Chapter 8
The Atmospheric System: Air Quality and Greenhouse Gases

David J. Nowak

Abstract Trees in cities affect air quality and greenhouse gases in numerous ways and consequently affect environmental quality and human health. Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmospheric environment. The main ways that urban trees affect air quality and greenhouse gases are through (a) air temperature reduction and other microclimatic effects, (b) removal of air pollutants and atmospheric carbon, (c) emission of volatile organic compounds and emissions associated with tree maintenance, and (d) altering energy use in buildings and consequently pollutant and carbon emissions from power plants. By understanding the effects of trees and forests on the atmospheric environment, managers can design appropriate and healthy vegetation structure in cities to improve air quality and consequently human health and well-being for current and future generations.

Keywords Pollution removal · Climate change · VOC emissions · Urban forests · Air temperature

8.1 Introduction

Trees in cities are a significant resource that affects the city atmosphere and consequently human health and environmental quality. Trees affect the atmosphere in numerous and interactive ways. This chapter will focus on the chemical constituents of the atmosphere related to air quality and greenhouse gases but will draw upon other atmospheric effects related to meteorology that are described elsewhere in this book. Trees significantly influence the local atmospheric environment through the

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exchange of gases and alteration of wind and solar radiation within the city. These influences are due mainly to the evaporation of water from tree leaves (transpiration), exchange of gases at the leaf surface, and the physical mass of the plants' woody and leafy tissue that can intercept materials and energy and alter wind patterns. Trees affect the urban atmosphere primarily by regulating air temperature (see Chap. 7) and altering air pollution and atmospheric carbon dioxide fluxes and concentrations. The purpose of this chapter is to provide a better understanding of how urban forests affect air quality and greenhouse gases.

8.2 Air Quality

Air pollution significantly affects human and ecosystem health [1]. Recent research indicates that global deaths directly or indirectly attributable to ambient air pollution reached almost 4.5 million in 2015 [2]. Air pollution is the largest environmental cause of disease and premature death in the world [3], with the World Health Organization [4] stating that air pollution is the largest environmental risk factor.

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 [2]. Human health problems from air pollution include 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), and increased susceptibility to respiratory infections, lung cancer, and premature death [5–7]. Worldwide, there are an estimated 300 million people with asthma and 210 million people affected by COPD [8]. Recent studies also suggest that air pollution can contribute to cognitive and mental disorders [9–11]. People with pre-existing conditions (e.g., heart disease, asthma, emphysema), diabetes, and 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 <2.5 µm ($PM_{2.5}$) and 4700 deaths to ozone (O_3) in 2005 [12].

Between 1990 and 2016, air quality in the United States has improved for the six common air pollutants, with lead (Pb) concentrations improving by 99%, sulfur dioxide (SO_2) by 85%, carbon monoxide (CO) by 77%, nitrogen dioxide (NO_2) by 50%, particulate matter <10 µm (PM_{10}) by 39%, and ozone (O_3) by 22%. In addition, particulate matter <2.5 µm ($PM_{2.5}$) has improved by 44% since 2000 [13]. Despite these improvements in air quality, approximately 107 million people live in areas of the U.S. that exceeded the national ambient air quality standards (NAAQS) for ozone in 2017, 23 million for $PM_{2.5}$ and three million for SO_2 [14].

In addition to affecting human health, air pollution affects the Earth's climate by either absorbing or reflecting energy that can lead to climate warming or cooling, respectively [15]. Air pollutants, particularly nitrogen oxides (NO_x) and SO_2, can also lead to acid rain. Acid rain can harm vegetation by damaging tree leaves and stressing trees through changing the chemical and physical composition of the soil. Acid can reduce soil nutrient availability through leaching of nutrients such as magnesium or releasing toxic substances in soils such as aluminum [16].

Air pollution can reduce visibility. The visual range in the eastern US parks has decreased 90 miles to 15–25 miles due to man-made air pollution. In the West, the average visual range has decreased from 140 to 35–90 miles [17].

Air pollution can also directly damage plants and affect growth. Air pollution can affect a tree's functioning or health [18–22]. Some pollutants under high concentrations can damage leaves (e.g., sulfur dioxide, nitrogen dioxide, ozone), particularly of pollutant-sensitive species. Given the pollution concentration in most US cities, these pollutants would not be expected to cause visible leaf injury. Any potential harmful effects of carbon monoxide on trees are believed to be minimal. Some of the carbon monoxide can be converted to carbon dioxide and metabolized by the plants. Acid rain and air pollution can be a source of the essential plant nutrients of sulfur and nitrogen to enhance plant health and growth [16].

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 [23].

Air pollution comes from numerous sources. Some pollutants, both gaseous and particulate, are directly emitted into the atmosphere and include sulfur dioxide, nitrogen oxides, carbon monoxide, and volatile organic compounds. Sulfur dioxide and nitrogen oxides are the primary causes of acid rain. Other pollutants are not directly emitted; rather, they are formed through chemical reactions. For example, ground-level ozone is often formed when emissions of NO_x and volatile organic compounds (VOCs) react in the presence of sunlight. Some particles are also formed from other directly emitted pollutants [1]. In the United States, emissions generally come from large stationary fuel combustion sources (e.g., electric utilities and industrial boilers and other processes (such as metal smelters, petroleum refineries, cement kilns, and dry cleaners), highway vehicles, and non-road mobile sources (such as recreational and construction equipment, marine vessels, aircraft, and locomotives).

8.2.1 Air Quality Regulations

In 1963, the Clean Air Act was passed in the United States. In 1970, a much stronger Clean Act was passed with Congress creating the US Environmental Protection Agency (EPA) and giving it the role in carrying out the Act. In 1990, the Act was revised and expanded giving the EPA broader authority to implement and enforce regulations to reduce air pollution emissions. Under the Clean Air Act, the EPA sets limits on the amount of pollution in the air and the emission of air pollutants. Individual states or tribes may have stronger air pollution laws, but they may not have weaker pollution limits. For several pollutants, the EPA establishes primary standards (permissible concentrations) that are designed to protect human health. A secondary standard is also established to prevent environmental and property damage. A geographic area with air quality that is cleaner than the primary standard is called an "attainment" area; areas that do not meet the primary standard are called "nonattainment" areas. In "nonattainment" areas, states and tribes develop state/tribal implementation plans to reduce air pollutants to allowable levels. These plans can include such items as cleaner vehicles, reformulated gasoline, changes in transportation policies (e.g., more buses or high-occupancy vehicle lanes), and vehicle inspection programs [24].

8.3 Tree Effects on Air Pollution

City trees have long been known to affect air quality. In the 1800s, parks in cities were referred to as "lungs of the city" due to the ability of the park vegetation to produce oxygen and remove industrial pollutants from the atmosphere [25]. 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 [26].

Urban vegetation can directly and indirectly affect local and regional air quality by altering the urban atmospheric environment. The four main ways that urban trees affect air quality are the following [27]:

- *T*emperature reduction and other microclimatic effects
- *R*emoval of air pollutants
- *E*mission of volatile organic compounds and tree maintenance emissions
- *E*nergy effects on buildings

8.3.1 Temperature Reduction

Cities tend to have higher temperatures than rural areas due to "urban heat islands" [28, 29]. Tree transpiration and tree canopies affect air temperature, radiation absorption, heat storage, wind speed, 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). These changes in local meteorology can alter pollution concentrations in urban areas [30]. Although trees usually contribute to cooler summer air temperatures, their presence can increase air temperatures in some instances [31]. For example, reduced windspeeds due to trees can increase air temperatures in treeless impervious areas on sunny days as cooler air is prevented from mixing with or dispersing the warm air coming off the impervious surfaces.

Maximum midday air temperature reductions due to trees are in the range of 0.04–0.2 °C per percent canopy cover increase [32]. Below individual and small groups of trees over grass, midday air temperatures at 1.5 m above ground are 0.7–1.3 °C cooler than in an open area [33] (tree effects on meteorology are discussed in more detail in Chap. 7). Reduced air temperature due to trees can improve air quality because the emission of many pollutants and/or ozone-forming chemicals is temperature dependent.

Topography also affects air temperatures (and pollution concentrations) through cold air drainage [34, 35]. The combination of natural landscapes (e.g., forests) and artificial landscapes (e.g., buildings) affects this cold air drainage. In Stuttgart, Germany, the identification of cold air drainage areas came to be labeled as the city's fresh air swathes. The maintenance of these natural ventilators became a critical component of the city's postwar planning policy [36].

In addition to temperature effects, trees affect wind speeds and hence mixing of pollutants in the atmosphere and local pollution concentrations [30, 37]. These changes in wind speeds can lead to both positive and negative effects related to air pollution. On the positive side, reduced wind speeds due to trees and forests will tend to reduce winter-time heating energy use in buildings by tending to reduce cold air infiltration into buildings, thereby reducing pollutant emissions associated with winter heating. For example, in residential neighborhoods in Central Pennsylvania, wind speed reductions by trees in the summer ranged from 28 to 46%, depending on tree cover in the neighborhood. However, even though the trees were mostly deciduous, winter wind speed reductions averaged 14–41% [37]. On the negative side, reductions in wind speed can reduce the dispersion of pollutants, which will tend to increase local pollutant concentrations. In addition, with lower windspeeds the height of atmosphere in which the pollutant mixes is often reduced. This reduction in the "mixing height" will also tend to increase pollutant concentrations as the same amount of pollution is now mixed within a smaller volume of air.

8.3.2 Removal of Air Pollutants

Healthy trees in cities can remove substantial amounts of air pollution. The amount of pollution removed is directly related to the amount or air pollution in the atmosphere. Areas with a high proportion of tree cover (e.g., forest stands) will remove more pollution and have the potential to have greater reduction in air pollution concentrations in and around these areas.

One acre of tree cover has an average pollution removal of about 100 pounds/year, but this value could range up to over 200 pounds/year in more polluted areas with long growing seasons (e.g., Los Angeles) (Fig. 8.1). These per acre pollution removal rates differ among cities according to the amount of air pollution, length of in-leaf season, precipitation, and other meteorological variables, such as temperature, wind speeds, and amount of solar radiation. Large healthy trees >30 in. in stem diameter remove approximately 60–70 times more air pollution annually (3.1 lbs/year) than small healthy trees <3 in. in diameter (0.05 lbs/year) (Fig. 8.2). As the number of trees in a size class tends to decrease with increasing size, while pollution removal tends to increase, overall pollution removal among tree 3-in. dbh classes can stay relatively stable (Fig. 8.3).

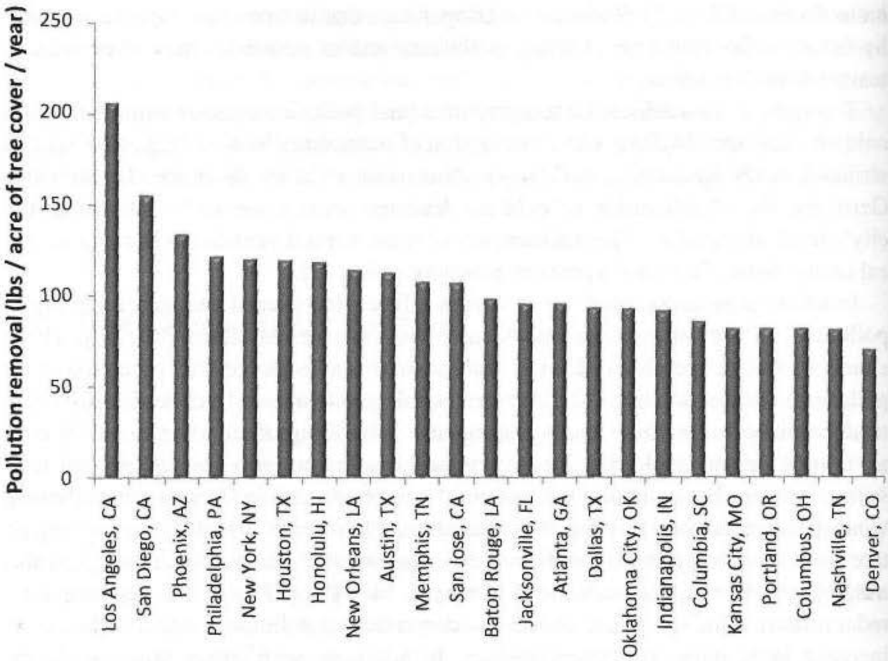

Fig. 8.1 Pollution removal values per acre of tree cover in select cities. Estimates assume a leaf area index of 6 and 10% evergreen species. Leaf area index is per unit tree cover and calculated as total leaf area (m^2) divided by tree cover (m^2)

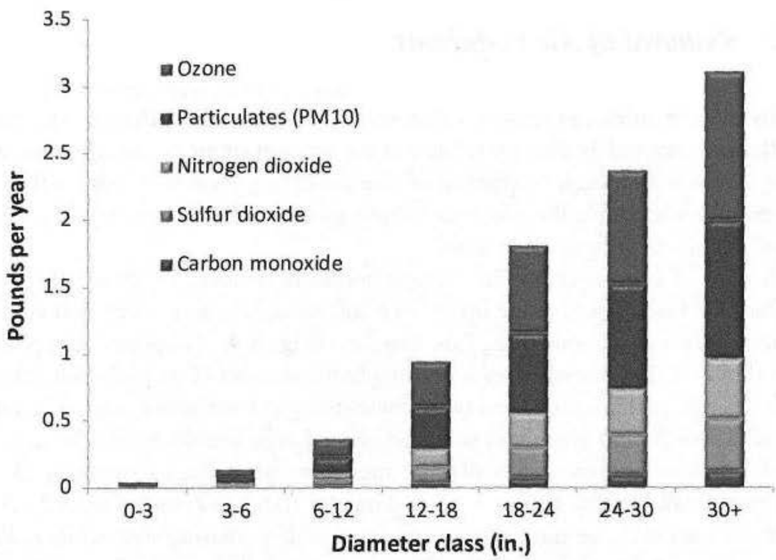

Fig. 8.2 Estimated pollution removal by individual trees by diameter class in Chicago, IL [38]

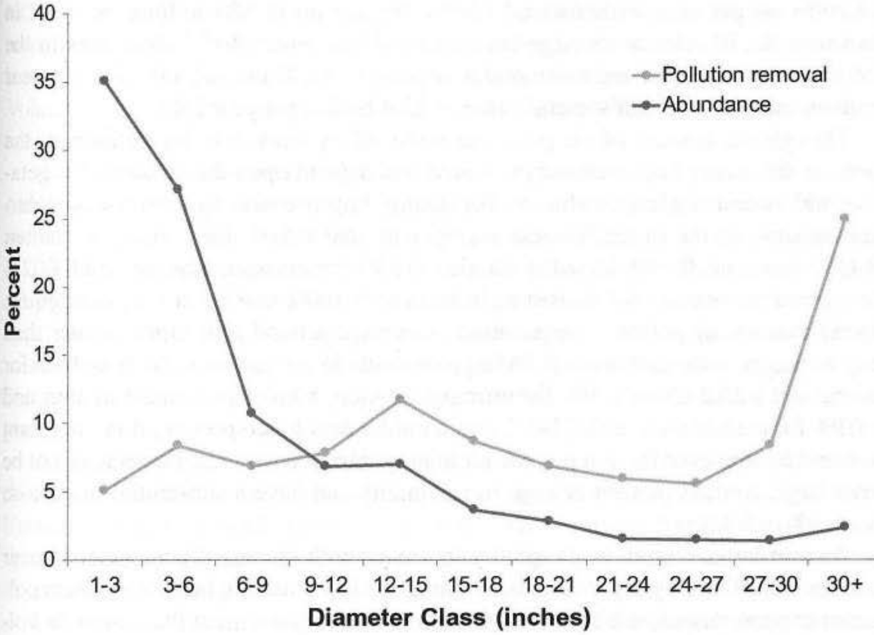

Fig. 8.3 Percentage of total population and pollution removal by diameter class, Philadelphia PA, 2012 [39]

Trees remove gaseous air pollution primarily by uptake through the 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 [23]. Trees also remove pollution by intercepting airborne particles on the plant surface. Although some particles can be absorbed into the tree [40–42], many intercepted particles 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 removed within the leaf interior.

At the species level, pollution removal of gaseous pollutants will be affected by tree transpiration rates (gas exchange rates) and amount of leaf area. Particulate matter removal rates will vary depending upon leaf surface characteristics and area. Species with dense and fine-textured crowns and complex, small, and rough leaves would capture and retain more particles than open and coarse-textured crowns and simple, large, smooth leaves [23, 43]. Evergreen trees provide for year-round removal of particles. A species ranking of trees in relation to pollution removal is estimated in i-Tree Species (www.itreetools.org).

Although the individual tree and per acre tree cover values may be relatively small, the combined effects of large numbers of trees and tree cover in aggregate can lead to significant effects. Pollution removal by trees in cities can range up to

11,100 tons per year with societal values ranging up to $89 million per year in Jacksonville, FL, due to its large land area and tree cover [44]. Urban trees in the lower 48 United States are estimated to remove 822,000 tons of pollution per year with an estimated annual societal value of $5.4 billion per year [45].

Though the amount of air pollution removed by trees may be significant, the percent air quality improvement in an area will depend upon the amount of vegetation and meteorological conditions. Air quality improvement by trees in cities during daytime of the in-leaf season averages around 0.51% for particulate matter, 0.45% for ozone, 0.44% for sulfur dioxide, 0.33% for nitrogen dioxide, and 0.002% for carbon monoxide [44]. However, in areas with 100% tree cover (i.e., contiguous forest stands), air pollution improvements average around four times greater than city averages with short-term (1 h) improvements in air quality as high as 16% for ozone and sulfur dioxide, 9% for nitrogen dioxide, 8% for particulate matter, and 0.03% for carbon monoxide [44]. 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 [2].

Percent improvement in air quality increases with increased percent tree cover and decreased mixing-layer heights. Although reduced mixing heights increase pollutant concentrations, it also increases the relative improvement from trees as volume of mixing in the atmosphere has decreased. To illustrate this reduction, consider identical air cleaners having the same rates of cleansing in cubic feet per hour, one cleaner is put in a large room, the other put in a small room, both with the same pollutant concentration. Though the cleaners are identical, the percent impact will be greater in the smaller room as there is less air to clean and less total pollution in the room.

8.3.3 Emission of Chemicals

While trees can reduce air pollution by changing the local microclimate and directly removing pollution, trees can also emit various chemicals that can contribute to air pollution [46]. Trees emit varying amounts of volatile organic compounds (e.g., isoprene, monoterpenes). 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. Complete oxidation of volatile organic compounds ultimately produces carbon dioxide, but carbon monoxide is an intermediate compound in this process. Oxidation of volatile organic compounds is an important component of the global carbon monoxide budget.

Emissions of volatile organic compounds by trees and other sources can also contribute to the formation of ozone, particularly during warm, sunny days in areas with high nitrogen oxide concentrations, which is common in the summer of many cities due to NO_x emissions from vehicles and power plants. However, in atmospheres with low nitrogen oxide concentrations (e.g., some rural environments), VOCs may actually remove ozone [47, 48]. 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 [49]. Volatile organic emissions of urban trees generally are <10% of total emissions in urban areas [50].

VOC emission rates vary by species. Nine tree genera that have the highest standardized isoprene emission rate [51, 52], 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, due to the high degree of uncertainty in atmospheric modeling, results are inconclusive as to whether these genera will contribute to an overall net formation of ozone in cities (i.e., where ozone formation from VOC emissions is greater than ozone removal).

Trees generally are not considered as a source of atmospheric nitrogen oxides, though plants, particularly agricultural crops, are known to emit ammonia [53]. Emissions occur primarily under conditions of excess nitrogen (e.g., after fertilization) and during the reproductive growth phase. Highly fertilized turf can also lead to emissions of nitrogen.

Trees can make minor contributions to sulfur dioxide concentration by emitting sulfur compounds such as hydrogen sulfide and sulfur dioxide [54]. Hydrogen sulfide, the predominant sulfur compound emitted, is oxidized in the atmosphere to form sulfur dioxide. Higher rates of sulfur emissions from plants are observed in the presence of excess atmospheric or soil sulfur. However, sulfur compounds also can be emitted with a moderate sulfur supply.

Trees can contribute to particle concentrations in urban areas by releasing pollen [55] and emitting volatile organic and sulfur compounds that serve as precursors to particle formation [46]. In addition to the health effects of particles listed previously, pollen particles can lead to allergic reactions [56]. 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. [55].

Relatively large inputs of energy, primarily from fossil fuels, are often used to maintain vegetation structure. The emissions from these maintenance activities need to be considered in determining the ultimate net effect of urban forests on air quality. Various types of equipment are used to plant, maintain, and remove vegetation in cities. This equipment includes vehicles for transport or maintenance, chainsaws, backhoes, 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 [57]. In California, gas-powered leaf blowers, hedge trimmers, and mowers are about to pass cars as the worst air polluters. By 2020, ozone-contributing pollutants from small off-road engines will exceed those same emissions from cars [58].

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 <1% [59].

8.3.4 Energy Effects on Buildings

Trees reduce building energy use by lowering temperatures and shading buildings during the summer and blocking winds in winter [60]. However, they also can increase energy use by shading buildings in winter and may increase or decrease energy use by blocking summer breezes. 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 $5.4 billion per year [45].

When building energy use is lowered, pollutant emissions from power plants are also lowered. Urban forests in the conterminous United States avoid the emission of thousands of tons of pollutants (carbon dioxide, nitrogen oxides, sulfur dioxide, methane, carbon monoxide, particulate matter <2.5 and 10 μm, and volatile organic compounds (VOCs)) valued at $2.7 billion per year [45]. Some utilities (e.g., Sacramento Municipal Utility District) have funded millions of dollars for tree planting to reduce energy use [61].

8.3.5 Trees Along Roadways

Trees along roadways can also affect how automobile emissions are dispersed to nearby residents [62]. Though a relatively new area of research, trees and bushes along roadways offer a complex and porous structure that can increase air turbulence and promote mixing as air flows through and around the vegetation. These vegetation effects can potentially reduce pollutant concentrations near roadways. However, tree canopies can also reduce wind speed and mixing-layer heights [30], which can reduce dispersion and potentially increase concentrations in the highway or street corridor. Modeling, wind tunnel experiments, and field measurements have evaluated the role of vegetation on pollutant concentrations near roadways [63–67]. Variables such as the vegetation type, height, and thickness influence the extent of mixing and pollutant deposition, although specific interrelationships of these factors have not been identified. In addition, the porosity of vegetation relative to solid structures may promote wind flow off the road and reduce on-road pollutant concentrations, although the resulting effect on downwind concentrations may be variable [68].

8.3.6 *Overall Effect of Vegetation on Air Pollution*

There are many factors that determine the ultimate effect of trees on pollution. Many tree effects are positive in terms of reducing pollution concentrations. For example, trees can reduce temperatures and thereby reduce emissions from various sources, and they can directly remove pollution from the air. However, the altering of wind patterns and speeds can affect pollution concentration in both positive and negative ways. Also plant compound emissions and emissions from vegetation maintenance can contribute to air pollution. Various studies on ozone, a chemical that is not directly emitted but rather formed through chemical reactions, help illustrate the cumulative and interactive effects of trees.

One model simulation illustrated that a 20% loss in forest cover in the Atlanta area due to urbanization led to a 14% increase in ozone concentrations [49]. Although there were fewer trees to emit volatile organic compounds, an increase in Atlanta's air temperatures due to the increased urban heat island, which occurred concomitantly with tree loss, increased volatile organic compound emissions from the remaining trees and other sources (e.g., evaporative emissions from cars), and altered ozone chemistry such that concentrations of ozone increased. This is an example of how decision makers might achieve counterintuitive results based on partial information, i.e. not systems thinking, as discussed in Chap. 1 and illustrates the importance of modeling to test well-intended policies before undertaking implementation.

Another 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 is a decrease in ozone concentrations if the additional trees are low VOC emitters [69].

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. Trees changed pollution removal rates and meteorology, particularly air temperatures, wind fields, and mixing-layer heights, which, in turn, affected ozone concentrations. Changes in urban tree species composition had no detectable effect on ozone concentrations [30]. Modeling of the New York City metropolitan area also revealed that increasing tree cover 10% reduced maximum ozone levels by about 4 ppb, which was about 37% of the amount needed for attainment of the ozone air quality standard, revealing that increased tree cover can have a significant impact on reducing peak ozone in this region [70].

Though reduction in wind speeds can increase local pollution concentrations due to reduced dispersion of pollutants and mixing height of the atmosphere, 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 (a 40% reduction in ozone concentrations) [71]. 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 ground level. This effect could be particularly important in heavily treed areas where automobiles drive under tree canopies (Fig. 8.4). At the local scale, pollution concentrations can be increased if trees (a) trap the pollutants beneath tree canopies near emission sources (e.g., along roadways) [68, 72–74], (b) limit dispersion by reducing wind speeds, and/or (c) lower mixing heights by reducing wind speeds [30, 75]. However, standing in the interior of stands of trees can offer cleaner air if there are no local ground sources of emissions (e.g., from automobiles) nearby. Various studies [76, 77] have illustrated reduced pollutant concentrations in the interior of forest stands compared to outside of the forest stand.

While increased tree cover will enhance pollution removal and reduce summer air temperatures, local scale forest designs need to consider the location of pollutant sources relative to the distribution of human populations to minimize pollution

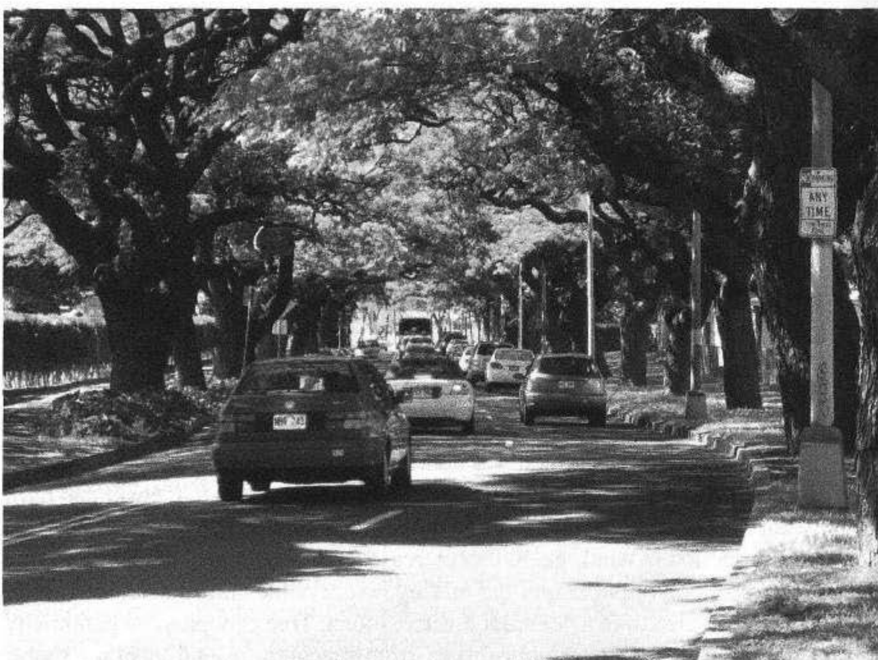

Fig. 8.4 Design of vegetation near roadways is important to minimize potential negative effects, such as trapping of pollutants (image source: D. Nowak)

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.).

8.3.7 *Health Effects*

There are numerous studies that link air pollution to human health effects. With regards to trees, most studies have investigated the magnitude of the effect of trees on pollution removal or concentrations, while only a limited number of studies have looked at the estimated health effects of pollution removal by trees. In the United Kingdom, woodlands are estimated to prevent between five and seven deaths and between four and five hospital admissions per year due to reduced pollution of sulfur dioxide and particulate matter (PM10) [78]. Modeling for London estimates that 25% city tree cover removes 90.4 metric tons of PM10 pollution per year, which equates to a reduction of two deaths and two hospital stays per year [79]. Nowak et al. [80] reported that the total amount of $PM_{2.5}$ removed annually by trees in ten US cities in 2010 varied from 4.7 tons in Syracuse to 64.5 tons in Atlanta, with health values ranging from $1.1 million in Syracuse to $60.1 million in New York City. Health impacts from air pollution removal by US urban trees in 2010 included the avoidance of 670 deaths and 575,000 acute respiratory incidences [75].

8.3.8 *Importance of Trees to Clean Air*

In September 2004, the US Environmental Protection Agency (EPA) released a guidance document titled "Incorporating Emerging and Voluntary Measures in a State Implementation Plan (SIP)" [81]. This EPA guidance details how new measures, which may include "strategic tree planting," can be incorporated in SIPs as a means to help meet air quality standards set by the EPA. As many of the standard strategies to meet clean air standards may not be sufficient to reach attainment, new and emerging strategies (e.g., tree planting, increasing surface reflectivity) may provide a means to help an area reach compliance with the new clean air standard for ozone. "In light of the increasing incremental cost associated with stationary source emission reductions and the difficulty of identifying additional stationary sources of emission reduction, EPA believes that it needs to encourage innovative approaches to generating emissions reductions" [81]. As many urban areas are designated as nonattainment areas for the ozone clean air standard and are required to reach attainment, trees in cities may play an important role in reaching clean air standards and can be integrated within SIPs [82].

8.4 Climate Change

Climate change refers to any significant change in measures of climate (e.g., temperature, precipitation) that occurs over an extended period (e.g., decades). This change could be due to natural factors and/or from human activities. Increasing levels of atmospheric carbon dioxide and other "greenhouse" gases (e.g., methane, chlorofluorocarbons, nitrous oxide) are contributing to an increase in atmospheric temperatures by the trapping of certain wavelengths of heat in the atmosphere.

The Intergovernmental Panel on Climate Change (IPCC) report [83] states that "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased." "Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. In the Northern Hemisphere, 1983–2012 was likely the warmest 30-year period of the last 1400 years." Observed long-term changes in climate include changes in Arctic temperatures and ice, widespread changes in precipitation amounts, strengthening wind patterns, and aspects of extreme weather events including droughts, heavy precipitation, and heat waves. Some future effects of climate change are projected to be (a) warmer and fewer cold days and nights over most land areas; (b) warmer and more frequent hot days and nights over most land areas; (c) increased frequency and duration of heat waves; (d) increased frequency, intensity, and number of heavy precipitation events; and (e) increased incidence and/or magnitude of extreme high sea levels. The societal and ecological impacts of climate change include potential changes to heat-related deaths, length of growing seasons, plant hardiness zones, leaf-out and flowering dates, and bird wintering ranges [15]. The projected average surface temperature warming by 2100 (relative to the 1980–1999 temperature average) is likely between 1.8 and 4.0 °C based on climate modeling projections. Increase of global mean surface temperatures for 2081–2100 relative to 1986–2005 is projected to likely be between 0.3 °C and 4.8 °C depending upon model simulation used [83].

As carbon dioxide is one of the dominant greenhouse gases and trees can influence carbon dioxide concentrations, tree effects on carbon dioxide are addressed in this section. Fossil fuel combustion is the primary source contributing to carbon dioxide emissions. Major sources of fossil fuel combustion include electricity generation, transportation, industrial processes, residential, and commercial land use. Electricity generation contributes approximately 39% of carbon dioxide emissions from fossil fuel combustion in the United States, while transportation contributes approximately 33% [84].

8.5 Tree Effects on Climate Change

Tree effects on climate change are similar to the types of effects of trees on air pollution. They (a) remove carbon dioxide from the atmosphere, (b) emit carbon dioxide, and (c) reduce air temperatures and alter building energy use and consequently emissions from power plants and other sources (e.g., evaporation of gasoline).

8.5.1 Carbon Storage and Annual Sequestration

Trees, through their growth process, directly remove carbon dioxide from the atmosphere and sequester the carbon within their biomass. Carbon storage by trees in a city can range up to over 1.3 million tons of carbon with societal value of approximately $28 million (New York, NY) [85]. Annual removal of carbon by trees in a city can reach over 45,000 tons of carbon per year with a value of approximately $1.0 million per year (Atlanta, GA). One acre of tree cover will likely store, on average, around 34 tons of carbon and remove about 1.2 tons of carbon per year (Figs. 8.5 and 8.6).

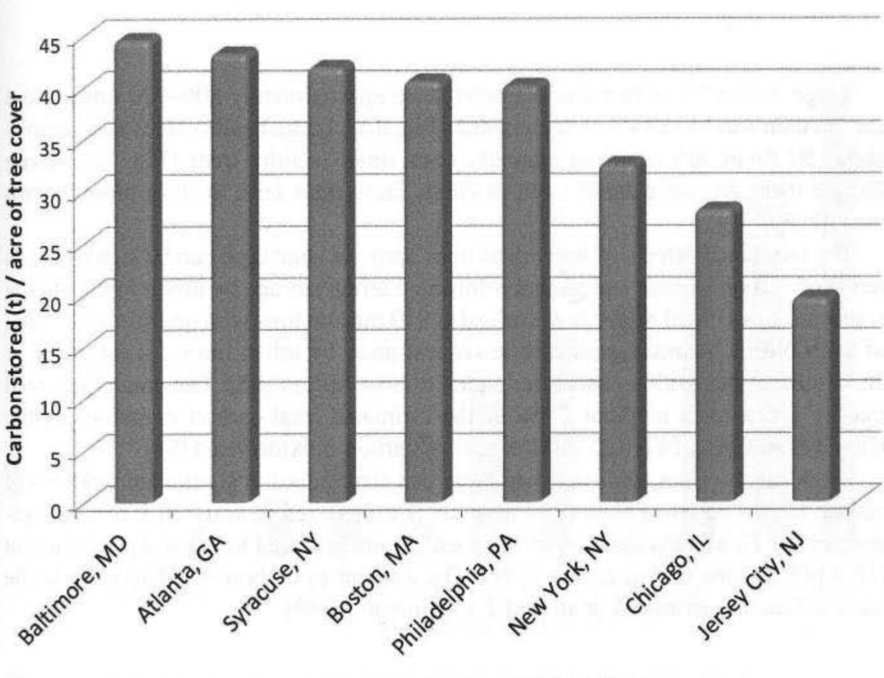

Fig. 8.5 Carbon storage per acre of tree cover in select cities [85, 86]

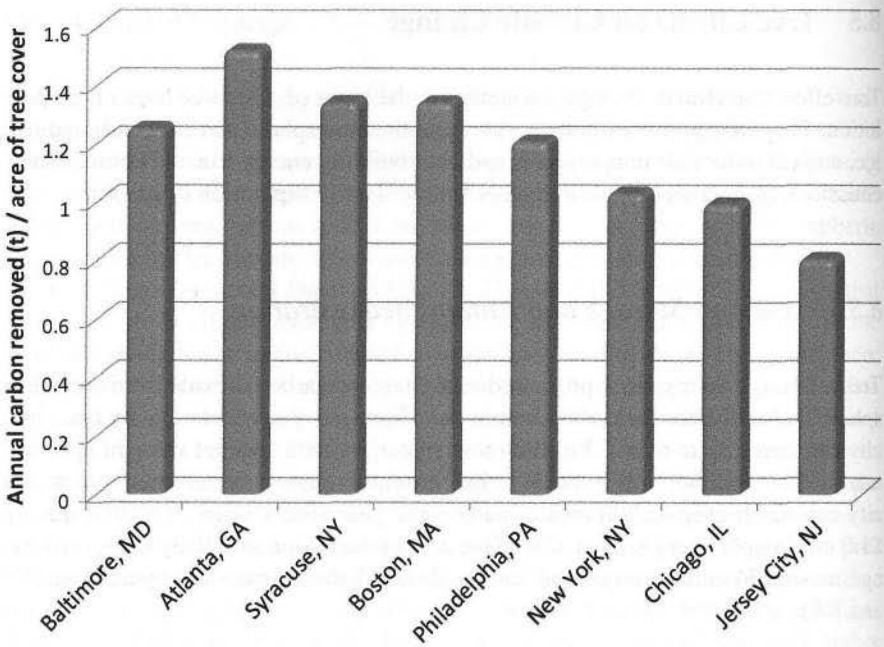

Fig. 8.6 Annual carbon removed per acre of tree cover in select cities [85, 86]

Large trees >30 in. in trunk diameter store approximately 800–900 times more carbon than small trees <3 in. in diameter (Fig. 8.7). Large healthy trees also remove about 50 times more carbon annually than small healthy trees (Fig. 8.8). Even though there are more small trees in cities, large trees tend to store more carbon overall (Fig. 8.9).

The combined effects of individual trees across a landscape can be significant in terms of carbon storage and annual removal. Carbon storage by urban forests in the conterminous United States is estimated at 919 million tons with an estimated value of $119 billion. Annual gross carbon sequestration by urban forests is estimated at 36.7 million tons with an estimated value of $4.8 billion [45]. The annual removal rate by urban trees is about 2.2% of the estimated total carbon emissions in the United States in 2014 (6123 million tons of carbon dioxide/year) [84].

In addition to trees, soils in urban areas can also sequester significant amounts of carbon as carbon from plants and animals is transferred to soils. In forest ecosystems in the United States, 38% of the total carbon is stored in the soil environment (18.9 billion tons of soil carbon) [88]. The amount of carbon in urban soils in the United States is estimated at around 2.1 billion tons [89].

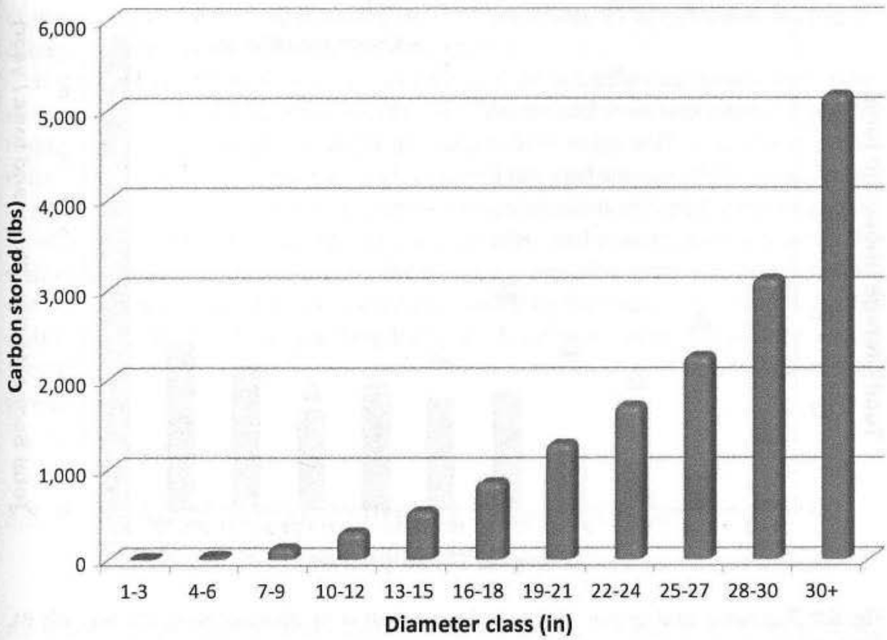

Fig. 8.7 Average carbon stored per tree by diameter class in Chicago [87]

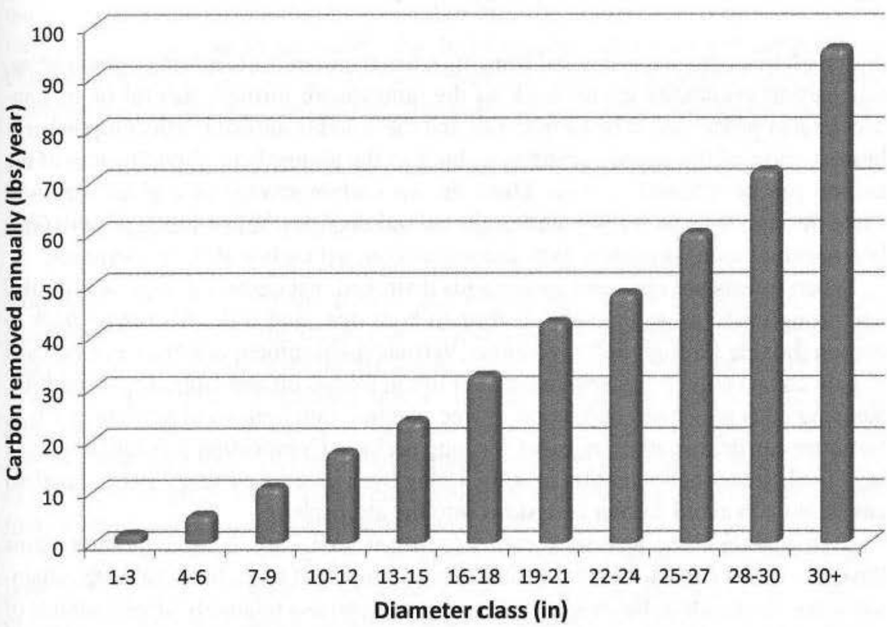

Fig. 8.8 Average carbon removal per tree per year by diameter class in Chicago [87]

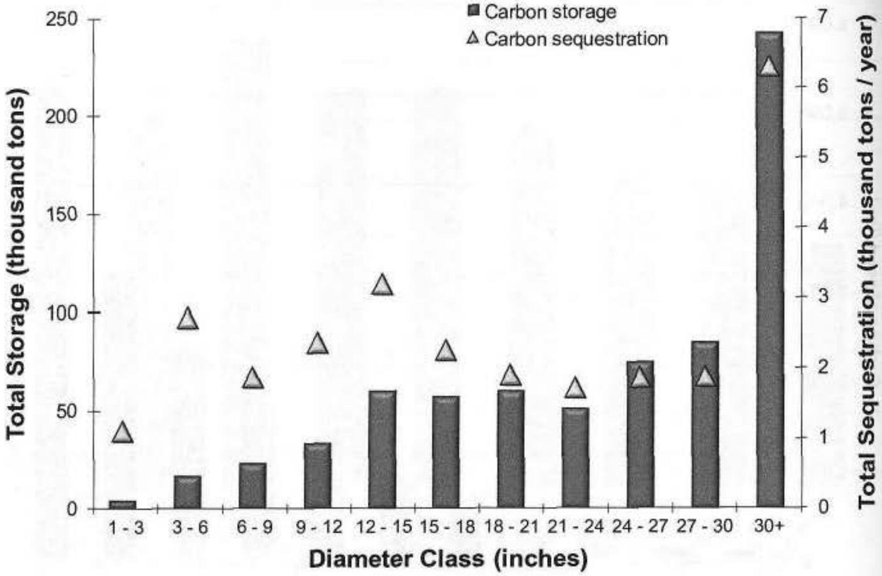

Fig. 8.9 Estimated total carbon storage and sequestration by diameter class, Philadelphia PA, 2012 [39]

8.5.2 Carbon Emissions: Carbon Cycling

Although trees can sequester and store significant amounts of carbon in urban areas, this carbon eventually cycles back to the atmosphere through natural or human-accelerated processes. When a tree dies and the wood is allowed to decompose or is burned, most of the stored carbon goes back to the atmosphere, though some of the carbon can be retained in soils. Thus, the net carbon storage in a given area will cycle through time as the population grows and declines. When forest growth (carbon accumulation) is greater than decomposition, net carbon storage increases.

When forests are removed and/or soils disturbed, net carbon storage will diminish through time as accumulated carbon in both trees and soil will convert back to carbon dioxide through decomposition. Various management practices can be used to help enhance the long-term impacts of urban forests on atmospheric carbon [90]. Keeping soils intact and utilization of tree biomass into long-term products such as furniture can delay carbon releases for long periods. Composting plant material can help facilitate carbon retention in soils. Using trees to reduce energy use and carbon emissions can avoid carbon emissions into the atmosphere.

Tree maintenance activities can also offset tree carbon sequestration gains through carbon emissions from maintenance equipment (e.g., from vehicles, chainsaws, backhoes, etc.). Because tree management can use relatively large amounts of fossil fuel-based energy to maintain vegetation, the emissions from maintenance/management activities need to be considered in determining the ultimate net effect of urban forests on global climate change. (See Chap. 11 for discussion of lower energy-requiring urban *ecological* landscaping.)

If trees are maintained using fossil fuels and do not offset emissions from other sources (e.g., reducing building energy use), maintained trees will ultimately be net emitters of carbon at some point in the future. This point will occur when carbon emissions due to maintenance activities exceed the total storage capacity of the tree or stand [90]. The number of years until carbon emissions exceed the carbon capacity of the site varies by tree species, tree density, and maintenance intensity. For maintained trees that do not survive the first few years after planting, carbon deficits can occur from the onset because carbon removal by the trees is less than the initial carbon inputs invested into planting the trees. If removed trees are used for energy production, they can also help reduce carbon emissions from fossil fuel burning power plants.

8.5.3 Reduced Carbon Emissions Through Cooler Temperatures and Reduced Energy Use

As discussed previously, trees can help mitigate heat island effects and reduce energy use and consequently carbon emissions from power plants [91, 92]. Vegetation designs to reduce air temperatures and building energy use in cities can lead to reduced carbon emissions from power plants and other sources and consequently help avoid emissions of carbon dioxide. The cooling effect of trees may be particularly important in the future due to projected warmer temperatures due to climate change [93]. Cities may be particularly warmer in the future due to climate change concomitant with urban heat islands that are already warming urban areas.

8.5.4 Climate Change Effects on Trees

Not only can trees affect the causes and effects of climate change, but climate changes will also affect the urban tree composition. Future changes in temperature and precipitation, along with increasing levels of carbon dioxide, are likely to lead to shifts in natural and cultivated species in cities. As urban areas already exhibit climatic differences compared to rural environs, due in part to numerous artificial surfaces and high level of fossil fuel combustion, climate change impacts may be exacerbated in these areas. These environmental changes can affect urban vegetation structure and functions in multiple ways.

Tree stress and/or decline may be increased due to elevated air temperatures, possible increased air pollution concentrations due to temperature changes, limited or excessive moisture, and intensified storm damage. Conversely, some trees/plants may benefit from increased air temperatures [94], increased air pollutants (e.g., sulfur and nitrogen) that can have a fertilizing effect [22], and/or increased CO_2 levels that may enhance growth rates [95]. If the environmental stresses induced by global climate change reduce tree growth and transpiration, or increase tree mortality, then tree benefits could decrease. However, if stresses are minimal, then carbon sequestration and pollution removal by trees may be enhanced with increased concentrations of carbon dioxide and air pollutants.

Increased plant stress/decline and/or storm damage frequency/intensity has the potential to increase tree maintenance activities needed to sustain healthy tree cover, thereby increasing associated maintenance emissions. In addition, if tree stress/mortality increases, it is likely that management will respond with shifts toward species that are better adapted to the changing climate. Along with changes in urban vegetation structure due to humans, species changes will likely also occur in more natural areas as species compositions shift with altered environments [96, 97]. Thus, the composition of urban forests may change in the future due to both natural and human-facilitated species changes due to a changing climate.

8.6 Conclusion

Overall, trees and forests have a positive effect on human health and well-being by improving air quality and reducing greenhouse gases, mainly through reducing air temperatures and energy use and through direct pollution removal and carbon sequestration. However, trees also have some negative effects related to the emission of VOCs, pollen, and carbon (via decomposition) and the lowering of wind speeds. Local scale forest designs near pollutant sources need to consider that trees alter wind flows and 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 the effects of trees and forests on the atmospheric environment, managers can design appropriate and healthy vegetation structure in cities to improve air quality and consequently human health and well-being for current and future generations.

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