO_2$), and particulate matter (PM), which includes particulate matter less than 10 microns ($PM_{10}$) and particulate matter less than 2.5 microns ($PM_{2.5}$) in aerodynamic diameter. Health effects related to air pollution include impacts on pulmonary, cardiac, vascular, and neurological systems (e.g., Pope et al., 2002). In the United States, approximately 130,000 $PM_{2.5}$-related deaths and 4700 $O_3$-related deaths in 2005 were attributed to air pollution (Fann et al., 2012).

Trees and forests, like air pollution, vary throughout the United States (e.g., percent tree cover, species composition). Trees affect air quality through the direct removal of air pollutants, altering local microclimates and building energy use, and through the emission of volatile organic compounds (VOCs), which can contribute to $O_3$ and $PM_{2.5}$ formation (e.g., Chameides et al., 1988). However, integrative studies have revealed that trees, particularly low VOC emitting species, can be a viable strategy to help reduce urban $O_3$ levels (e.g., Taha, 1996; Nowak et al., 2000).

Trees remove gaseous air pollution primarily by uptake via leaf stomata, though some gases are removed by the plant surface. For $O_3$, $SO_2$ and $NO_2$, most of the pollution is removed via leaf stomata. Once inside the leaf, gases diffuse into intercellular spaces and may be absorbed by water films to form acids or react with inner-leaf surfaces. Trees directly affect particulate matter in the atmosphere by intercepting particles, emitting particles (e.g., pollen) and resuspension of particles captured on the plant surface. Some particles can be absorbed into the tree, though most intercepted particles are retained on the plant surface. The intercepted particles often are resuspended to the atmosphere, washed off by rain, or dropped to the ground with leaf and twig fall. During dry periods, particles are constantly intercepted and resuspended, in part, dependent upon wind speed. The accumulation of particles on the leaves can affect photosynthesis (e.g., Darley, 1971) and therefore potentially affect pollution removal by trees. During precipitation, particles can be washed off and either dissolved or transferred to the soil. Consequently, vegetation is only a temporary retention site for many atmospheric particles, where particles are eventually moved back to the atmosphere or moved to the soil. Pollution removal by urban trees in the United States has been estimated at 711,000 tonnes (t) per year (Nowak et al., 2006a).

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While various studies have estimated pollution removal by trees (e.g., Nowak et al., 2006a; McDonald et al., 2007; Tallis et al., 2011), most studies on pollution removal do not directly link the removal with improved human health effects and associated health values. A few studies that have linked removal and health effects include one in London where a 10 × 10 km grid with 25% tree cover was estimated to remove 90.4 t of $PM_{10}$ annually, which equated to the avoidance of 2 deaths and 2 hospital admissions per year (Tiwary et al., 2009). In addition, Nowak et al. (2013) reported that the total amount of $PM_{2.5}$ removed annually by trees in 10 U.S. cities in 2010 varied from 4.7 t in Syracuse to 64.5 t in Atlanta. Estimates of the annual monetary value of human health effects associated with $PM_{2.5}$ removal in these same cities (e.g., changes in mortality, hospital admissions, respiratory symptoms) ranged from \$1.1 million in Syracuse to \$60.1 million in New York City. Mortality avoided was typically around 1 person $yr^{-1}$ per city, but was as high as 7.6 people $yr^{-1}$ in New York City.

Tree cover in the United States is estimated at 34.2 percent and varies from 2.6 percent in North Dakota to 88.9 percent in New Hampshire (Nowak and Greenfield, 2012). As people and trees exist throughout a landscape in varying densities, not only will pollution removal and its effects on local pollution concentrations vary, but so will the associated human health impacts and values. The objectives of this paper are to estimate the amount of air pollution ($NO_2$, $O_3$, $PM_{2.5}$, $SO_2$) permanently removed by trees and forests within urban and rural areas of the conterminous United States in 2010, and its associated monetary value and impact on human health.

## 2. Methods

To estimate avoided health impacts and associated dollar benefits of air pollution removal by trees and forests in the conterminous United States in 2010, four types of analyses were conducted. These analyses were conducted at the county-level for all urban and rural areas to estimate: 1) the total tree cover and leaf area index on a daily basis, 2) the hourly flux of pollutants to and from the leaves, 3) the effects of hourly pollution removal on pollutant concentration in the atmosphere, and 4) the health impacts and monetary value of the change in $NO_2$, $O_3$, $PM_{2.5}$ and $SO_2$ concentration using information from the U.S. EPA Environmental Benefits Mapping and Analysis Program (BenMAP) model (US EPA, 2012a). Urban and rural areas were delimited using 2010 Census data with rural land defined as land not classified as urban (U.S. Census Bureau, 2013).

### 2.1. Tree cover and Leaf Area Index

Tree cover within each county was derived from 2001 National Land Cover Database (NLCD) 30-m resolution tree cover maps (USGS, 2008). These maps were used to determine tree cover within specific geographic locations. However, these maps generally underestimate tree cover (Nowak and Greenfield, 2010). To adjust for potential underestimates, NLCD percent tree cover within each county's NLCD land-cover class was modified according to the Nowak and Greenfield (2010) photo-interpreted values within individual mapping zones (i.e., tree cover estimates were adjusted to match the photo-interpreted estimates for each land cover class within each mapping zone). Adjusted NLCD tree cover estimates were within 0.1 percent of estimates derived from photo-interpretation (PI) of the conterminous United States (PI = 34.2 percent, adjusted NLCD = 34.1 percent), but this difference could be greater at the local scale.

Maximum (mid-summer) leaf area index (LAI: $m^2$ leaf area per $m^2$ projected ground area of canopy) values were derived from the level-4 MODIS/Terra global Leaf Area Index product for the 2007 growing season across the conterminous United States (USGS, 2013). In some areas, LAI values per unit of tree cover were missing or abnormally low and were estimated as 4.9 (Nowak et al., 2008) for urban areas (65 percent of urban areas had missing values) and 3.2 (Schlerf et al., 2005) for rural areas (14.5 percent of rural areas had missing values). Many urban areas had missing LAI estimates due to the coarseness of the MODIS data and relatively low amounts of forest cover in urban areas.

Percent tree cover classified as evergreen was determined for each county based on evergreen, deciduous and mixed forest land covers as classified by the NLCD. The proportion of mixed forest cover that was evergreen was estimated as the proportion of evergreen to evergreen plus deciduous forest cover in each county. LAI values were combined with percent evergreen information and local leaf-on and leaf-off (frost) dates (NCDC, 2005) to estimate total daily leaf surface area in each county assuming a four-week transition period centered on leaf-on and leaf-off dates for spring and autumn, respectively.

### 2.2. Pollution removal by trees

Hourly pollution removal or flux ($F$ in $\mu g\ m^{-2}\ h^{-1}$) was estimated as:

$$F = V_d \times C$$

Where $V_d$ is the deposition velocity of the pollutant to the leaf surface ($m\ h^{-1}$) and $C$ is pollutant concentration ($\mu g\ m^{-3}$) (e.g., Hicks et al., 1989). Hourly concentrations for each pollutant were obtained from the U.S. EPA's Air Quality System national database for the year 2010 (US EPA, 2013b). For PM data, if hourly data did not exist, then daily and 6-day measurements were used to represent the hourly concentration values throughout the day (e.g., the average daily value was applied to each hour of the day). The number of monitors ranged from 399 for $NO_2$ to 1232 for $O_3$ (Fig. 1). If no pollutant monitors existed within the rural or urban area of a particular county, the closest data monitor was assigned to represent that area. As there are substantially more counties than monitors, most monitor data were derived from the nearest monitor that existed outside of the county (between 75 percent for $O_3$ and 92 percent for $NO_2$). If more than one monitor existed, hourly pollution removal was estimated for each monitor and averaged for the annual results.

To calculate the hourly deposition velocity, local hourly weather data for 2010 from the National Climatic Data Center (NCDC, 2013) were used to obtain hourly meteorological data (910 weather stations) (Fig. 1). If no weather data existed within a rural or urban area of a particular county, the closest monitor data was assigned to represent that area (72 percent of counties used data from outside the county). If more than one monitor existed, the weather data closest to the geographic center of the area was used. Deposition velocities for all pollutants and resuspension rates for particulate matter were calculated based on methods detailed in Nowak et al. (2006a, 2013) and Hirabayashi et al. (2011, 2012). Total removal of a pollutant in a county was calculated as the annual flux value ($\mu g\ m^{-2}\ yr^{-1}$) times total tree cover ($m^2$). Minimum and maximum estimates of removal were based on the typical range of published in-leaf dry deposition velocities (Lovett, 1994).

### 2.3. Change in pollutant concentration

To estimate percent air quality improvement due to dry deposition, hourly mixing heights from the nearest radiosonde station (74 stations; NOAA, 2013, Fig. 1) were used in conjunction with local