

Chapter 4

Environmental and Economic Benefits of Preserving Forests within Urban Areas: Air and Water Quality

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INTRODUCTION

Forests and trees in urban areas provide many environmental and economic benefits that can lead to improved environmental quality and human health. These benefits include improvements in air and water quality, richer terrestrial and aquatic habitat, cooler air temperatures, and reductions in building energy use, ultraviolet radiation levels, and noise. As urbanization expands within forested regions, trees and forests are replaced with compacted soils, buildings, roads, and cars. This shift from forest to urban land uses changes the local and downwind/downstream environment and consequently impacts local and regional air and water quality.

Poor air quality leads to diminished human health, decreased visibility, and degradation of materials. In the United States, 158 million people live in areas that have not reached attainment for the national eight-hour ozone (O_3) standard; more than 29 million live in nonattainment areas for particulate matter less than 10 microns (PM_{10}); 15 million live in carbon monoxide (CO) nonattainment areas; and about 1 million live in sulfur dioxide (SO_2) nonattainment areas (U.S. EPA 2006).

Poor water quality also affects human health and degrades aquatic habitats, which may also degrade human health and amenities by increasing insect- and waterborne diseases and causing odor and visual degeneration. Although various streams are monitored for attributes of water quality across the nation (U.S. EPA 1998), there is currently no national standard monitoring system in place to assess the wide range of water quality impacts on society (Lombardo et al. 2001). The U.S. Environmental Protection Agency (EPA) expects that state water-monitoring programs will evolve over the next ten years so that states will have a common foundation for such programs. Core indicators have been recommended to monitor water quality that affect aquatic life and wildlife, recreation, drinking water, and fish/shellfish consumption. These indicators include dissolved oxygen, temperature, pH, stream flow, nutrients, sediments, total dissolved solids, nitrates, pathogens, trace metals, and specific pesticides (WEF/ASCE 1998). However, other physical and biological indices are needed (Rogers et al. 2002).

In addition to water quality degradation, other problems associated with changes in stream flows include instability in the drainage system, reduced infiltration of water into soils, and increase peak flows in streams (Herricks 1995; Thorne 1998; FISRWG 1999). Instability in the drainage system can rapidly erode streambanks, damage streamside vegetation, and widen stream channels (Hammer 1972). In turn, this instability will result in lower water depths during nonstorm periods, higher than normal water levels during wet weather periods, increased sediment loads, and higher water temperatures (Brookes 1988).

Preserving or expanding forest stands in and around urban areas is critical to sustaining air and water quality. The objective of this paper is to review the effect and value of urban trees and forest stands on air and water quality.

TREE EFFECTS ON AIR QUALITY

Urban vegetation directly and indirectly affects local and regional air quality by altering the urban atmospheric environment. The four main ways that urban trees affect air quality are (Nowak 1995):

Temperature reduction and other microclimatic effects
Removal of air pollutants
Emission of volatile organic compounds and tree maintenance emissions
Energy effects on buildings

TEMPERATURE REDUCTION

Tree transpiration and tree canopies affect air temperature, radiation absorption and heat storage, wind speed, relative humidity, turbulence, surface albedo, surface roughness, and, consequently, the evolution of the mixing-layer height (height of the atmosphere in which pollutants are mixed). These local meteorological changes can alter pollution concentrations in urban areas (Nowak et al. 1998). Although trees usually contribute to cooler summer air temperatures, their presence can increase air temperatures in some instances (Myrup, McGinn, and Flocchini 1991). In areas with scattered tree canopies, radiation reaches and heats ground surfaces; at the same time, the canopy may reduce atmospheric mixing such that cooler air is prevented from reaching the area. In this case, tree shade and transpiration may not compensate for the increased air temperatures due to reduced mixing (Heisler et al. 1995). Maximum midday air temperature reductions due to trees range from 0.04°C to 0.20°C per percentage canopy cover increase (Simpson 1998). Below individual and small groups of trees over grass, midday air temperatures at 1.5 meters above ground are 0.70°C to 1.30°C cooler than in an open area (Souch and Souch 1993). Reduced air temperature improves air quality because the emission of many pollutants and/or ozone-forming chemicals is temperature dependent. Decreased air temperature can also reduce ozone formation.

REMOVAL OF AIR POLLUTANTS

Trees remove gaseous air pollution primarily by uptake via 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). Trees also remove pollution by intercepting airborne particles. Some particles can be absorbed into the tree, though most intercepted particles are retained on the plant surface. The intercepted particle often is resuspended to the atmosphere, washed off by rain, or dropped to the ground with leaf and twig fall (Smith 1990). Consequently, vegetation is only a temporary retention site for many atmospheric particles.

In 2000, estimated annual pollution removal by trees in Atlanta, Boston, New York, and Philadelphia varied from 257 to 1,521 metric tons (figure 4.1). Pollution removal per square meter of canopy cover was fairly similar among these cities (Boston: 8.1 grams per square meter per year; New York: 9.1 grams per square meter per year; Philadelphia: 9.7 grams per square meter per year; Atlanta: 12.0 grams per square meter per year). These standardized pollution removal rates differ among cities according to the amount of air pollution, length of in-leaf season, precipitation, and other meteorological variables..

Figure 4.1. Estimated Pollution Removal by Trees

Pollutant*	Atlanta		Boston		New York		Philadelphia	
	Removal (metric tons)	Value (\$ in thousands)	Removal (metric tons)	Value (\$ in thousands)	Removal (metric tons)	Value (\$ in thousands)	Removal (metric tons)	Value (\$ in thousands)
O ₃	672 (158–858)	\$4,539 (1,066–5,793)	108 (27–132)	\$729 (184–892)	536 (136–722)	\$3,622 (920–4,873)	185 (49–239)	\$1,246 (332–1,615)
PM ₁₀	528 (206–824)	\$2,378 (\$929–3,716)	73 (29–114)	\$330 (\$129–515)	354 (138–553)	\$1,595 (623–2,493)	194 (76–302)	\$872 (341–1,363)
NO ₂	181 (93–231)	\$1,220 (\$628–1,559)	48 (22–61)	\$324 (\$148–409)	364 (171–507)	\$2,459 (1,155–3,421)	93 (46–123)	\$630 (312–827)
SO ₂	89 (42–149)	\$147 (\$ 69–246)	23 (11–34)	\$37 (\$18–56)	199 (106–337)	\$329 (\$175–557)	41 (22–68)	\$67 (\$36–112)
CO	39	\$37	6	\$5	67	\$64	10	\$10
Total	1,509 (538–2,101)	\$8,321 (\$2,729–11,351)	257 (94–346)	\$1,426 (\$484–1,878)	1,521 (619–2,185)	\$8,071 (\$2,938–11,408)	522 (203–742)	\$2,826 (\$1,030–3,927)

*Pollutant:

O₃ – ozone

PM₁₀ – particulate matter less than 10 microns; assumes 50% resuspension of particles

NO₂ – nitrogen dioxide

SO₂ – sulfur dioxide

CO – carbon monoxide

Note: The figure shows estimated pollution removal (metric tons) by trees during nonprecipitation periods (dry deposition) and associated monetary value (thousand dollars) for Atlanta (341 square kilometers; 36.7 percent tree cover), Boston (143 square kilometers; 22.3 percent tree cover), New York (799 square kilometers; 20.9 percent tree cover), and Philadelphia (341 square kilometers; 15.7 percent tree cover). Estimates were made using the Urban Forest Effects (UFORE) model (Nowak and Crane 2000) based on tree data collected in the late 1990s and local hourly meteorological and pollutant data from 2000. Numbers in parentheses represent expected range of values (no range determined for CO). Monetary value of pollution removal by trees was estimated using the median externality values for United States for each pollutant (Murray et al. 1994). Externality values for O₃ were set to equal the value for NO₂.

Air quality improvement in these cities from pollution removal by trees during daytime of the in-leaf season averaged 0.6 percent for particulate matter, 0.57 percent for ozone, 0.55 percent for sulfur dioxide, 0.35 percent for nitrogen dioxide, and 0.009 percent for carbon monoxide. Air quality improves with increased percent tree cover and decreased mixing-layer heights. In urban areas with 100 percent tree cover (i.e., contiguous forest stands), short term improvements in air quality (one hour) from pollution removal by trees were as high as 15 percent for ozone and sulfur dioxide, 8 percent for particulate matter and nitrogen dioxide, and 0.05 percent for carbon monoxide (figure 4.2). To estimate pollution removal by trees in numerous U.S. cities, a pollution removal calculator can be found at <http://www.fs.fed.us/ne/syracuse/Tools/tools.htm>. Pollution removal by urban trees in the United States is estimated at 711,000 metric tons (\$3.8 billion value) annually (Nowak, Crane, and Stevens, 2006).

Figure 4.2. Air Quality Improvement by Trees

Pollutant*	Atlanta		Boston		New York		Philadelphia	
	City	Forest	City	Forest	City	Forest	City	Forest
O ₃	0.8%	14.8%	0.7%	14.6%	0.5%	11.4%	0.3%	9.4%
PM ₁₀	0.9%	8.5%	0.6%	7.3%	0.5%	6.8%	0.4%	7.7%
NO ₂	0.5%	8.3%	0.4%	7.4%	0.3%	6.3%	0.2%	5.3%
SO ₂	0.7%	14.8%	0.7%	14.9%	0.5%	11.3%	0.3%	9.6%

*Pollutant:

O₃ – ozone

PM₁₀ – particulate matter less than 10 microns; assumes 50% resuspension of particles

NO₂ – nitrogen dioxide

SO₂ – sulfur dioxide

Note: The figure shows the estimated average percentage air quality improvement in cities due to pollution removal by trees during daytime of the in-leaf season (city) and maximum estimated hourly air quality improvement in areas with 100 percent tree cover (forest). Maximum air quality improvement was less than 0.03 percent for carbon monoxide for all cities.

EMISSION OF VOLATILE ORGANIC COMPOUNDS

Emissions of volatile organic compounds (VOCs) by trees can contribute to the formation of ozone and carbon monoxide. However, in atmospheres with low nitrogen oxide concentrations (e.g., some rural environments), VOCs can actually remove ozone (Crutzen et al. 1985; Jacob and Wofsy 1988). 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 (Cardelino and Chameides 1990).

VOC emission rates also vary by species. Nine genera that have the highest standardized isoprene emission rate (Geron, Guenther, and Pierce 1994; Nowak et al. 2002), and therefore the greatest relative effect among genera on increasing ozone, are beefwood (*Casuarina* spp.), *Eucalyptus* spp., sweet gum (*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 currently inconclusive as to whether these genera will contribute to an overall net formation of ozone in cities (i.e., ozone formation from VOC emissions are greater than ozone removal). Some common genera in Brooklyn, New York, with the greatest relative effect on lowering ozone were mulberry (*Morus* spp.), cherry (*Prunus* spp.), linden (*Tilia* spp.), and honey locust (*Gleditsia* sp.) (Nowak et al. 2002).

Because urban trees often receive relatively large inputs of energy, primarily from fossil fuels, 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, chain saws, backhoes, leaf blowers, chippers, and shredders. The use of fossil fuels to power this equipment leads to the emission of carbon dioxide (approximately 0.7 kilograms per liter of gasoline, including manufacturing emissions [Graham, Wright, and Turhollow 1992]) and other chemicals such as VOCs, carbon monoxide, nitrogen and sulfur oxides, and

particulate matter (U.S. EPA 1991).

Trees in parking lots also affect evaporative emissions from vehicles, particularly through tree shade. In Sacramento County, California, increasing parking lot tree cover from 8 to 50 percent could reduce light-duty vehicle VOC evaporative emission rates by 2 percent and nitrogen oxide emissions when starting a vehicle by less than 1 percent (Scott, Simpson, and McPherson, 1999).

ENERGY EFFECTS ON BUILDINGS

Trees reduce building energy use by lowering temperatures and shading buildings in summer and blocking winds in winter (Heisler 1986). However, trees 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.

When building energy use is reduced, pollutant emissions from power plants are also lowered. While lower pollutant emissions generally improve air quality, lower nitrogen oxide emissions, particularly ground-level emissions, may lead to a local increase in ozone concentrations under certain conditions due to nitrogen oxide scavenging of ozone (Rao and Sistla 1993). The cumulative and interactive effects of trees on meteorology, pollution removal, and VOC and power plant emissions determine the overall impact of trees on air pollution.

COMBINED EFFECTS

Changes in urban microclimate affect pollution emission and formation, particularly the formation of ozone. A model simulation of a 20 percent loss in the Atlanta-area forest due to urbanization led to a 14 percent increase in ozone concentrations for a modeled day (Cardelino and Chameides 1990). Although there were fewer trees to emit VOCs, an increase in Atlanta's air temperatures due to the urban heat island, which occurred concomitantly with tree loss, increased VOC emissions from the remaining trees and anthropogenic sources. This, in turn, altered ozone chemistry such that concentrations of ozone increased.

A 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. The net basinwide effect of increased urban vegetation is 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, D.C., to central Massachusetts reveals that urban trees generally reduce ozone concentrations in cities but tend to slightly increase average ozone concentrations in the overall modeling domain (Nowak et al. 2000). Interactions of the effects of trees on the physical and chemical environment demonstrate that trees can cause changes in pollution removal rates and meteorology, particularly air temperatures, wind fields, and mixing-layer heights, which, in turn, affect ozone concentrations. Changes in urban tree species composition had no detectable effect on ozone concentrations (Nowak et al. 2000). Modeling of the New York City metropolitan area also reveals that a 10 percent increase in tree cover within urban areas reduced maximum ozone levels by about 4 parts per billion, which was about 37 percent of the amount needed for attainment (Luley and Bond 2002).

TREE AND IMPERVIOUS EFFECTS ON WATER QUALITY AND QUANTITY

Human activity can dramatically alter land cover characteristics, impeding water infiltration rates (Hamilton and Waddington 1999; Pitt and Lantrip 2000) and reducing percolation and, consequently, water table levels (Lerner 2002) and stream baseflow regimes

(Faulkner, Edmonds-Brown, and Green 2000). When water is captured in engineered retention or detention basins, rather than infiltrated through forested plots, it undergoes less sorption and is found to pollute subsurface water quality (Thomas 2000; Fischer, Charles, and Baer, 2003) as well as the quality of surface runoff. The result of traditional urban development is to impair important hydrological and watershed recharge and cleansing processes. Research has shown the importance of increasing pervious cover and augmenting subsurface recharge (Argue 1994; Nowakowska-Blaszczyk and Blaszczyk 1997). Removal of forest cover and/or increased impervious area due to urbanization is known to increase stream flow and peak runoff in streams (Leopold 1968; Kidd 1978; Codner, Laurenson, and Mein 1988; Mein and Goyen 1988). These changes in stream flows can lead to flooding, soil erosion, and sedimentation in streams (Anderson 1970; Urbonas and Benik 1995; McMahon and Cuffney 2000; Paul and Meyer 2001; Rose and Peters 2001).

Conventional urban development increases the amount of stormwater runoff generated by the landscape (Chow and Yen 1976; Boyd, Bufill, and Knee 1994; Beach 2002). The principal causes of this effect are impervious surfaces—streets, parking lots, and buildings (Leopold 1968; Schueler 1994)—and compaction of the soil due to construction activities (Hamilton and Waddington 1999; Pitt et al. 2003). Instead of soaking into the ground, rainfall is converted quickly to runoff and then rapidly removed from the site via sewers and manmade channels. As the volume of urban stormwater runoff has increased throughout the United States from the increase in impervious surfaces, the quality of surface runoff has degraded significantly (U.S. EPA 1983).

According to U.S. General Accounting Office (2001), when natural ground cover is present over the entire site, normally 10 percent of precipitation runs off the land into nearby creeks, rivers, and lakes. In contrast, when a site is 75 percent impervious, 55 percent of the precipitation runs off into receiving waters. Runoff from parking lots and other paved areas is estimated at 98 percent of precipitation (USDA NRCS 1986). Water that runs off urban landscapes can no longer recharge groundwater supplies. For communities that depend on locally recharged aquifers, water shortages could limit future development and necessitate sprinkling bans and other restrictions. Increased runoff peaks and decreased lag time (the elapsed time between the onset of a storm and when the peaks occurs) are costly to a city as drainage systems must be designed for peak runoff conditions (Urbonas and Roesner 1993), which can increase downstream flooding.

Water that runs over developed areas, including paved surfaces such as roads and parking lots, before reaching a water body is known as urban runoff and is an increasingly important category of water pollution (U.S. General Accounting Office 2001). Because of impervious surfaces, a typical city block may generate nine times more runoff than a woodland area of the same size (U.S. EPA 1996a). Urban runoff can adversely affect the quality of the nation's waters, and urban stormwater runoff has been identified as one of the leading sources of pollution to rivers, streams, lakes, and estuaries (U.S. General Accounting Office 2001).

Urban runoff is known to be contaminated with numerous water pollutants (U.S. EPA 1983) that are by-products of urban activities, such as automobile use, lawn care, and industrial fallout (WEF/ASCE 1998). Urban runoff and its pollutants from both point and nonpoint sources can cause increases in sedimentation, water temperature, and pathogen levels and decreases in dissolved oxygen levels in bodies of water (Horner 1995; WEF/ASCE 1998).

With regard to water, urban trees can affect both stream flow volume and quality. To date, most of the research has been on the effect of urban trees on stream flow. Trees affect stream flow rates primarily through three mechanisms: rainfall interception, soil water infiltration, and evapotranspiration.

RAINFALL INTERCEPTION

Trees intercept rainfall on leaves and branch surfaces, thereby potentially reducing runoff volumes and delaying the onset of peak flows. Natural forest canopy interception, with subsequent evaporation from a wet canopy, which is affected by tree types and weather conditions, ranges from 11 to 36 percent of annual precipitation in deciduous canopies and from 9 to 48 percent in coniferous canopies (Hörmann et al. 1996). The forest interception fraction is 35 to 40 percent of annual precipitation in the United Kingdom, where annual rainfall exceeds 1,000 millimeters (Calder 1990, 2003). Such findings suggest that deforestation may have a significant effect on runoff generation.

Urban tree interception of precipitation may be different from that of natural forests because both the microclimate and the tree architecture are different. Compared with more rural forests, urban forests have fewer trees per unit area, typically larger tree size, a more diverse mix of species with different phenological patterns, and greater spatial variation in canopy cover (McPherson 1998). In Sacramento, the urban forest canopy is estimated to intercept 11.1 percent of the annual precipitation (Xiao et al. 1998). In summer, tree interception in Sacramento was 36 percent for an urban forest stand dominated by large, broadleaf evergreens and conifers (leaf area index = 6.1) and 18 percent for a stand dominated by medium-size conifers and broadleaf deciduous trees (leaf area index = 3.7). For five precipitation events with return frequencies ranging from 2 to 200 years, interception was greatest for small storms and least for large storms (Xiao et al. 1998). By intercepting and lowering the rainfall rate and intensity impacting the ground beneath the canopy, soil erosion can be reduced and soil water infiltration and percolation to groundwater increased.

SOIL WATER INFILTRATION

In addition to lowering rainfall rates beneath canopies, root growth and decomposition in forested land can increase the capacity and rate of soils to infiltrate rainfall and reduce overland flow. Forests can be used as buffers around water bodies or between impervious areas to naturally filter and infiltrate runoff. Thus, forest buffers reduce not only the quantity of urban runoff, but also pollutants carried with urban runoff through physical, chemical, and biological processes in the soil.

EVAPOTRANSPIRATION

Land cover affects evapotranspiration (ET). ET is a measure of the amount of water evaporated from surfaces or transpired (evaporated) from leaf surfaces and is important in the hydrologic process because it is a means by which liquid water is removed from the groundwater cycle and converted to atmospheric water vapor. Looking at a global average, two-thirds of the precipitation that falls on the continents is evapotranspired. Of this amount, 97 percent is ET from land surfaces and 3 percent is open-water evaporation (Hornberger et al. 1998). Removal of forest cover can increase stream flow as a result of reduced ET. In the interior Columbia River Basin, annual average increases in runoff ranged from 4.2 to 10.7 percent, and reductions in evapotranspiration ranged from 3.1 to 12.1 percent due to decreased vegetation maturity as a result of logging (Matheussen et al. 2000). Evergreen trees usually have the highest actual ET, followed by deciduous trees, shrubs, and grasses, with differences diminished in areas with low mean annual precipitation (Matheussen et al. 2000).

CUMULATIVE EFFECTS ON STREAM FLOWS AND RUNOFF

Relatively little research has been conducted on the effects of urban trees on stream flows and runoff compared to forest areas. In a review of vegetation changes on annual water yields across the world, Bosch and Hewlett (1982) found that, on average, a 10 percent change in tree cover caused an estimated 40 millimeter change in annual water yield for

coniferous forest and 25 millimeters for deciduous forest. A complete conversion from grass to evergreen trees on average decreases mean annual runoff by 400 millimeters and vice versa; a conversion from grass to deciduous trees on average decreases mean annual runoff by 250 millimeters and vice versa; and a conversion from grass to shrubs/scrub on average decreases mean annual runoff by 100 millimeters and vice versa. In a study of runoff changes in Victoria, Australia, following the clearing of a forest, the average maximum increase in runoff occurred two years after clearing and was approximately equal to an additional 33 millimeters of runoff per year per 10 percent of area cleared (Nandakumar and Mein 1997). Forests also slow stormwater runoff and provide watershed stability and critical habitat for fish and wildlife (Sedell et al. 2000).

Little research has been conducted on the effects of urban trees on stream flows and runoff. Several estimates of the effects of urban forests on runoff have been calculated using the TR-55 model (Soil Conservation Service 1975). Although these estimates are limited in their capability to accurately estimate effects of urban forests on runoff volume and peak rate due to some important limitations of the model (e.g., Xiao et al. 1998), these studies represent most of the literature on this topic and provide first-order estimates of urban forest effects.

Using this model to simulate urban forest impacts on stormwater runoff in Dayton, Ohio, Sanders (1986) demonstrated that existing tree canopy cover (22 percent) could lower potential runoff from a six-hour, one-year storm by about 7 percent. By increasing tree cover to 50 percent over all pervious surfaces, runoff reduction was increased to nearly 12 percent. A study of Tucson, Arizona, showed that increasing tree canopy cover from 21 (existing) to 35 percent and 50 percent could reduce mean annual runoff by 2 and 4 percent, respectively (Lormand 1988). In Austin, Texas, it was estimated that the existing trees reduce the potential runoff volume by 850 million gallons, or 7 percent of a 5.5 inch, five-year storm (Walton 1997).

Using the HSPF model (Bicknell et al. 1997), Neville (1996) studied the effects of alternative vegetation patterns in the Gwynns Falls watershed (Baltimore, Maryland) as a viable alternative for reducing stormwater discharges. Results indicated that tree canopy cover can have a substantial impact depending on land use. Model simulations revealed that changing tree cover from 0 to 100 percent for the existing conditions would reduce total runoff by about 26 percent. Base flow would decrease by more than 13 percent.

Based on a newly developed model (Wang, Endreny, and Nowak in review), estimates of the effects of urban tree cover in the Dead Run watershed (1,410 hectares) in Baltimore revealed that increasing tree cover over pervious surface from 12 to 24 percent and increasing tree cover over impervious surfaces from 5 to 20 percent reduced total annual runoff by 3 percent (~140,000 cubic meters per year) and decreased peak flow from a 3.6 mm storm on August 13, 2000, by 12 percent. Reducing tree cover over pervious areas from 12 to 6 percent and replacing it with impervious surfaces connected to streams led to a 10 percent increase in total annual runoff (~500,000 cubic meters per year) and a 30 percent increase in peak flow during the 3.6 millimeter storm event. These model simulations illustrate how urban forest management can have a modest influence on runoff volume.

The societal value of runoff reduction in urban streams is difficult to determine. Urban forests can reduce the need for stormwater management infrastructure, particularly at the urban fringe. Some studies have used proxy values related to retention pond costs and suggest that the value of reduced runoff is on the order of hundreds of millions of dollars per year (e.g., Walton 1997). However, further research and evaluation of runoff reduction values are needed before a more certain valuation can be made.

WATER QUALITY EFFECTS

More than a third of our nation's streams, lakes, and estuaries are impaired by some form of water pollution (U.S. EPA 1998). Pollutants can enter surface waters from point sources, such as single-source industrial discharges and wastewater treatment plants. However, most pollutants result from nonpoint source pollution activities, including runoff from agricultural lands, urban areas, construction and industrial sites, and failed septic tanks. These activities introduce harmful sediments, nutrients, bacteria, organic wastes, chemicals, and metals into surface waters. Damage to streams, lakes, and estuaries from nonpoint source pollution was estimated at about \$7 billion to \$9 billion a year in the mid-1980s (Ribaudo 1986). Point sources of pollution are largely controlled by requirements of the Clean Water Act. However, nonpoint source pollution remains the "nation's largest source of water quality problems" (U.S. EPA 1996b).

Nonpoint source pollution is difficult to control, measure, and monitor because it is diffuse in nature. Forests can reduce nonpoint source water pollution in many ways, helping to ensure a cleaner water supply; they can serve as filters, sinks, or transformers of pollutants. Pollutants are trapped in the forest and are then used by the plants as food for growth or are transformed through chemical and biological processes into nonharmful forms. A continuous litter layer can help maintain a porous soil surface and high water infiltration rates; consequently, overland flow can be minimized in a forest. By decreasing the rate of surface runoff, groundwater recharge from seepage is increased, forest soil nutrients are conserved, and the productivity of the forest is maintained.

Although there is a dearth of research on the effects of urban trees on water quality, data from the EPA's Nationwide Urban Runoff Program reveal that pollutant loadings from runoff in parks and low-density residential areas (areas that typically have higher tree cover and lower impervious cover) are significantly lower than from other urban land uses (U.S. EPA 1999). Research from rural areas also reveals that forests and trees can help improve water quality. Trees divert captured rainwater into the soil, where bacteria and other microorganisms filter out impurities. This bio-filtration can dramatically reduce the sediment, pollutants, and organic matter that reach streams. Important environmental processes for water quality improvement include soil filtration of particles and adsorption of chemicals, nutrient assimilation by plants, and the degradation or volatilization of chemicals by microorganisms (Winogradoff 2002).

One effective management practice in influencing water quality is the construction or conservation of riparian forest buffers along streams, lakes, and other surface waters. These forests can buffer nonpoint source pollution of waterways from adjacent land, reduce bank erosion, protect aquatic environments, enhance wildlife, and increase biodiversity. Through the interaction of their unique soils, hydrology, and vegetation, riparian forest buffers influence water quality as contaminants are taken up into plant tissues, adsorbed onto soil particles, or modified by soil organisms. Riparian forests can affect stream sediment loads and the concentration of nutrients and other contaminants.

SEDIMENTS

Sediment refers to soil particles that enter streams, lakes, and other bodies of water from eroding land, including plowed fields, construction and logging sites, urban areas, and eroding stream banks (U.S. EPA 1995). Sedimentation of streams can have a pronounced effect on water quality and stream life, and reduces water clarity. In addition to mineral soil particles, eroding sediments may transport other substances, such as plant and animal wastes, nutrients, pesticides, petroleum products, metals, and other compounds that can lower water quality (Clark 1985; Neary, Swank, and Riekerk 1988). Urban sediment is typically more of a problem during site construction or restoration than during normal use of a site.

Forested lands produce a small fraction of the sediment yielded by more intensive

land uses (Patric, Evans, and Helvey 1984; Yoho 1980). In a study of upper Chattahoochee River Basin, Georgia, the greatest suspended sediment yields were from urban areas, compared with forested and agricultural lands (Faye et al. 1980). In Virginia, forestry practices contributed little sediment, agriculture was an important source of sediment, and urban development contributed the most sediment (as well as other pollutants) (Jones and Holmes 1985).

Studies indicate that forest riparian buffers can effectively trap sediment, with removal rates ranging from 60 to 90 percent of the sediment (Cooper et al. 1987; Daniels and Gilliam 1996). Along the Little River in Georgia, riparian forests have accumulated between 311,600 and 471,900 pounds per acre of sediment annually over the last 100 years (Lowrance, Sharpe, and Sheridan 1986). Many factors influence the effectiveness of the buffer in removing sediments from land runoff, including sediment size and loads, slope, type and density of riparian vegetation, presence or absence of a surface litter layer, soil structure, subsurface drainage patterns, and frequency and force of storm events (Osborne and Kovacic 1993).

NUTRIENTS

Nutrients are essential elements for aquatic ecosystems, but in excess amounts, nutrients can lead to many changes in the aquatic environment and reduce the quality of water for human uses (Dupont 1992). Lawn and crop fertilizers, sewage, and manure are major sources of nutrients in surface waters. Industrial sources and atmospheric deposition also contribute significant amounts of nutrients (Guldin 1989). One of the most significant impacts of nutrients on streams is eutrophication, the excessive growth of algae and other aquatic plants in response to high levels of nutrient enrichment (U.S. EPA 1995). In addition, some forms of nutrients can be directly toxic to humans and other animals (Chen, McCutcheon, and Carsel 1994; Evanylo 1994).

Streams draining agricultural watersheds have, on average, considerably higher nutrient concentrations than those draining forested watersheds. Nutrient concentrations are usually proportional to the percentage of land in agriculture and inversely proportional to the percentage of land in forest (Omernik 1977). The highest nitrogen and phosphorus yields typically occur in highly agricultural and urbanized watersheds, and lowest nutrient yields occur in streams of forested watersheds (e.g., Spruill et al. 1998; Hampson et al. 2000).

Forest riparian zones have been shown to reduce between 48 and 95 percent of nitrogen and/or nitrates from runoff (Lowrance et al. 1984; Peterjohn and Correll 1984; Jordan, Correll, and Weller 1993; Snyder et al. 1995). In New Zealand, where subsurface water flows moved through organic soils before entering streams, nitrate levels were reduced by as much as 100 percent. However, mineral soils located along the same streams exhibited little capacity to decrease nitrogen (Cooper 1990). The processes by which soils remove nitrates include denitrification, uptake by vegetation and soil microbes, and retention in riparian soils (Beare, Lowrance, and Meyer 1994; Evanylo 1994).

Plants can take up large quantities of nitrogen as they produce roots, leaves, and stems. However, much of this is returned to the soil as plant materials decay. For example, scientists in Maryland estimated that deciduous riparian forests took up 69 pounds of nitrogen per acre annually, but returned 55 pounds (80 percent) each year in the litter (Peterjohn and Correll 1984). Nevertheless, Correll (1997) suggested that vegetative uptake is still a very important mechanism for removing nitrate from riparian systems because vegetation (especially trees) removes nitrates from deep in the ground, converts the nitrate to organic nitrogen in plant tissues, then deposits the plant materials on the surface of the ground where the nitrogen can be mineralized and denitrified by soil microbes.

Riparian areas can be important sinks for phosphorus but are generally less effective in removing phosphorus than sediment or nitrogen (Parsons et al. 1994). Riparian stands remove 30 to 80 percent of phosphorus (Cooper et al. 1987; Lowrance et al. 1984; Peterjohn and Correll 1984). Some phosphorus may be taken up and used by vegetation and soil microbes, but like nitrogen, much of this phosphorus eventually is returned to the soil. For example, researchers estimated that less than 3 percent of the phosphate entering a floodplain forest in eastern North Carolina was taken up and converted to woody tissue, while scientists in Maryland reported a deciduous riparian forest buffer took up 8.8 pounds per acre per year of phosphorus but returned 7 pounds per acre per year (80 percent) as litter (Brinson, Bradshaw, and Kane, 1984; Peterjohn and Correll 1984). In some riparian areas, small amounts of phosphorus (0.05–2.14 pounds per acre per year) may be stored as peat (Walbridge and Struthers 1993). Riparian forests have been found to be effective filters for nutrients, including nitrogen, phosphorus, calcium, potassium, sulfur, and magnesium (Lowrance, Todd, and Asmussen, 1984; Lowrance et al. 1984).

METALS

Riparian areas may slow the movement of metals and other contaminants to surface waters and increase the opportunity for the contaminants to become buried in the sediments, adsorbed into clays or organic matter, or transformed by microbial and chemical processes (Johnston et al. 1984). The fate of metals in riparian areas is not well understood. However, scientists in Virginia have found significant amounts of lead, chromium, copper, nickel, zinc, cadmium, and tin buried in the sediments in the floodplain along the Chickahominy River downstream of Richmond (Hupp, Woodside, and Yanoksy 1993). Analysis of the woody tissue of the trees revealed that these compounds also are taken up by the trees. Therefore, sediment deposition and uptake by woody vegetation may help mitigate heavy metals in riparian areas.

PATHOGENS

Pathogens, such as waterborne bacteria, viruses, and protozoa, are the source of many diseases that infect humans, livestock, and other animals (Chesters and Schierow 1985; Palmateer 1992). There is relatively little information on the role of riparian buffers on pathogens. In one study, strips of corn, oats, orchard grass, and sorghum/Sudan grass were all effective in reducing bacterial levels by nearly 70 percent (Young, Huntrods, and Anderson 1980). It was estimated that a buffer 118 feet wide would be required to reduce total coliform bacteria to levels acceptable for human recreational use (Young, Huntrods, and Anderson 1980). Other researchers have demonstrated the ability of grass sod filter strips to trap bacteria from dairy cow manure under laboratory conditions (Larsen et al. 1994). They found that even a narrow (two-foot) strip successfully removed 83 percent of the fecal coliform bacteria, while a seven-foot filter strip removed nearly 95 percent.

PESTICIDES

Few studies have been made to examine the fate of pesticides in riparian areas. However, where the proper conditions exist, riparian forest buffers have the potential to remove and detoxify pesticides in runoff. Probably the most important process is the breakdown of organic chemicals by soil microorganisms (MacKay 1992). For decades, scientists have observed that soil microorganisms adapt to the presence of a pesticide and begin to metabolize it as an energy source (Fausey et al. 1995). As it is metabolized, the pesticide is broken down to various intermediate compounds and, ultimately, carbon dioxide. In addition, most pesticides have a high affinity for clay and organic matter and may be removed from the soil water as they are bound to soil particles. Once bound, pesticides are often difficult to desorb from the soil (Clapp et al. 1995).

As these studies indicate, riparian forest buffers can reduce the amount of sediment, nutrients, and other contaminants that enter surface waters. However, the studies also suggest that these effects vary from one riparian area to another. The degree to which the riparian buffer protects water quality is a function of the area's hydrology, soils, and vegetation. Riparian forests will have the greatest influence on water quality where field runoff follows direct, shallow flow paths from upland areas to the stream. Riparian forests will have less impact on water quality where surface runoff is concentrated and runs through the buffer in defined channels, or where deep subsurface flows cause groundwater to move below the roots of trees. One significant problem in urban areas is the lowering of the water table and, consequently, the level of base flow. With lowered water tables, the contaminants in water can pass below plant rooting zones and limit chemical uptake by plants. Riparian forests may not be able to provide all of the necessary functions in urban watersheds as a result of numerous channelized sources of runoff in urban watersheds. Therefore, other actions should be taken beyond buffer protection to minimize the effect of urban runoff. These actions would include the reduction of surface runoff, by reducing both the amount of impervious areas and the detention and reinfiltration of any surface runoff generated.

SUMMARY OF EFFECTS OF PRESERVING FORESTS STANDS AND TREE COVER IN URBAN AREAS

The preservation of forest stands in urban areas can lead to many environmental and economic effects related to air and water quality. The magnitude of these effects and values will depend on the amount of forestland or tree cover conserved along with other factors, such as location of the stand relative to urban development or waterways. As much of the research related to urban forest effects on air and water quality is relatively new, the economic values of many of these effects are currently unknown but are very likely quite substantial. Though some values are estimated, there are likely numerous other secondary economic impacts due to cleaner air and water (e.g., increased tourism, business, and/or recreation) that are not accounted for in the value estimate. Continued research is needed on the economic valuation of many of these effects to quantify the economic impact of land conservation at varying scales and locations. The following forest/tree effects related to air and water quality are known:

❁ Reduced Air Temperatures

Effect: Through transpiration and shade, trees lower air temperatures and consequently lead to reduced pollution emission and formation, reduced summertime energy use of nearby buildings and consequent pollutant emissions from power plants, increased human comfort, and reduced thermal stress.

Economic Value: Unknown. However, the cost of reducing a single part per billion of ozone through electric utility nitrogen oxides limitations is estimated at one-half to three-quarters of a billion dollars annually (U.S. EPA 1997). Thus, the economic impact of any temperature reduction effects on reduced pollution formation or emissions will likely be significant as the costs of reducing ozone precursor emissions through other techniques are large.

❁ Pollution Removal

Effect: Trees directly remove pollution in the atmosphere through interception of particles and uptake of gases through leaf stomata. Typical removal rates are on the order of 11 grams per square meter of canopy cover per year (ozone, particulate matter less than 10 microns, sulfur and nitrogen dioxide, and carbon monoxide combined).

Economic Value: Average annual value per hectare of canopy cover is about \$663 in Atlanta, \$447 in Boston, \$482 in New York, and \$527 in Philadelphia.

✿ VOC Emissions

Effect: Although trees emit VOCs that can contribute to ozone formation, integrative studies are revealing that combined effects of trees tend to reduce ozone. In addition, conversion of forest stands to urban development will most likely increase total VOC emissions in the area due to the relatively high VOC emissions associated with urbanization.

Economic Value: Unknown..

✿ Energy Conservation

Effect: Tree cover around buildings can reduce building energy use in summer through shade or reduced air temperatures. Tree cover can increase or decrease building energy use in winter depending on tree locations around a building due to tree effects of shade and blocking of winds. Alterations in energy use will affect pollutant emissions from power plants.

Economic Value: Savings to homeowners due to altered building energy use from trees in Minneapolis is about \$216,000 per year (Nowak et al. 2006a) and about \$2.7 million per year in Washington, D.C. (Nowak et al. 2006b). Monetary impact on air quality is unknown.

✿ Reduced Runoff

Effect: Trees can reduce runoff through the processes of rainfall interception, evapotranspiration, and increasing soil infiltration. The effects of trees can reduce and delay peak flows, reduce the need for stormwater treatment facilities, and improve water quality.

Economic Value: Likely in the millions of dollars per year for a city for the entire urban forest.

✿ Improved Water Quality

Effect: Trees can improve water quality by reducing runoff and air pollution and, in combination with the soil environment, by filtering, assimilating, adsorbing, volatilizing, or degrading many chemicals in the water that flow through the forest. Water quality related to sediments, nutrients, pathogens, pesticides, metals, and other contaminants in forested areas tends to be improved.

Economic Value: Damage to streams, lakes, and estuaries from nonpoint source pollution was estimated to be about \$7 billion to \$9 billion a year in the mid-1980s (Ribaudo 1986). Local effects in terms of stream quality and human health are likely substantial.

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