Chapter 10
Improved Air Quality and Other Services from Urban Trees and Forests

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10.1 Introduction

Worldwide, there are an estimated 3.0 trillion trees (Crowther et al. 2015) and 7.7 billion people (http://www.worldometers.info/world-population/). These trees produce numerous benefits to society but also create various costs. Trees can improve human health and well-being by moderating climate, reducing building energy use and atmospheric carbon dioxide (CO_2), improving air quality, mitigating rainfall runoff and flooding, providing protection from ultraviolet radiation and soil erosion, lowering noise levels and providing food, lumber, medicines, aesthetic environments, and recreational opportunities (e.g., Millennium Ecosystem Assessment 2005; Nowak and Dwyer 2007; Costanza et al. 2014). However, trees can also produce environmental and monetary costs associated with allergies from pollen, volatile organic compound emissions, potential increased energy use due to trees near buildings, invasive plants that alter local biodiversity, higher taxes from increased property values, and tree maintenance. Both the positive and negative aspects of trees and forest must be considered when designing landscapes to improve human health and well-being.

As trees can be a dominant element in a landscape, understanding the magnitude and the means of how trees affect the environment can lead to better vegetation management and designs to optimize environmental quality and human health for current and future generations. In urban areas, the impacts of trees become more important due to the relatively high concentrations of humans and impervious surfaces that alter the environment.

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In the United States, tree cover in urban areas averages 39.4%, but ranges from a low of 10.1% in North Dakota to a high of 61.6% in Connecticut (Nowak and Greenfield 2018). Tree cover within cities varies depending on the region, with cities developed in forests having greater tree cover than cities developed in grassland and desert areas (Nowak et al. 1996). These regional differences are due to water availability and local tree seed sources, which affect natural regeneration and growth of trees. In US urban areas, only about one in three trees come from tree planting, the rest are due to natural regeneration. The proportion of trees planted varies by region (it tends to increase in drier regions due to limited regeneration), land use (more intensely managed (e.g., residential) areas tend to have a higher proportion of planted trees), and population density (as population density increases, so does the proportion of planted trees) (Nowak 2012). Although forest structure will inherently vary by region and water availability, natural regeneration can be used to sustain urban forests in many areas.

Another dominant element in urban landscapes is impervious cover (e.g., buildings, roads, parking lots). These surfaces provide essential services, but limit water infiltration into soils and tend to increase air temperatures. Impervious cover in US urban areas average 26.6%, but ranges from a low of 16.3% in New Hampshire to a high of 46.4% in Nevada (Nowak and Greenfield 2018). Percent impervious cover among states had less variation than percent tree cover.

At the global scale, tree cover in developed areas averages 26.5%, while impervious cover averages 25.9%. The tree cover in developed land varies by ecoregion, similar to the United States, with tree cover averaging 30.4% in forested regions, 18.2% in grasslands, and 12.0% in desert areas (Nowak and Greenfield 2020). Thus, both trees and impervious surfaces are important landscape components that interact within urban landscapes. Understanding how trees function to affect the local environment can lead to improved engineering solutions with trees to improve environmental quality and human health.

The purpose of this chapter is to summarize how trees affect their local environment and the general benefits provided by trees, with a specific focus on air quality. By understanding how and what trees impact, better designs can be engineered using trees to improve the environment. The chapter concludes with a discussion of a modeling system designed to aid in assessing the environmental impacts and values of trees.

10.2 Tree Processes That Affect the Local Environment

Trees across a landscape vary in species composition, abundance, size, health, and location. These five factors affect two key structural attributes that affect the environment: (1) total leaf area and (2) total woody biomass. Both of these attributes provide physical mass that affects wind flow and solar radiation (e.g., tree shade), but leaf area is likely the most important attribute as it typically provides the greatest surface area and gas exchange with the environment.

Leaf area is the most important component of a tree as it affects not only tree health, but also numerous benefits provided by trees (Table 10.1). The leaf area provides a large visual component related to tree aesthetics and also blocks wind and solar radiation, deflects and masks sounds, and intercepts precipitation, all of which affect the local physical environment. The leaves also provide habitat and food for numerous creatures. More importantly, leaves exchange chemicals with the surrounding environment via leaf stomata.

Leaf stomata are tiny pores on leaves that regulate gas exchange between the leaf interior and exterior environment. Depending upon local moisture conditions, these stomata typically open during the daytime to exchange carbon dioxide, oxygen, and water through processes of photosynthesis and respiration (Salisbury and Ross 1978):

$$\text{Photosynthesis}: \quad n\,(CO_2) + n\,(H_2O) + \text{light} \rightarrow (CH_2O)_n + nO_2$$
$$\text{Respiration}: \quad (CH_2O)_n + nO_2 \rightarrow n\,(CO_2) + n\,(H_2O) + \text{energy}$$

Growing, healthy trees take in carbon dioxide, storing carbon within its biomass (i.e., carbon sequestration), and release oxygen. As a tree dies and decomposes, carbon from the biomass releases carbon dioxide and consumes oxygen.

When the stomata are open, air enters the leaves via gaseous diffusion. This air contains carbon dioxide and air pollutants that can be removed by the leaf interior water and surfaces. Water vapor from the leaf interior also diffuses into the atmosphere via transpiration. Through the transpiration process (evaporating of leaf water), some of the net radiation that would otherwise warm air temperature is directed to evaporating water (latent heat). Further, warm air passes its heat to the evaporating water, which also reduces the temperature of the air (sensible heat). In addition to water being released when stomata are open, some plant volatile organic compounds (e.g., isoprene) are also released by some species. These compounds can affect the formation of air pollution and may also be useful in attracting pollinators or repelling predators (Kramer and Kozlowski 1979).

While leaves provide important functions, so does the woody above and below ground plant biomass. This biomass, which is on the order of several tonnes per mature tree, also provides physical mass to block wind and solar radiation, deflect and mask sounds, intercept precipitation, and provide habitat and food for numerous creatures. The woody biomass is also the main storage vessel for sequestered atmospheric carbon, which can be lost when the tree dies and decomposes. Tree and leaf biomass vary by species and through time as trees grow and eventually die.

In addition to species and size, tree location is also an important attribute that affects tree benefits. Tree location relative to problem sources (e.g., air pollution from automobile) and the receiver of the impact (e.g., human breathing the pollution) need to be considered when determining tree locations and in designing forests to help combat specific issues. Of utmost importance in selecting tree species and location is ensuring that the tree can survive and thrive at that location. However, designs also need to consider the intent of the design and intended impact from trees. For energy conservation, location around buildings is important; for health effects,

Table 10.1 Tree attributes that most directly affect various tree benefits (see Sects. 10.3 and 10.4 for more detailed information on tree benefits)

Tree attribute	Aesthetics/human physiology	Air quality	Air temperature	Building energy use	Carbon sequestration	Noise	Oxygen production	Property values	Ultraviolet radiation	Water flow and quality	Wildlife/biodiversity	Wood products
Aboveground biomass	√			√	√	√		√	√	√	√	√
Belowground biomass					√					√	√	√
Leaf area	√	√	√	√	√	√	√	√	√	√	√	
Leaf gas exchange		√	√	√	√		√			√		

Note: all tree attributes are important to sustain tree health and affect most benefits to some degree, but only major and most direct impacts are given locations around people are important; for water effect, locations near streams or stream pollutant loading sources are important; etc. Forest designs and plantings need to consider best designs that combat the most important local environmental or social issues.

Through proper design and management, these forest attributes can be stewarded to sustain optimal outcomes even though forest populations change through time. Understanding tree biological, chemical, physical, and social impacts on the local environment and human population can lead to better forest design and management to sustain environmental and human health through time.

10.3 Services from Urban Trees

Vegetation provides numerous benefits to society. In general, due to their large mass and leaf area, trees provide more benefits than shrubs, which generally provide more benefits than herbaceous plants. However, each plant type can have specific benefits that may outweigh other vegetation types (e.g., a colorful flower bed providing an aesthetically pleasing carpet of color). Many of the services and costs provided by vegetation and their management affect human health. Thus, designing and managing natural processes to maximize these benefits and minimize the costs can help improve human health. In addition to tree effects on air temperatures, air quality, and building energy use, which are discussed in more detail in Sect. 10.4, the following are some of the other general benefits derived from trees.

10.3.1 Aesthetics and Human Physiological Responses/Well-Being

Trees and urban green space can provide aesthetic environments for residents, but close association with these green areas also affects human physiology and well-being. The evidence on health effects of trees is increasing, with consistent negative associations between urban green space exposure and mortality, heart rate, and violence, and positive associations with attention, mood, and physical activity. Associations are mixed, with some studies finding associations and other studies finding no association between urban green space exposure and general health, weight status, depression, and stress (via cortisol concentration). The number of studies is too low to generalize about birth outcomes, blood pressure, heart rate variability, cancer, diabetes, or respiratory symptoms (Kondo et al. 2018). Several pathways or mechanisms for these health effects have been suggested, such as increased physical activity (Sallis et al. 2016), social interactions (de Vries et al. 2013), and reduced stress levels (Egorov et al. 2017).

10.3.2 Carbon Storage and Sequestration

Urban trees and forests affect climate change by altering the level of greenhouse gases such as carbon dioxide (CO_2). Trees act as a sink for CO_2 by fixing carbon during photosynthesis and storing carbon within tree biomass. The net long-term CO_2 source/sink dynamics of forests changes through time as trees grow, die, and decay. Human influences on forests (e.g., management) can further affect CO_2 source/sink dynamics of forests through factors such as fossil fuel emissions and harvesting/utilization of biomass (Nowak et al. 2002b). Unlike some other services, the carbon sequestration from trees is temporary as much of the stored carbon will revert back to atmospheric carbon through tree death and decomposition (though some carbon can be retained in soils). However, secondary tree effects such as reduced building energy use can reduce carbon emissions due to lower space condition fuel usage (Nowak et al. 2002b). In the United States, urban forests store 919 million tonnes of carbon valued at $119 billion (Nowak and Greenfield 2018). This storage value will vary through time and can be lost if the urban forest population is not sustained. The US urban forest currently annually sequesters about 37 million tonnes of carbon, valued at $4.8 billion (Table 10.3).

10.3.3 Noise

Field tests have shown that properly designed plantings of trees and shrubs can significantly reduce noise. Leaves and stems reduce transmitted sound primarily by scattering it, while the ground absorbs sound (Aylor 1972). For optimum noise reduction, trees and shrubs should be planted close to the noise source rather than the receptor area (Cook and Van Haverbeke 1971). Wide belts (30 m) of tall dense trees combined with soft ground surfaces can reduce apparent loudness by 50% or more (6–10 decibels) (Cook 1978). For narrow planting spaces (less than 3 m wide), reductions of 3–5 decibels can be achieved with dense belts of vegetation, that is, one row of shrubs along the road and one row of trees behind it (Reethof and McDaniel 1978). Buffer plantings in these circumstances typically are more effective in screening views than in reducing noise.

Vegetation also can mask sounds by generating its own noise as wind moves tree leaves or as birds sing in the tree canopy. These sounds may make individuals less aware of offensive noises, because people are able to filter unwanted noise while concentrating on more desirable sounds (Robinette 1972). The perception of sounds by humans also is important. By visually blocking the sound source, vegetation can reduce individuals perceptions of the amount of noise they actually hear (Anderson et al. 1984). The ultimate effectiveness of plants in moderating noise is determined by the sound itself, the planting configuration used, the proximity of the sound source, receiver, and vegetation, as well as climatic conditions (Nowak and Dwyer 2007).

10.3.4 Oxygen Production

Oxygen production is directly tied to carbon sequestration, but in an inverse fashion. When a tree has a net carbon sequestration, it gives off oxygen. When tree biomass decomposes or is burned, it gives off carbon and consumes oxygen. Urban forests in the coterminous United States are estimated to produce about 61 million metric tons (67 million tons) of oxygen annually, enough oxygen to offset the annual oxygen consumption of about 2/3 of the US population. Although oxygen production is often cited as a significant benefit of trees, this benefit is relatively insignificant and of negligible value due to the large oxygen content of the atmosphere (Nowak et al. 2007).

10.3.5 Property Values

One of the more commonly cited benefits of urban trees relates to increased property values. Effects on property value vary from a slight overall increase in value with locally mixed positive and negative effects (e.g., Saphores and Li 2012) up to around 15% (Morales 1980; Thompson et al. 1999). Increases in property values due to trees are an indication of willingness to pay for various benefits associated with trees that the homeowner receives. However, these value transactions only occur at a point sale (e.g., adding a tree to a property may increase property values, but that value is only realized when the property is sold); however, the trees are providing other values (e.g., cooler air temperature) annually. While increases in property values may be considered a benefit, they are also a cost to the homeowner via higher annual taxes paid due to higher home prices.

10.3.6 Ultraviolet Radiation

Tree leaves absorb 90–95% of ultraviolet (UV) radiation and thereby affect the amount of UV radiation received by people under or near tree canopies (Na et al. 2014). This reduction in UV exposure affects incidence of skin cancer, cataracts, and other ailments related to UV radiation exposure (Heisler and Grant 2000).

10.3.7 Water Cycles and Quality

Trees impact surface stormwater runoff, soil moisture, stream flow, groundwater recharge, and water quality by intercepting precipitation (rain and snow), enhancing soil water infiltration, absorbing soil moisture and chemicals, shading surfaces, and evapotranspiring water. While these processes generally reduce runoff, increase baseflow in streams, and reduce peak stream flow events (e.g., flooding), unmanaged trees can also increase flooding if branches or leaves clog drains or dam streams. However, the relationship between trees and groundwater recharge is complex and can be either positive or negative. Water use by trees can outweigh water availability, thus depleting streamflow and groundwater recharge in certain areas (Albaugh et al. 2013). In dry regions, groundwater recharge is maximized at an intermediate tree density. Below this optimal tree density, the benefits from any additional trees on water percolation exceed their extra water use, leading to increased groundwater recharge, while above the optimum, the opposite occurs (Ilstedt et al. 2016).

Trees also affect water quality by generally decreasing the concentration and amount of sediments, nutrients, metals, pesticides, pathogens, microbes, and other pollutants reaching a water body (Nowak et al. 2020). Trees also shade surfaces and reduce air temperatures, which reduces thermal loads on shaded objects and can reduce the heating of river water, thereby mitigating biological activity that can degrade water quality (e.g., eutrophication) (Yang et al. 2008). At a larger scale, urbanization and forests can influence regional precipitation patterns (e.g., Keys et al. 2017). If managed properly, these hydrologic effects can reduce risk to flooding, help recharge aquifers, impact regional precipitation, and improve human health by reducing sediments, chemicals, and pathogens found within waterways.

10.3.8 Wildlife Populations

Tree species composition and structure directly affect wildlife habitat, food, and local biodiversity. Various procedures can be used to estimate the relationship between local forest structure and wildlife species habitat suitability and insect biodiversity (e.g., Tallamy and Shropshire 2009; Lerman et al. 2014).

10.3.9 Wood Products

Though often considered a waste product in urban areas, dead and removed trees can be used for various products such as timber, palettes, fiber, and chemicals (e.g., ethanol). As US urban forests contain about 1.7 billion tonnes of total tree dry-weight biomass (Nowak and Greenfield 2018), assuming a likely conservative annual mortality rate of 2% (Nowak et al. 2004), total above-ground dry-weight biomass removed annually would be around 26 million tonnes per year. This estimate would be slightly higher than a previous estimate of 16–38 million green tons per year (Bratkovich and Fernholz 2010). This biomass could be used to produce wood products and as a potential income source for cities (e.g., Cesa et al. 2003). In addition, leaf drop could be used to provide nutrients (e.g., N, P, and K) and plants' fruits could be used for food (e.g., Clark and Nicholas 2013).

10.3.10 Cumulative Benefits

Trees' effects in numerous cities have been evaluated and reveal benefits typically in the millions of dollars per year, with values varying by tree population size (Table 10.2). At the US national level, urban forest benefits are conservatively estimated at $18.4 billion per year; $5.4 billion from air pollution removal, $5.4 billion from reduced building energy use, $4.8 billion from carbon sequestration, and $2.7 billion from avoided pollutant emissions (Table 10.3). This estimate is conservative as it only addresses four benefits out of a myriad of potential benefits from trees.

10.4 Tree Effects on Air Quality

The World Health Organization (2016) states that air pollution is the largest environmental risk factor. Air pollution significantly affects human and ecosystem health (U.S. EPA 2010). Recent research indicates that 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: 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; Vieira 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) 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 less than 2.5 microns ($PM_{2.5}$) and 4700 deaths to ozone (O_3) in 2005 (Fann et al. 2012).

Elevated ambient temperatures are associated with increased 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

Table 10.2 City estimates of various tree benefits and values

		Trees	Carbon sequestration[a]		Pollution removal[b]		Energy savings[c]	Total	
		Number	t/year	$/year	t/year	$/year	$/year	$/year	
City	Year	(× 10^3)		(× 10^3)		(× 10^3)	(× 10^3)	(× 10^3)	References
Houston, TX	2009	33,975	182,900	34,385	2191	21,122[d]	53,900	109,407	Nowak et al. (2017)
Austin, TX	2007	33,843	83,200	15,642	1137	11,035[d]	18,900	45,577	Nowak et al. (2016b)
Los Angeles, CA	2008	5993	69,800	13,122	1792	14,173	10,200	37,495	Nowak et al. (2011)
New York, NY	2013	6977	55,200	10,378	1004	9222[d]	17,100	36,700	Nowak et al. (2018)
Toronto, ON	2008	10,220	46,700	8780[e]	1905	17,146[e]	9700[e]	35,626[e]	Nowak et al. (2013b)
Philadelphia, PA	2012	2918	24,600	4625	531	4602	6900	16,127	Nowak et al. (2016c)
Chicago, IL	2007	3585	22,800	4286	806	6398	360	11,044	Nowak et al. (2010b)
Washington, DC	2004	1928	14,700	2764	379	2858	2653	8275	Nowak et al. (2006d)
Minneapolis, MN	2004	979	8100	1523	277	2242	216	3981	Nowak et al. (2006c)
Syracuse, NY	2009	1088	5300	996	101	852	1100	2948	Nowak et al. (2016a)
Scranton, PA[f]	2006	1198	3700	696	65	514	628	1838	Nowak et al. (2010a)
Morgantown, WV	2004	658	2600	489	65	489	380	1358	Nowak et al. (2012)
Casper, WY	2006	123	1100	207	34	275	−27	455	Nowak et al. (2006b)

t metric tons

[a]Carbon sequestration value is based on social cost of carbon for 2020 updated to 2018 dollar values based on the producer price index ($188/tC) (Interagency Working Group on Social Cost of Carbon 2015)

[b]Pollution removal of carbon monoxide ($1407/t), nitrogen dioxide ($9906/t), ozone ($9906/t), particulate matter less than 10 microns ($6614/t), and sulfur dioxide ($2425/t) unless otherwise noted

[c]Saving from alter building energy use due to trees. Negative values indicate increase in energy use costs

[d]Pollution removal of nitrogen dioxide, ozone, particulate matter less than 2.5 microns and sulfur dioxide with value based on local health impacts (Nowak et al. 2014)

[e]In Canadian dollars; other values are in US dollars

[f]Urban area only

Table 10.3 State statistics regarding annual urban forest benefits and values

	Carbon sequestration				Air pollution removal		Avoided energy use		Avoided emissions		Total
	t/year	SE	$/year	SE	t/year	$/year	$/year	SE	$/year	SE	$/year
State	$\times 10^3$	$\times 10^3$	$\times 10^6$	$\times 10^6$	$\times 10^3$	$\times 10^6$	$\times 10^6$	$\times 10^6$	$\times 10^6$	$\times 10^6$	$\times 10^6$
Alabama	915.9	147.6	118.8	19.1	16.5	82.9	49.7	3.7	27.4	2.0	278.9
Arizona	575.9	92.8	74.7	12.0	10.5	33.1	102.2	4.4	29.9	1.3	239.9
Arkansas	478.5	77.1	62.1	10.0	8.3	40.4	34.4	2.5	18.3	1.3	155.2
California	**2880.2**	464.1	**373.6**	60.2	**63.4**	**639.4**	274.1	13.2	67.1	3.2	**1354.2**
Colorado	151.0	24.3	19.6	3.2	2.2	5.1	10.3	1.1	5.2	0.5	40.2
Connecticut	766.8	123.6	99.5	16.0	15.9	94.8	117.3	6.9	22.0	1.3	333.6
Delaware	136.3	22.0	17.7	2.8	2.7	14.6	43.7	3.4	29.7	2.3	105.7
Florida	**4163.5**	670.9	**540.1**	87.0	**80.7**	**554.4**	**512.7**	30.7	**272.0**	16.3	**1879.2**
Georgia	**2832.6**	456.5	**367.5**	59.2	**62.2**	255.6	124.6	8.8	92.5	6.5	840.1
Idaho	34.3	5.5	4.4	0.7	1.5	18.8	22.0	0.8	5.9	0.2	51.1
Illinois	999.7	161.1	129.7	20.9	14.6	157.7	281.4	8.8	147.2	4.6	716.0
Indiana	566.0	91.2	73.4	11.8	13.0	88.7	156.6	9.7	113.6	7.1	432.3
Iowa	177.3	28.6	23.0	3.7	2.6	21.0	59.8	4.9	53.1	4.4	156.9
Kansas	272.7	43.9	35.4	5.7	2.8	14.5	121.3	5.1	60.7	2.6	231.8
Kentucky	410.4	66.1	53.2	8.6	10.0	55.8	113.5	9.6	85.2	7.2	307.7
Louisiana	994.9	160.3	129.1	20.8	23.9	117.7	139.9	9.3	81.1	5.4	467.7
Maine	132.4	21.3	17.2	2.8	4.3	25.1	13.5	2.9	5.6	1.2	61.4
Maryland	963.4	155.2	125.0	20.1	29.2	177.1	230.2	14.1	**188.0**	11.5	720.3
Massachusetts	1229.2	198.1	159.5	25.7	29.5	197.1	192.2	10.6	64.7	3.6	613.5
Michigan	961.5	154.9	124.7	20.1	29.5	131.5	233.0	13.4	**147.8**	8.5	637.0
Minnesota	520.6	83.9	67.5	10.9	7.7	40.0	65.0	8.9	38.8	5.3	211.3
Mississippi	496.6	80.0	64.4	10.4	12.8	66.8	39.1	1.6	22.6	1.0	192.8
Missouri	654.4	105.4	84.9	13.7	14.4	88.3	174.5	10.1	105.7	6.1	453.3
Montana	33.4	5.4	4.3	0.7	1.3	13.3	2.0	0.4	1.6	0.3	21.2
Nebraska	72.8	11.7	9.4	1.5	0.6	4.2	34.7	1.2	25.4	0.9	73.7
Nevada	58.3	9.4	7.6	1.2	2.0	8.8	21.9	0.6	5.4	0.2	43.6
New Hampshire	224.7	36.2	29.2	4.7	5.7	15.2	14.5	1.8	4.5	0.6	63.4

(continued)

Table 10.3 (continued)

	Carbon sequestration				Air pollution removal		Avoided energy use		Avoided emissions		Total
	t/year	SE	$/year	SE	t/year	$/year	$/year	SE	$/year	SE	$/year
State	$\times 10^3$	$\times 10^3$	$\times 10^6$	$\times 10^6$	$\times 10^3$	$\times 10^6$	$\times 10^6$	$\times 10^6$	$\times 10^6$	$\times 10^6$	$\times 10^6$
New Jersey	1130.2	182.1	146.6	23.6	22.0	151.4	219.8	10.0	57.0	2.6	574.8
New Mexico	104.3	16.8	13.5	2.2	3.3	6.0	20.0	1.0	10.5	0.5	50.1
New York	1371.6	221.0	177.9	28.7	**41.5**	**408.2**	**345.8**	21.0	69.5	4.2	**1001.4**
North Carolina	**2146.9**	346.0	**278.5**	44.9	**50.3**	191.8	150.3	9.5	86.3	5.5	706.9
North Dakota	11.9	1.9	1.5	0.2	0.1	0.5	2.8	0.2	2.5	0.2	7.3
Ohio	1173.7	189.1	152.3	24.5	35.0	**265.6**	**313.3**	18.3	**240.3**	14.0	**971.5**
Oklahoma	301.3	48.6	39.1	6.3	5.5	34.6	17.8	2.5	9.9	1.4	101.5
Oregon	234.9	37.8	30.5	4.9	4.3	79.1	21.4	1.7	5.1	0.4	136.1
Pennsylvania	1337.3	215.5	173.5	28.0	40.6	**441.6**	**290.2**	18.7	**164.3**	10.6	**1069.6**
Rhode Island	149.1	24.0	19.3	3.1	3.0	26.1	37.2	2.2	5.1	0.3	87.8
South Carolina	1140.4	183.8	147.9	23.8	27.6	125.3	76.4	4.2	35.9	2.0	385.6
South Dakota	28.3	4.6	3.7	0.6	0.2	1.7	6.2	0.3	5.1	0.3	16.7
Tennessee	1033.4	166.5	134.1	21.6	23.1	108.2	83.7	5.8	50.8	3.5	376.7
Texas	**2453.1**	395.3	**318.2**	51.3	33.7	185.6	**308.4**	11.2	125.5	4.6	937.8
Utah	83.3	13.4	10.8	1.7	2.6	11.4	19.6	1.2	11.7	0.7	53.5
Vermont	46.7	7.5	6.1	1.0	1.1	5.7	8.2	1.3	0.5	0.1	20.4
Virginia	1007.7	162.4	130.7	21.1	30.6	134.7	114.4	5.2	69.3	3.1	449.2
Washington	614.5	99.0	79.7	12.8	16.4	180.3	56.2	3.8	11.9	0.8	328.2
West Virginia	218.7	35.2	28.4	4.6	5.3	30.6	21.4	2.0	15.6	1.5	95.9
Wisconsin	334.1	53.8	43.3	7.0	7.4	45.3	81.5	7.8	44.8	4.3	214.9
Wyoming	12.0	1.9	1.6	0.3	0.5	2.5	1.3	0.1	1.1	0.1	6.4
US48	36,653	5325	4755	690.7	821.7	5398	5380	61.7	2743	33.6	18,274
Alaska	59.3	9.6	7.7	1.2	na	na	na	na	na	na	Na
Hawaii	270.4	43.6	35.1	5.7	na	na	na	na	na	na	Na
US50	36,983	5361	4798	695.5	na	na	na	na	na	na	Na

From Nowak and Greenfield (2018)
Bold numbers indicate that the state is within the top five highest values for that category
SE standard error, *US48* conterminous US, *US50* entire US, *na* not analyzed, *t* tons

(Robine et al. 2008). The issue of heat-related morbidity and mortality is expected to increase substantially with climate change (Gasparrini et al. 2017). Both pollution and increased temperatures impact human health, but they may also interact to produce an even greater negative impact on health (Harlan and Ruddell 2011).

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). For centuries, it has been known that trees affect the atmospheric environment. 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 (Compton 2016). In addition to this "lung" capacity of vegetation, 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). Trees and forests can be used to improve air quality and reduce heat, and consequently improve human health.

To help understand how trees affect air quality, it is important to understand the different types of air pollutants. Some pollutants, both gaseous and particulate, are directly emitted into the atmosphere and include sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), particulate matter (PM) and volatile organic compounds (VOC). 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 VOCs react in the presence of sunlight. Some particles are also formed from other directly emitted pollutants. Trees affect these air pollutants in three main ways: they (1) alter local air temperatures, microclimates, and building energy use; (2) remove air pollution; and (3) emit various chemicals.

10.4.1 Trees' Effects on Air Temperatures, Local Microclimate, and Building Energy Use

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 (Myrup et al. 1991). For example, reduced windspeeds due to trees can increase 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. Reduced air temperature due to trees can improve air quality because the emission of many pollutants and/or ozone-forming chemicals is 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). These 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. 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 winds, the height of the atmosphere in which the pollutant mixes is often reduced. This reduction in the "mixing height" will tend to increase pollutant concentrations as the same amount of pollution is now mixed within a smaller volume of air.

In addition, reduced air temperatures and shading of buildings can reduce the amount of energy used to cool buildings in the summer-time. However, shading of buildings in winter can lead to increased building energy use (e.g., Heisler 1986). This altered energy use consequently leads to altered pollutant emissions from power plants. 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 by $5.4 billion per year and avoid the emission of thousands of tonnes of pollutants valued at $2.7 billion per year (Table 10.3).

Methods for estimating tree effects on building energy use are given in McPherson and Simpson (1999) and coded within the i-Tree Eco model (www.itreetools.org). Methods for estimating tree effects on air temperatures (Yang et al. 2013) are also integrated within i-Tree.

10.4.2 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). Some pollutants under high concentrations can damage leaves (e.g., sulfur dioxide, nitrogen dioxide, ozone) (e.g., Nowak 1994; Nowak et al. 2015), particularly of pollutant-sensitive species. Given the pollution concentration in most cities, these pollutants would not be expected to cause visible leaf injury, but could in cities or areas with high pollutant concentrations.

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 (Little 1977; Smith 1990). 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).

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 have greater reductions in air pollution concentrations in and around these areas. One hectare of tree cover has a US average pollution removal of about 75 kg/year in urban areas, but this value could range up to over 200 kg per year in more polluted areas with long growing seasons (e.g., Los Angeles) (Fig. 10.1). 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 (Nowak 1994). 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.

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. (2013a) reported that the total amount of $PM_{2.5}$ removed annually by trees in 10 US 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.

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 (Nowak et al. 2006a). Trees and forests in the conterminous United States removed 22.4 million tonnes of air pollution in 2010, with human health effects valued at \$8.5 billion. Most of the pollution removal occurred in rural areas, while most of the health benefits were within urban areas. In urban areas, trees removed 822,000 tonnes per year valued at \$5.4 billion (Table 10.3). Nationwide, health impacts included the avoidance of more than

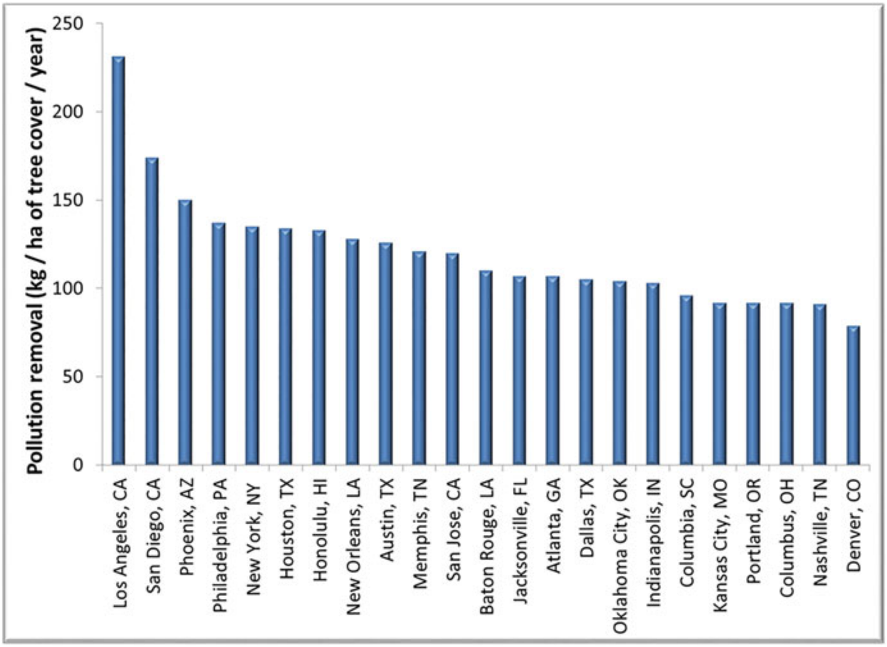

Fig. 10.1 Pollution removal values per acre of tree cover in select cities. Estimates assume a leaf area index of 6 and 10% evergreen species. Leaf area index is per unit tree cover and calculated as total leaf area (m^2) divided by tree cover (m^2). (Derived from Nowak et al. 2006a)

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).

Though the amount of air pollution removal by trees may be substantial, the percent air quality improvement in an area will depend upon the amount of vegetation and meteorological conditions. Average air quality improvement due to pollution removal by trees in cities during daytime of the in-leaf season is less than 1%. However, in areas with 100% tree cover, hourly air pollution improvements average around 4 times greater and can reach up to 16% (Nowak et al. 2006a). 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).

Methods of Estimating Pollution Removal by Trees

Hourly pollution removal by vegetation can be estimated with information regarding tree cover (m^2), leaf area index (total one-sided leaf/total projected ground area of canopy), leaf type (deciduous or evergreen), hourly meteorological data (e.g., air temperature, wind speed, cloud cover), and air pollution concentrations. Pollution removal or downward pollutant flux (F; in g/m^2/s) is calculated as the product of the deposition velocity (V_d; in m/s) and the pollutant concentration (C; in g/m^3):

$$F = V_d\,C$$

Deposition velocity is calculated as the inverse of the sum of the aerodynamic (R_a), quasi-laminar boundary layer (R_b), and canopy (R_c) resistances (Baldocchi et al. 1987).

$$V_d = 1/\left(R_a + R_b + R_c\right)$$

Hourly estimates of R_a and R_b are calculated using standard resistance formulas (Killus et al. 1984; Pederson et al. 1995; Nowak et al. 1998) and hourly weather data. Hourly canopy resistance values for O_3, SO_2, and NO_2 can be calculated based on a modified hybrid of big-leaf and multilayer canopy deposition models (Baldocchi et al. 1987; Baldocchi 1988). Canopy resistance (R_c) has three components: stomatal resistance (r_s), mesophyll resistance (r_m), and cuticular resistance (r_t), such that

$$1/R_c = 1/\left(r_s + r_m\right) + 1/r_t$$

In the i-Tree model, mesophyll resistance is set to zero s/m for SO_2 (Wesely 1989) and 10 s/m for O_3 (Hosker and Lindberg 1982). Mesophyll resistance is set to 100 s/m for NO_2 to account for the difference between transport of water and NO_2 in the leaf interior, and to bring the computed deposition velocities in the range typically exhibited for NO_2 (Lovett 1994). Base cuticular resistances are set at 8000 s/m for SO_2, 10,000 s/m for O_3, and 20,000 s/m for NO_2 to account for the typical variation in r_t exhibited among the pollutants (Lovett 1994). Deposition velocities are sensitive to leaf area index, with velocities increasing as the index increases (Hirabayashi et al. 2011).

As removal of CO and particulate matter by vegetation is not directly related to transpiration, R_c for CO is set to a constant for in-leaf season (50,000 s/m) and leaf-off season (1,000,000 s/m) based on data from Bidwell and Fraser (1972). For PM_{10}, the median deposition velocity from the literature (Lovett 1994) is 0.0128 m/s for the in-leaf season. Base particle V_d is set to 0.064 based on an LAI of 6 and a 50% resuspension rate of particles back to the atmosphere (Zinke 1967). The base V_d is adjusted according to actual LAI and in-leaf versus leaf-off season parameters. For $PM_{2.5}$, hourly deposition velocities and resuspension rates vary with wind speed and leaf area as detailed in Nowak et al. (2013a).

To limit deposition estimates to periods of dry deposition, deposition velocities in i-Tree are set to zero during periods of precipitation. The model is run at the population scale to estimate pollution removal effects. Hourly pollutant flux (g/m^2 of tree canopy coverage) among the pollutant monitor sites is multiplied by total tree-canopy coverage (m^2) to estimate total hourly pollutant removal by trees across the study area.

10.4.3 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).

VOC emission rates vary by species. Nine tree genera that have the highest standardized isoprene emission rate 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, just because these genera have relatively high emission rates, does not mean that they lead to a net production of ozone as they also remove ozone and lower air temperatures.

Other factors to consider in addition to VOC emissions are tree maintenance and pollen emission. Because some vegetation, particularly urban vegetation, often requires relatively large inputs of energy for maintenance activities, resulting pollutant emissions from maintenance equipment need to be considered. Pollen particles from trees can lead to allergic reactions (e.g., Cariñanos 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).

Methods for Calculating VOC Emissions by Trees

Tree VOC emissions can be estimated using procedure from the EPA’s Biogenic Emissions Inventory System (BEIS) (U.S. EPA 2017). The amount of VOC emissions depends on tree species, leaf biomass, air temperature, and other environmental factors. Species leaf biomass is multiplied by genus-specific emission factors (e.g., Nowak et al. 2002a) to produce emission levels standardized to 30 °C and photosynthetically active radiation (PAR) flux of 1000 μmol m^{-2} s^{-1}. Standardized emissions are converted to actual emissions based on light and temperature correction factors (Geron et al. 1994) and local meteorological data.

VOC emission (E) (in μgC/tree/hr at temperature T (K) and PAR flux L (μmol/m^2/s)) for isoprene, monoterpenes, and OVOC is estimated as follows:

$$E = B_{\mathrm{E}} \times B \times \gamma$$

where B_{E} is the base genus emission rate in μgC (g leaf dry weight)/hr at 30 °C and PAR flux of 1000 μmol/m^2/s; B is species leaf dry weight biomass (g); and

$$\gamma = \left[\alpha \cdot c_{\mathrm{L1}} L \Big/ \left(1 + \alpha^2 \cdot L^2\right)^{\frac{1}{2}}\right] \cdot \left[\exp\left[c_{\mathrm{T1}}\left(T - T_{\mathrm{S}}\right)/R \cdot T_{\mathrm{S}} \cdot T\right] / \left(0.961 + \exp\left[c_{\mathrm{T2}}\left(T - T_{\mathrm{M}}\right)/R \cdot T_{\mathrm{S}} \cdot T\right]\right)\right]$$

for isoprene where L is PAR flux; $\alpha = 0.0027$; $c_{\mathrm{L1}} = 1.066$; R is the ideal gas constant (8.314 K^{-1} mol^{-1}); T(K) is leaf temperature, which is assumed to be air temperature; T_{S} is standard temperature (303 K); and $T_{\mathrm{M}} = 314$ K, $C_{\mathrm{T1}} = 95{,}000$ J mol^{-1}, and $C_{\mathrm{T2}} = 230{,}000$ J mol^{-1} (Geron et al. 1994; Guenther et al. 1995; Guenther 1997).

For monoterpenes and OVOC,

$$\gamma = \exp\left[\beta\left(T - T_{\mathrm{s}}\right)\right]$$

where $T_{\mathrm{S}} = 303$ K and $\beta = 0.09$.

10.4.4 Overall Effects of Trees on Air Pollution

There are many factors, both positive and negative, that determine the ultimate effect of trees on 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.

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

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% lower concentration below the canopy) (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 (Fig. 10.2). This effect could be particularly important in heavily treed areas where automobiles drive under tree canopies. 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; and/or (c) lower mixing heights by reducing wind speeds (Nowak et al. 2000, 2014). 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 (e.g., Dasch 1987; Cavanagh et al. 2009) 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 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.).

Fig. 10.2 Design of vegetation near roadways is important to minimize potential negative effects, such as trapping of pollutants. (Image source: D. Nowak)

10.5 Software to Assess Urban Forest Effects and Values

Computer models have been developed to assess forest composition and its associated effects on environmental quality and human health. While research is still needed regarding many of the environmental services that trees provide, resource managers can utilize existing models to better understand the role of vegetation in improving human health and environmental quality, lower costs of maintenance, and increase resource stewardship as an effective means to provide substantial economic savings to society.

Structure is a key variable as it is what managers manipulate to influence forest benefits and values. Structure represents the physical attributes of the urban forest, such as abundance, size, species, health, and location of trees. Managers often choose what species to plant, where and when to plant it, and what trees are removed from the landscape. These actions directly influence structure and consequently the benefits derived from the urban forest.

Field data on urban forest structure can be obtained from either inventories or sampling of the local urban forest. For large tree populations, field data in conjunction with aerial-based assessments will likely provide the best and most cost-effective means to assess forest structure. The most important tree characteristics to measure are species, diameter, crown dimensions, and tree condition. This information is helpful to managers regarding population management and assessing risks to the forest, but is also essential for estimating forest benefits and costs. The most important tree attribute is leaf area. While not directly measured in the field, this variable can be modeled from species, crown, and condition information. Diameter measures are also essential for estimating carbon storage. Leaf and tree biomass are other important variables that can be modeled from the core tree variables. Other information that is important for estimating forest benefits is crown competition (important for tree growth estimation and carbon sequestration) and location around buildings (important of energy conservation). Numerous forest benefits can currently be modeled from these tree variables, in conjunction with other local information (e.g., weather, pollution concentrations, and population data). Once the benefits are quantified, various methods of market as well as nonmarket valuation can be applied to characterize their monetary value (e.g., Hayden 1989).

There are various models that quantify forest benefits. Some free models include InVEST (Natural Capital Project 2016), Biome-BGC (Numerical Terradynamic Simulation Group 2016), and numerous other tools to assess forest carbon (e.g., U.S. Forest Service 2016). However, few models quantify urban forests. To date, the most comprehensive model developed to quantify urban forest structure, benefits, and values is i-Tree (www.itreetools.org). This freely available suite of tools was developed by the US Forest Service through a public-private partnership. The model is based on peer-reviewed science and can be used globally, with over 750,000 users in 180 countries. i-Tree was designed to accurately assess local forest structure and its impacts on numerous benefits, costs, and values (Table 10.4). Model results have been validated against numerous field measurements (e.g., Morani et al. 2014) to provide sound estimates of urban forest benefits. The model focuses on estimating forest structure and the magnitude of services received (e.g., tons removed). It then relies on economic valuation (e.g., $/ton removed) to estimate a value of the service. Various economic estimates are used and many can be adjusted by the users if local economic values are available.

The core program is *i-Tree Eco* – this model uses sample or inventory data and local environmental data to assess and forecast forest structure, benefits, threats, and values for any tree population (Nowak et al. 2008). The program includes plot selection tools, mobile data entry applications, table and graphic reporting and exporting, and automatic report generation. Urban forest assessments have been conducted in numerous cities globally (e.g., Barcelona, Spain; Calles, Mexico; Chicago, IL, USA; Medellin, Colombia; Milan, Italy; London, England; New York, NY, USA; Perth, Australia; Porto, Portugal; Santiago, Chile; Seoul, South Korea; Strasbourg, France; Toronto, Canada; – Chaparro and Terradas 2009; Escobedo et al. 2006; Graca et al. 2017; Nowak et al. 2010b, 2013b, 2018; Rogers et al. 2015; Selmi et al. 2016). See Table 10.2 for results from US cities.

Table 10.4 Ecosystem effects of trees currently quantified and in development in i-Tree

Ecosystem effect	Attribute	Quantified	Valued
Atmosphere	Air temperature	○	○
	Avoided emissions	•	•
	Building energy use	•	•
	Carbon sequestration	•	•
	Carbon storage	•	•
	Human comfort	○	
	Pollen	•	
	Pollution removal	•	•
	Transpiration	•	
	UV radiation	•	○
	VOC emissions	•	
Community/Social	Aesthetics/property value	○	○
	Food/medicine	○	
	Health Index[a]	○	
	Forest products[b]	•	•
	Underserved areas	•	
Terrestrial	Biodiversity	○	
	Invasive plants	•	
	Nutrient cycling	•	
	Wildlife habitat	•	
Water	Avoided runoff	•	•
	Flooding	○	○
	Rainfall interception	•	
	Water quality	•	○

Many of the listed ecosystem effects are both positive and negative depending on specific conditions or perspective. For example, trees can increase or decrease energy use depending upon location; pollen can be positive in terms of food production or negative in terms of allergies depending upon species

• Attribute currently quantified or valued in i-Tree

○ Attribute in development in i-Tree

[a]Developing a health index based on mapping of green viewing ("forest bathing")

[b]Estimating product potential based on forest structure (e.g., timber, wood pellets, ethanol)

Other tools in i-Tree include,

- *i-Tree Species*: This tool selects the most appropriate tree species based on desired environmental functions and geographic area.
- *i-Tree Hydro*: This tool simulates the effects of changes in tree and impervious cover on runoff, stream flow, and water quality.
- *i-Tree Canopy*: This tool allows users to easily photo-interpret Google aerial images to produce statistical estimates of land cover types. Use of historical imagery in Google Earth can also be used to aid in change analyses of land cover types.

- *i-Tree Design*: This tool links to Google Maps and allow users to quantify the current and future benefits of trees on their property.
- *MyTree*: This tool easily assesses the benefits of one to a few trees using a phone via a mobile web browser.
- *i-Tree Landscape*: This tool allows users to explore tree canopy, land cover, tree benefits, forest and health risks, and basic demographic information anywhere in the United States and prioritize areas for tree planting and protection.

Many new forest benefits and costs are currently being added to the model (Table 10.4). i-Tree is developed using a collaborative effort among numerous partners to better understand and quantify how changes in forest structure will affect numerous benefits and values, and to aid in urban forest management and planning.

10.6 Conclusion

Urban vegetation provides numerous benefits to society regarding physical, mental, and environmental health. Many benefits and costs remain to be quantified, but science and science-based tools are aiding our understanding of the myriad of vegetation benefits. By understanding these benefits and how vegetation affect these benefits, urban systems can be better engineered using plants and other natural elements and processes to help improve human and environmental health for current and future generations.

Disclaimer The use of trade names in this chapter is for the information and convenience of the reader. Such does not constitute an official endorsement or approval by the US Department of Agriculture or Forest Service of any product or service to the exclusion of others that may be suitable.

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