CHAPTER TWO

URBAN TREES, AIR QUALITY AND HUMAN HEALTH

DAVID J. NOWAK

USDA FOREST SERVICE, NORTHERN RESEARCH STATION, SYRACUSE, NY. EMAIL: DAVID.NOWAK@USDA.GOV

Introduction

The World Health Organization (2016) states that air pollution is the largest environmental risk factor to human health, accounting for about one in nine deaths annually. The problems associated with air pollution and higher air temperatures in cities have been known for over a century, but so have the impacts of trees and forests on improving air quality and regulating air temperatures. Trees, through their interaction with the atmosphere, affect air quality and consequently human health, particularly when in close association with people (e.g., in cities).

In the 1800s, parks in cities were referred to as "lungs of the city" because of the ability of park vegetation to produce oxygen and remove industrial pollutants from the atmosphere (Compton 2016). This term was a form of an earlier expression "lungs of London", which was first attributed to William Pitt, by Lord Windham in a speech in the House of Commons in 1808, during a debate on the encroachment of buildings upon Hyde Park (History House 2017).

In addition to this “lung” capacity, a cooling capacity of vegetation has also long been known to affect the local environment. Historical home designs dating back over a millennia often included trees and water features to help cool the environment (Laurie 1986). As cities and populations expand, and the world warms, this ability to cool the environment becomes even more essential. Cities tend to create “heat islands”, a term first coined in 1818 (Howard 1818), where cities are warmer than surrounding rural areas. While cities are often cultural and economic centers, the enhanced heat, pollution and population density can contribute to increased prevalence of human mortality and several illnesses, including heat stress, respiratory diseases, and mental disorders.

While changes in air quality and air temperatures affect human health, trees also influence other attributes that affect human health. These attributes include reducing ultraviolet radiation (Heisler and Grant 2000), mitigating atmospheric carbon (Heath et al. 2011), altering water quality (Nowak et al. in press) and various impacts on human physiology (e.g., stress reduction) (van den Bosch and Ode 2017). While these attributes are important, the intent of this chapter is to only review how trees affect air quality, including air temperatures, and its consequent impact on human health. By understanding these impacts, forest management plans can be developed to improve air quality and human health.

Air Pollution and Air Temperature Effects on Human Health and Well-Being

Air pollution significantly affects human and ecosystem health (U.S. EPA 2010a). Global deaths directly or indirectly attributable to ambient air pollution reached almost 4.5 million in 2015 (Cohen et al. 2017). Air pollution is the largest environmental cause of disease and premature death in the world (WHO 2014).

Ambient air pollution caused 107.2 million disability adjusted life years (number of years lost due to ill-health, disability or early death) in 2015 (Cohen et al. 2017). Human health problems from air pollution include the following: aggravation of respiratory and cardiovascular diseases; increased frequency and severity of respiratory symptoms (e.g., difficulty breathing and coughing, chronic obstructive pulmonary disease (COPD), and asthma); increased susceptibility to respiratory infections, lung cancer, and premature death (e.g., Pope et al. 2002; Marino et al. 2015; Vieria 2015). Recent studies also suggest that air pollution can contribute to cognitive and mental disorders (e.g., Calderón-Garcidueñas et al. 2011; Brauer 2015; Annavarapu and Kathi 2016). People with pre-existing conditions (e.g., heart disease, asthma, emphysema, diabetes), older adults, and children are at greater risk for air pollution-related health effects. In the United States, approximately 130,000 deaths were related to particulate matter less than 2.5 microns ($PM_{2.5}$) and 4,700 deaths to ozone (O_3) in 2005 (Fann et al. 2012).

Elevated ambient temperatures are associated with increased human mortality due to heat stress (Basu and Ostro 2008). Heat exposure increases mortality risk for groups with pre-existing medical conditions, such as cardiovascular, respiratory, and cerebrovascular diseases (Basu 2009). Several high-risk populations have been identified, including the elderly, children, people engaging in outdoor occupations and people living alone, especially on higher floors of apartment buildings (Basu and Ostro 2008). In July 1995, Chicago sustained a heat wave that resulted in more than 600 deaths, 3300 emergency department visits, and a substantial number of intensive care unit admissions for near-fatal heat stroke (Dematte et al. 1998). A heat wave in Europe in the summer of the 2003 led to more than 70,000 deaths (Robine et al. 2008). The issue of heat related morbidity and mortality is expected to increase substantially with climate change (Gasparrini et al. 2017).

Air pollution affects various attributes of the atmosphere that can affect both human and plant health. Air pollution affects the earth's climate by either absorbing or reflecting energy that can lead to climate warming or cooling, respectively (US EPA 2010b). Air pollutants, particularly nitrogen and sulfur oxides, can also lead to acid rain. Acid rain can harm vegetation by damaging tree leaves and stressing trees through changes in the chemical and physical composition of the soil. Acid rain can reduce soil nutrient availability through leaching of nutrients such as magnesium, or releasing toxic substances in soils, such as aluminum (NAPAP 1991). Air pollution can also reduce visibility. The visual range in the eastern U.S. parks has decreased from 90 miles to 15 to 25 miles due to man-made air pollution. In the West, the average visual range has decreased from 140 miles to 35-90 miles (US EPA 2017).

Air pollution can also directly damage plants, thereby affecting tree growth, functioning and health (e.g., Darley 1971, Ziegler, 1973, Shafer and Heagle 1989, Shiner et al. 1990, Saxe 1991). Some pollutants under high concentrations can damage leaves (e.g., sulfur dioxide, nitrogen dioxide, ozone), particularly of pollutant sensitive species. However, acid rain and air pollution can be a source of the essential plant nutrients of sulfur and nitrogen to enhance plant health and growth (NAPAP 1991). Particulate trace metals can be toxic to plant leaves. The accumulation of particles on leaves can reduce photosynthesis by reducing the amount of light reaching the leaf and thereby reduce plant growth and productivity. Particles can also affect tree disease populations with dust deposits leading to more fungal infections in some plant leaves (Smith 1990).

Both pollution and increased temperatures impact human and plant health, but they may also interact to produce an even greater negative impact on health (Harlan and Ruddell 2011). Trees can be used to improve air quality and reduce heat, and consequently improve human health.

Tree Effects on Air Quality

Trees affect air pollution in four main ways:

Temperature reduction and other microclimate effects
Removal of air pollution
Emission of chemicals
Energy conservation in buildings

The interactions of these various effects ultimately affect air pollution concentrations, air temperatures and human health. By understanding these effects and interactions, forest designs can implemented to help improve human health.

Tree effects on air temperatures and local microclimates

Increased air temperatures can lead to increased building energy demand in the summer, increased air pollution, and heat-related illness. Trees alter microclimates and cool air temperatures through evaporation from tree transpiration, blocking winds, and shading various surfaces. Vegetated areas can cool the surroundings by several degrees C, with higher tree and shrub cover leading to cooler air temperatures (Chang et al. 2007). Although trees usually contribute to cooler summer air temperatures, their presence can increase air temperatures in some instances (Myrop et al. 1991). Maximum mid-day air temperature reductions due to trees are in the range of 0.04^{o}C to 0.2^{o}C per percent canopy cover increase (Simpson 1998). Below small groups of trees over grass, mid-day air temperatures at 1.5 m above ground are 0.7^{o}C to 1.3^{o}C cooler than in an open area (Souch and Souch 1993). Reduced air temperature due to trees can improve air quality because the emission of many pollutants and/or ozone-forming chemicals are temperature dependent.

Tree transpiration and tree canopies also affect radiation absorption and heat storage, relative humidity, turbulence, surface albedo, surface roughness and mixing-layer height (i.e., height within which wind and surface substances (e.g., pollution) are dispersed by vertical mixing processes). Topography also affects air temperatures (and pollution concentrations) through cold-air drainage (Heisler and Brazel 2010, Heisler et al. 2016). The combination of natural landscapes (e.g., forests) and artificial landscapes (e.g., buildings) affect this cold air drainage. In Stuttgart, Germany, the identification of cold air drainage areas came to be labelled as the city’s fresh air swathes. The maintenance of these natural ventilators became a critical component of the city's post-war planning policy (Hebbert 2014). Changes in local meteorology can alter pollution concentrations in urban areas (Nowak et al. 2000).

Changes in wind speeds can lead to both positive and negative effects related to air pollution. On the positive side, reduced wind speeds will tend to reduce winter-time heating energy use in buildings (and associated pollutant emissions from power plants) by reducing cold air infiltration into buildings. For example, in residential neighborhoods in Central Pennsylvania, wind speed reductions by trees in the summer ranged from 28 to 46 percent, depending on tree cover in the neighborhood. However, even though the trees were mostly deciduous, winter wind speed reductions averaged 14 to 41 percent (Heisler 1990). On the negative side, reductions in wind speed can reduce the dispersion of pollutants, which will tend to increase local pollutant concentrations. In addition, lower wind speeds tend to reduce the "mixing height" of the atmosphere, which tends to increase pollutant concentrations as the same amount of pollution is now mixed within a smaller volume of air.

Removal of air pollutants

Trees remove gaseous air pollution primarily by uptake through leaf stomata, though some gases are removed by the plant surface. 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 (Smith 1990), which can be a source of the essential plant nutrients of sulfur and nitrogen (NAPAP 1991). Trees also directly affect particulate matter in the atmosphere through the interception of particles, emission of particles (e.g., pollen) and resuspension of particles captured on the plant surface. Many of the particles that are intercepted are eventually resuspended back to the atmosphere, washed off by rain, or dropped to the ground with leaf and twig fall. Consequently, vegetation is only a temporary retention site for many atmospheric particles. The removal of gaseous pollutants is more permanent as the gases are often absorbed and transformed within the leaf interior (Smith 1990).

Healthy trees in cities can remove significant amounts of air pollution. Areas with a high proportion of tree cover (e.g., forest stands) will remove more pollution and have the potential to create greater reductions in air pollution concentrations in and around these areas. One hectare of U.S. urban tree cover averages about 67 kg of pollution removal per year (Nowak et al. 2014). However, this value could range up to over 200 kg per year in more polluted areas with long growing seasons (Nowak et al. 2006a; Figure

1). Large healthy trees (> 76 cm in stem diameter) remove approximately 60-70 times more air pollution annually than small healthy trees (< 7.6 cm in stem diameter), with large trees removing about 1.4 kg per year (Figure 2). Pollution removal rates by vegetation differ among regions according to the amount of vegetative cover, the amount of air pollution, length of in-leaf season, precipitation, and other meteorological variables. Average air quality improvement by trees in cities is typically less than one percent. However, in areas with 100% tree cover, hourly air quality improvements due to pollution removal average around 4 times more and can reach up to 16 percent (Nowak et al. 2006). From a public health perspective, it is important to consider that even though percent air quality improvement from trees may not be very large, a small percent change in air quality can have a substantial impact on human health (Cohen et al., 2017).

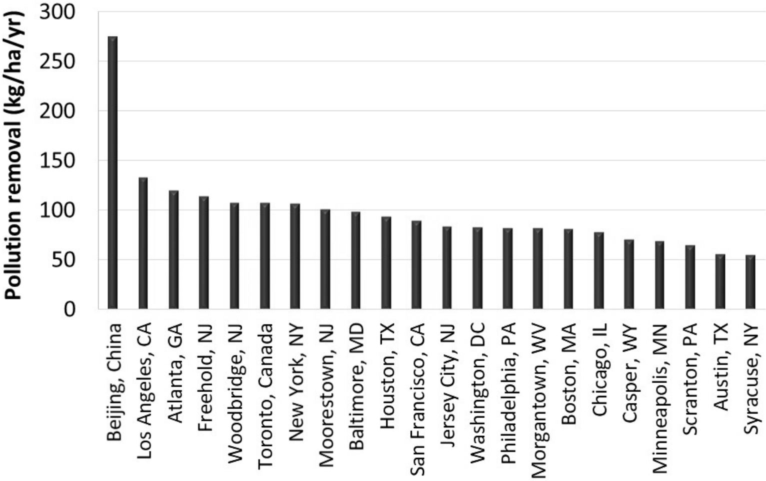

Figure 1. Average pollution removal per hectare of tree cover in select cities. Estimate is the combined total of carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), particulate matter less than 10 microns (PM_{10}) and sulfur dioxide (SO_2) removal (Nowak et al. 2006b,c,d; 2010a,b; 2011; 2012; 2013b; 2016a,b,c,d; 2017; 2018; Yang et al. 2005).

At the species level, pollution removal of gaseous pollutants will be affected by tree transpiration (i.e., stomatal opening) and amount of leaf area. Particulate matter removal rates will vary depending upon leaf surface characteristics and area. Species with moderately dense and fine textured crowns with complex, small, or rough leaves would capture and retain more particles than trees with open and coarse textured crowns with simple, large, or smooth leaves (Little 1977; Smith 1990). Evergreen trees provide for year-round removal of particles. A species ranking of trees in relation to pollution removal are estimated in i-Tree Species (www.itreetools.org).

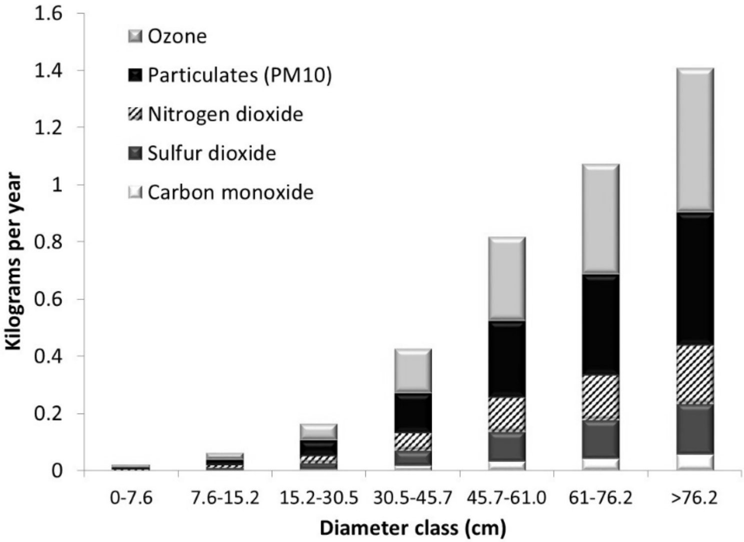

Figure 2. Estimated pollution removal by individual trees by diameter class in Chicago, IL (Nowak 1994).

Emission of chemicals

While trees reduce air pollution by reducing air temperatures and directly removing pollution, trees also emit various chemicals that can contribute to air pollution (Sharkey et al. 1991). Trees emit varying amounts of volatile organic compounds (e.g., isoprene, monoterpenes) (Geron et al. 1994; Guenther 2002). These compounds are natural chemicals that make up essential oils, resins, and other plant products, and may be useful in attracting pollinators or repelling predators (Kramer and Kozlowski 1979). Oxidation of volatile organic compounds is an important component of the global carbon monoxide budget (Tingey et al. 1991). VOCs emitted by trees can also contribute to the formation of ozone and particulate matter (Sharkey et al. 1991). Because VOC emissions are temperature dependent and trees generally lower air temperatures, increased tree cover can lower overall VOC emissions and, consequently, ozone levels in urban areas (e.g., Cardelino and Chameides 1990). Ozone inside leaves can also be reduced due to the reactivity with biogenic compounds (Calfapietra et al. 2009). It is likely that under non-stressful conditions, ozone uptake dominates over ozone potentially formed from VOC emissions. However, under high temperatures and drought, ozone removal by trees will likely drop and VOC emissions increase (Calfapietra et al. 2013).

Volatile organic emissions of urban trees generally are less than 10 percent of total emissions in urban areas (Nowak 1992). In large metropolitan areas that are NOx limited, urban tree biogenic VOC emissions may have minimal effects on ozone formation (Nowak et al. 2000). However, urban biogenic VOC emissions can lead to local ozone formation (e.g., Ren et al. 2017).

VOC emission rates vary by species. Nine tree genera that have the highest standardized isoprene emission rates and therefore the greatest relative effect on increasing ozone, are: beefwood (*Casuarina* spp.), *Eucalyptus* spp., sweetgum (*Liquidambar* spp.), black gum (*Nyssa* spp.), sycamore (*Platanus* spp.), poplar (*Populus* spp.), oak (*Quercus* spp.), black locust (*Robinia* spp.), and willow (*Salix* spp.). However, given that these genera also remove ozone and lower air temperatures, it is unknown if these genera lead to a net production of ozone.

Other factors to consider in addition to VOC emissions are tree maintenance and pollen emissions. Because some vegetation, particularly urban vegetation, often require inputs of energy for maintenance activities, resulting pollutant emissions from maintenance equipment need to be considered. This equipment includes vehicles for transport or maintenance, chain saws, back hoes, leaf blowers, chippers, and shredders. The combustion of fossil fuels to power this equipment leads to the emission of carbon dioxide and other chemicals such as VOCs, carbon monoxide, nitrogen and sulfur oxides, and particulate matter (US EPA 1991). By 2020, gas-powered leaf blowers, hedge trimmers and mowers (i.e., small off-road engines) are projected to exceed cars as the worst air polluters in California (Gorn 2017).

Trees in parking lots can also affect evaporative emissions from vehicles, particularly through tree shade. Increasing parking lot tree cover from 8% to 50% could reduce Sacramento County, CA light duty vehicle VOC evaporative emission rates by 2% and nitrogen oxide start emissions by less than 1% (Scott et al. 1999).

In addition to VOC emissions, pollen emission from trees needs to be considered. Pollen particles from trees can lead to allergic reactions (e.g., Cariñanosa et al. 2014). Examples of some of the most allergenic species are: *Acer negundo* (male), *Ambrosia* spp., *Cupressus* spp., *Daucus* spp., *Holcus* spp., *Juniperus* spp. (male), *Lolium* spp., *Mangifera indica*, *Planera aquatica*, *Ricinus communis*, *Salix alba* (male), *Schinus* spp. (male) and *Zelkova* spp. (Ogren 2000). Pollen can interact with air pollutants, which can increase the allergenic properties of pollen and thereby increase the risk for allergic and asthmatic reactions (e.g., Steerenberg et al. 1999, Fernvik et al.2002, Beck et al. 2013, Ouyang et al. 2016, Schiavoni et al. 2017, Sedghy et al. 2018).

Energy effects on buildings

Trees reduce building energy use by lowering temperatures and shading buildings during the summer, and blocking winds in winter. However, they also can increase energy use by shading buildings in winter (e.g., Heisler 1986). Thus, proper tree placement near buildings is critical to achieve maximum building energy conservation benefits. Urban forests in the conterminous United States annually reduce residential building energy use to heat and cool buildings by 7.2% or about $5.4 billion per year (Nowak and Greenfield 2018). This altered energy use consequently leads to changes in pollutant emissions from power plants.

Due to lowered building energy use, urban forests in the conterminous United States avoid the emission of thousands of tons of pollutants (i.e., carbon dioxide, nitrogen oxides, sulfur dioxide, methane, carbon monoxide, particulate matter less than 2.5 and 10 microns and volatile organic compounds (VOC)) from power plants, which is valued at $2.7 billion per year (Nowak and Greenfield 2018).

Overall effect of trees on air pollution

There are many factors, both positive and negative, that determine the ultimate effect of trees on air pollution. While pollution removal, reduced air temperatures and general reduction in energy use improve air quality, the emission of VOCs and changes in wind speed can offset some of the improvement and can lead to local increases in pollution concentrations under certain conditions.

One model simulation illustrated that a 20 percent loss in forest cover in the Atlanta area due to urbanization led to a 14 percent increase in ozone concentrations (Cardelino and Chameides 1990). Although there were fewer trees to emit volatile organic compounds, an increase in Atlanta's air temperatures, due to tree loss and the urban heat island effect, increased

VOC emissions from trees and other sources and altered ozone chemistry such that concentrations of ozone increased.

A different model simulation of California's South Coast Air Basin suggests that the air quality impacts of increased urban tree cover may be locally positive or negative with respect to ozone. However, the net basin-wide effect of increased urban vegetation was a decrease in ozone concentrations if the additional trees are low VOC emitters (Taha 1996).

Modeling the effects of increased urban tree cover on ozone concentrations from Washington, DC to central Massachusetts revealed that urban trees generally reduce ozone concentrations in cities, but tend to slightly increase average ozone concentrations regionally. The dominant tree effects on ozone were due to pollution removal and change in air temperatures, wind fields, and mixing-layer heights (Nowak et al. 2000). Modeling of the New York City metropolitan area also revealed that increasing tree cover by 10% reduced maximum ozone levels by about 4 ppb. This reduction was about 37% of the amount needed for attainment of the U.S. Environmental Protection Agency's one-hour ozone air quality standard, revealing that increased tree cover can have a significant impact on reducing peak ozone concentrations in this region (Luley and Bond 2002).

Field measurements in Berlin, Germany indicate that vegetation substantially lowered air pollution with ozone concentrations being reduced the most by coniferous forests, likely due reactive biogenic VOC emissions. Regarding land use potentials to reduce air pollution, forests showed the largest decrease in air pollution, followed by parks and sports facilities. Surface temperatures were generally 0.6–2.1°C lower in vegetated regions, which impacted tropospheric chemical processes (Bonn et al. 2016). These study results suggest that increased urban green spaces and forests could be a viable method to reduce particulate pollution if the forest area is large enough, but these findings not necessarily hold for ozone or nitrogen.

Though reduction in wind speeds can increase local pollution concentrations due to reduced dispersion of pollutants and lowering of mixing heights, altering of wind patterns can also have a potential positive effect. Tree canopies can potentially prevent pollution in the upper atmosphere from reaching ground-level air space. Measured differences in ozone concentration between above- and below-forest canopies in California's San Bernardino Mountains have exceeded 50 ppb (40-percent lower concentration below the canopy than above) (Bytnerowicz et al. 1999). Forest canopies can limit the mixing of upper air with ground-level air, leading to significant below-canopy air quality improvements. However, where there are numerous pollutant sources below the canopy (e.g., automobiles), the forest canopy could increase concentrations by minimizing the dispersion of the pollutants away at the ground level (Figure 3). This effect could be particularly important in heavily-treed areas where automobiles drive under tree canopies.

Figure 3. Design of vegetation near roadways is important to minimize potential negative effects, such as trapping of pollutant (image source: D. Nowak)

The interactions of removal, emissions, temperature, and wind speed (i.e., potential trapping) can create a myriad of local effects on pollution concentrations. Field studies have revealed mixed results. Some studies have found lower pollution concentrations near trees (e.g., Yin et al. 2011, Fantozzi et al. 2015, Irga et al. 2015, Garcia-Gomez et al. 2016, Viippola et al. 2016, Yli-Pelkonen et al. 2017a,b), but others have found no differences (Setala et al. 2013, Irga et al. 2015, Viippola et al. 2016, Yli-Pelkonen et al. 2017a,b) or increased concentrations (Viippola et al. 2016, Yli-Pelkonen et al. 2017c).

At the local scale, pollution concentrations can be increased if trees: a) trap pollutants beneath tree canopies near emission sources (e.g., along road ways) (Gromke and Ruck 2009; Wania et al. 2012; Salmond et al. 2013; Vos et al. 2013); b) limit dispersion by reducing wind speeds (Long et al. 2018); and/or c) lower mixing heights by reducing wind speeds (Nowak et al. 2000, 2014). While the trapping of pollutants near roadways (Figure 3) can be detrimental to people on or near the roadway, this trapping does limit pollution movement into surrounding areas, which could have a beneficial effect of lower surrounding pollutant concentrations. It is also important to note that near roadways, the vast majority of the pollution is created by automobiles, not trees. Trees can be used to create barriers between people and automobile emissions to help reduce pollution exposure (Baldauf et al. 2011, 2103; Brandley et al. 2014,). While trees may increase local pollutant concentrations and reduce pollutant concentrations elsewhere, the overall effect of pollution removal by trees is positive as it reduces the amount of pollution in the atmosphere. Standing in the interior of stands of trees can also offer cleaner air if there are no local ground sources of emissions (e.g., from automobiles) nearby. Various studies (Dasch 1987; Cavanagh et al. 2009) have illustrated reduced pollutant concentrations in the interior of forest stands compared to outside of the forest stand.

Local scale forest designs need to consider the location of pollutant sources relative to the distribution of human populations to minimize pollution concentrations and maximize air temperature reduction in heavily populated areas. Forest designs also need to consider numerous other tree impacts that can affect human health and well-being (e.g., impacts on ultraviolet radiation, water quality, aesthetics, etc).

Health Effects of Trees Due to Changes in Air Quality

There are numerous studies that link air quality to human health effects, but only a limited number of studies have looked at the estimated health effects of air pollution removal by trees. In the United Kingdom, woodlands are estimated to reduce between 5 and 7 deaths and between 4 and 6 hospital admissions per year due to reduced sulfur dioxide and particulate matter less than 10 microns (PM_{10}) (Powe and Willis 2004). In London, it is estimated that the city’s 25% tree cover removes 90.4 tonnes of PM_{10} pollution per year, which equates to a reduction of 2 deaths and 2 hospital stays per year (Tiwary et al. 2009). 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 tonnes in Syracuse to 64.5 tonnes in Atlanta, with health values ranging from \$1.1 million in Syracuse to \$60.1 million in New York City.

Trees in the conterminous United States removed 22.4 million tonnes of air pollution in 2010, with human health effects valued at 8.5 billion U.S. dollars. Most of the pollution removal occurred in rural areas, while most of the health benefits were within urban areas. Health impacts included the avoidance of more than 850 incidences of human mortality. Other substantial health benefits include the reduction of more than 670,000 incidences of acute respiratory symptoms, 430,000 incidences of asthma exacerbation and 200,000 school loss days (Nowak et al. 2014).

Modeling of tree effects in Portland, Oregon reveal that trees reduce the NO_2 by about 15% (1.4 ppb), which equated to health benefits (e.g., >21,000 fewer incidences of asthma) valued at $7 million per year (Rao et al. 2014). Various studies have also found associations between increased vegetation cover and decreased prevalence of asthma (e.g., Lovasi et al. 2008, Maas et al. 2009, Sbihi et al. 2015; Ulmer et al. 2016, Donovan et al. 2018). Yet, other studies have found no link between asthma and tree cover (Pilat et al. 2012) or even possible increases in asthma prevalence with increased tree cover (Lovasi et al. 2013).

Increased tree pollen has been linked to seasonal peaks in emergency room visits and hospitalizations for asthma (e.g., Jariwala et al., 2011, 2014; Darrow et al., 2012, Weinberger et al. 2015, Dales et al., 2004; Dales et al. 2008), and increases in purchases of allergy medication (Sheffield et al., 2011, Ito et al. 2015). However, increased tree density has been linked to reduced asthma hospitalizations under high air pollutant levels (Alcock et al. 2017).

The association between trees and air quality and consequently human health at the local scale are complicated by a myriad of pollutants, various human health responses to pollutant exposure, and the interaction of multiple positive and negative impacts of trees. These impacts include pollutant uptake by plant surfaces, resuspension of atmospheric particles, emission of VOC and pollen, and changes in wind speeds, temperatures, and the local environment that can affect pollution dispersion, removal and formation (e.g., Eisenman et al. 2019).

Conclusion

Overall, trees have a positive effect on improving air quality, mainly through reducing air temperatures and energy use, and direct pollution removal. However, trees also have some negative effects related to the emission of VOCs and pollen, and the lowering of wind speeds. Local scale forest designs near pollutant sources need to consider that trees alter wind patterns and flows between pollutant sources (e.g., automobiles) and humans. Thus, trees can limit pollution dispersion and increase local pollutant concentrations (e.g., along streets), but trees can also protect sites from pollutant emissions and lower pollution concentrations (e.g., in forest stands). By understanding how trees affect air quality and air temperatures, better landscape designs can be implemented to use trees to improve human health.

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