

Institutionalizing urban forestry as a “biotechnology” to improve environmental quality

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Abstract

Urban forests can provide multiple environmental benefits. As urban areas expand, the role of urban vegetation in improving environmental quality will increase in importance. Quantification of these benefits has revealed that urban forests can significantly improve air quality. As a result, national air quality regulations are now willing to potentially credit tree planting as means to improve air quality. Similarly, quantification of other environmental benefits of urban trees (e.g., water quality improvement, carbon sequestration) could provide for urban vegetation to be incorporated in other programs/regulations designed to improve environmental quality.

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Introduction

Urbanization concentrates people, materials, and energy into relatively small geographical areas to facilitate the functioning of society. Urbanization often degrades local and regional environmental quality as natural landscapes are replaced with anthropogenic materials. Byproducts of urbanization (e.g., heat, combustion, and chemical emissions) affect the health of the local and regional landscapes, as well as the health of people who reside, visit, and/or work in and around urban areas.

In the lower 48 United States, percent of land classified as urban increased from 2.5% in 1990 to 3.1% in 2000 (44,834 km²), an area about the size of Vermont and New Hampshire combined. Patterns of urban expansion reveal that increased growth rates are likely in the future (Nowak et al., 2005a, b). Urban land

is projected to increase from 3.1% in 2000 to 8.1% in 2050, an area (392,000 km²) greater than the size of Montana. By 2050, four states (Rhode Island, New Jersey, Massachusetts, and Connecticut) are projected to be more than half urban land (Nowak and Walton, 2005).

Urban vegetation, through its natural functioning, can improve environmental quality and human health in and around urban areas. These benefits include improvements in air and water quality, building energy conservation, cooler air temperatures, reduction in ultraviolet radiation, and many other environmental and social benefits (Nowak and Dwyer, 2000). Properly designed and managed, urban vegetation can be used as a natural “biotechnology” to reduce some of the adverse environmental and health effects associated with urbanization. With the extent of urbanization expanding across the landscape, there is an urgent need to incorporate the effects of urban vegetation on reducing the adverse effects of urbanization into long-term planning, policies, and regulations to improve environmental quality.

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The purpose of this paper is to detail effects of urban forests on air quality and streams flows in particular cities and discuss the role of urban forests within national programs/regulations related to environmental quality and human health.

Methods

To incorporate the effects of urban trees in meeting environmental standards, the impacts of trees on the environment need to be quantified. The urban forest functions that appear to be most critical to environmental quality and associated regulations are tree effects on air and water quality, and carbon sequestration. To quantify these urban forest effects in various cities, the Urban Forest Effects (UFORE) model was used. The UFORE model uses standardized field data from randomly located urban forest plots and local hourly air pollution and meteorological data to quantify urban forest structure, functions, and values (e.g., Nowak et al., 2000, 2001, 2002a, b, 2005a, b; Nowak and Crane, 2000, 2002). The model currently quantifies: (a) urban forest structure by land use type (e.g., species composition, tree density, tree health, leaf area, leaf and tree biomass, species diversity, etc.); (b) hourly amount of pollution removed by the urban forest, its value, and its associated percent air quality improvement throughout a year. Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and particulate matter ($<10\mu\text{m}$); (c) hourly urban forest volatile organic compound (VOC) emissions and the relative impact of tree species on net ozone and carbon monoxide formation throughout the year; (d) total carbon stored and net carbon annually sequestered by the urban forest, including its value to society; and (e) effects of trees on building energy use and consequent effects on carbon dioxide emissions from power plants.

To date, urban forest structural data (e.g., tree species composition, number of trees, trees size, health) have been or are being collected and analyzed with the UFORE model for about 30 cities, with about one-third of the analyses occurring in cities outside of the United States – e.g., Beijing, China (Yang et al., 2005); Fuenlabrada, Spain (Lozano, 2004); Santiago, Chile (Escobedo et al., 2006); and Toronto, Ontario, Canada (Kenney et al., 2001). From this basic field data, leaf area and leaf biomass estimates are made and combined with local meteorological and pollution data to estimate hourly air pollution removal, total carbon storage, and annual carbon sequestration.

Hourly pollution removal is based on the downward pollutant flux (F ; in $\text{g}/\text{m}^2\text{s}$) 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 was calculated as the inverse of the sum of the aerodynamic (R_a), quasi-laminar boundary layer (R_b), and canopy (R_c) resistances. Hourly estimates of R_a and R_b were calculated using standard resistance formulas and local hourly weather data. Hourly canopy resistance values for O_3 , SO_2 , and NO_2 were calculated based on a modified hybrid of big-leaf and multilayer canopy deposition models (Baldocchi et al., 1987; Baldocchi, 1988). As removal of CO and particulate matter by vegetation are not directly related to photosynthesis/transpiration, R_c for CO was set to a constant for in-leaf season (50,000 s/m) and leaf-off season (1,000,000 s/m) (Bidwell and Fraser, 1972). For particles, the median deposition velocity (Lovett, 1994) was set to 0.064 m/s based on 50% resuspension rate (Zinke, 1967). The base V_d was adjusted according to in-leaf vs. leaf-off season parameters. To limit deposition estimates to periods of dry deposition, deposition velocities were set to zero during periods of precipitation. Detailed methods of pollution removal are given in Nowak et al. (1998, 2002b, 2006).

To calculate current carbon storage and annual carbon sequestration, biomass for each measured tree is calculated using allometric equations from the literature (Nowak, 1994; Nowak et al., 2002b). Equations that predict above-ground biomass were converted to whole tree biomass based on root-to-shoot ratio of 0.26 (Cairns et al., 1997). Equations that compute fresh-weight biomass were multiplied by species- or genus-specific conversion factors to yield dry-weight biomass. Open-grown, maintained trees tend to have less above-ground biomass than predicted by forest-derived biomass equations for trees of the same diameter at breast height (Nowak, 1994). To adjust for this difference, biomass results for urban trees were multiplied by a factor 0.8 (Nowak, 1994). No adjustment was made for trees found in more natural stand conditions (e.g., on vacant lands or in forest preserves). Total tree dry-weight biomass was converted to total stored carbon by multiplying by 0.5 (Forest Products Lab, 1952; Chow and Rolfe, 1989).

The multiple equations used for individual species were combined together to produce one predictive equation for a wide range of diameters for individual species. The process of combining the individual formulas (with limited diameter ranges) into one, more general species formula, produced results that were typically within 2% of the original estimates for total carbon storage of the urban forest (i.e., the estimates using the multiple equations). Formulas were combined to prevent disjointed sequestration estimates that can occur when calculations switch between individual biomass equations. If no allometric equation could be found for an individual species, the average of results from equations of the same genus were used. If no genus equations were found, the average of results from all

broadleaf or conifer equations was used. Average diameter growth from the appropriate land use, diameter class, and tree health was added to the existing tree diameter (year x) to estimate tree diameter and carbon storage in year $x + 1$. Detailed methods for carbon storage and sequestration are given in Nowak et al. (2002b) and Nowak and Crane (2002).

A semi-distributed, physical-based urban forest effects hydrological model (UFORE-Hydro) was created to simulate and study tree effects on urban runoff at the catchment scale. Key processes for each hydrologically representative unit are precipitation, interception, evaporation, infiltration, and runoff. Algorithms are designed to simulate runoff generation from different land and soil types. Tree interception estimation used an hourly simulation time step for precipitation, evaporation, and tree storage updates and a daily leaf area index. This GIS-based program uses digital elevation data and calibrates against local gauging station data to quantify hourly changes in stream flows and water quality due to changes in tree and impervious surface cover within a watershed (Wang et al., in review a, b). As this model is new, few analyses have been conducted to date, but simulation results are presented for the

Dead Run watershed, located near Baltimore, Maryland.

Results – urban forest effects

Air quality

Urban vegetation can directly and indirectly affect local and regional air quality by removing air pollution and altering the urban atmospheric environment. Factors that affect pollution removal by trees include the amount of healthy leaf-surface area, concentrations of local pollutants, and local meteorology. In the US, urban forests are estimated to remove about 711,000 metric tons (\$3.8 billion value) of air pollution per year (Nowak et al., 2006). Computer simulations using the UFORE model with local field data reveal that pollution removal by urban trees in selected cities range from 8 metric tons per year in the developed portion of Fuenlabrada, Spain, to over 1500 metric tons per year in Atlanta and New York (Table 1). Amount of pollution removed was typically greatest for ozone, followed by

Table 1. Total estimated pollution removal (metric tons) by trees during non-precipitation periods (dry deposition), and associated monetary value for various cities (pollutant year = 2000 unless otherwise noted)

City	Pollution removed						Range (t)	g/m ² cover ^a	\$ (USD)	\$/ha cover ^b
	CO (t)	NO ₂ (t)	O ₃ (t)	PM10 (t)	SO ₂ (t)	Total (t)				
New York, NY	67	364	536	354	199	1521	(619–2185)	9.1	8,071,000	482
Atlanta, GA	39	181	672	528	89	1508	(538–2101)	12.0	8,321,000	663
Beijing, China ^c	na	132	256	772	101	1261	na	27.5	6,264,000	1223
Toronto, Canada ^d	33	199	405	284	77	997	(383–1394)	7.7	5,512,000	425
Baltimore, MD	9	94	223	142	55	522	(183–725)	9.9	2,876,000	545
Philadelphia, PA	10	93	185	194	41	522	(203–742)	9.7	2,826,000	527
Washington, DC	18	50	152	107	51	379	(150–568)	8.3	1,956,000	429
Boston, MA	6	48	108	73	23	257	(94–346)	8.1	1,426,000	447
Woodbridge, NJ	6	42	66	62	15	191	(72–267)	10.8	1,037,000	586
San Francisco, CA	7	25	47	42	7	128	(51–195)	9.0	693,000	486
Moorestown, NJ	2	14	43	38	9	107	(41–157)	10.1	576,000	541
Syracuse, NY	2	12	55	23	7	99	(37–134)	6.6	568,000	378
Morgantown, WV	1	5	26	18	9	60	(22–98)	7.5	311,000	387
Jersey City, NJ	2	9	13	9	5	37	(16–56)	8.4	196,000	445
Freehold, NJ	1	3	9	6	1	20	(7–27)	11.4	110,000	632
Fuenlabrada, Spain ^e	0	2	3	3	0	8	(3–12)	10.6	48,000 ^f	640

Estimates are for particulate matter less than 10 μ m (PM10), ozone (O₃), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and carbon monoxide (CO). Monetary value of pollution removal by trees was estimated using the median externality values for United States for each pollutant. Externality values are: NO₂ = \$6750/t, PM10 = \$4500/t, SO₂ = \$1650/t, and CO = \$950/t (Murray et al., 1994). Externality values for O₃ were set to equal the value for NO₂.

^aAverage grams of pollution removal per year per square meter of canopy cover.

^bAverage dollar value of pollution removal per year per hectare of canopy cover.

^cCentral city area (301 km²); Yang et al. (2005); year = 2002.

^dMunicipality of Metropolitan Toronto (632 km²); Kenney et al. (2001); year = 1998.

^eDeveloped area only (8 km²); Lozano (2004); year = 2002.

^fValues based on euros per ton for Spain (Lozano, 2004); converted to US dollars (1EUR = 1.32 US\$).

particulate matter less than 10 μm , nitrogen dioxide, sulfur dioxide, and carbon monoxide. Annual value of pollution removal, based on national median externality values for each pollutant (Murray et al., 1994), ranged from \$48,000 in Fuenlabrada to \$8.3 million in Atlanta.

Average annual pollution removal per square meter of canopy cover was 10.4 g, but ranged between 6.6 g/m² in Syracuse to 27.5 g/m² in Beijing, China (Table 1). Excluding Beijing, which has a relatively high pollution concentration, the average is 9.3 g/m². The average annual dollar value of pollution removed per hectare of tree cover was \$552 (\$508 excluding Beijing), but ranged between \$378/ha cover in Syracuse to \$1223/ha cover in Beijing. Increasing tree cover in urban areas will lead to greater pollution removal, as well as reduced air temperatures that can help improve urban air quality.

Average percent improvement in air quality from pollution removal by trees during the daytime of the in-leaf season among 13 US cities was 0.64% for particulate matter less than 10 μm (PM10), 0.62% for ozone (O₃), 0.61% for sulfur dioxide (SO₂), 0.40% for nitrogen dioxide (NO₂), and 0.002% for carbon monoxide (CO). Air quality improvement increases with increased percent tree cover and decreased boundary-layer heights (i.e., the height of the layer of atmosphere that, because of turbulence, interacts with the earth's surface on a time scale of a few hours or less (Lenschow, 1986)). In urban areas with 100% tree cover (i.e., contiguous forest stands), short-term improvements (1 h) in air quality attributed to pollution removal from trees were as high as 14.9% for SO₂, 14.8% for O₃, 13.6% for PM10, 8.3% for NO₂, and 0.05% for CO.

Though trees remove pollutants from the air, it is the combined effect of trees on local microclimate (e.g., air temperature reduction); pollution removal; emission of VOCs, which can contribute to ozone formation; and altering of building energy use that make up the total net effect of trees on air quality, particularly ozone (Nowak, 1995). Integrated studies are revealing that the net effect of increased tree cover in urban areas is a reduction in ozone concentrations. A model that simulated of a 20% loss in the Atlanta area forest due to urbanization led to a 14% 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, and 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 basin-wide 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, DC, 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. 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 increasing tree cover 10% within urban areas reduced maximum ozone levels by about 4 ppb, which was about 37% of the amount needed for attainment of the pollutant standard (Luley and Bond, 2002).

Carbon sequestration

Trees can reduce atmospheric carbon dioxide (CO₂), the dominant greenhouse gas, by directly storing carbon (C) from CO₂ as they grow. In addition, urban trees can also reduce CO₂ emissions from power plants by reducing building energy use by lowering temperatures and shading buildings during the summer, and by blocking winds in winter (Heisler, 1986). Healthy trees sequester carbon each year; large, healthy trees sequester about 93 kg C/yr as compared to 1 kg C/yr for small trees. Net annual sequestration by trees in the Chicago area (140,600 t C) equals the amount of carbon emitted from transportation in the Chicago area in about 1 week (Nowak, 1994).

Urban trees in the coterminous United States currently store 700 million metric tons of carbon (335 million t C to 980 million t C; \$14,300 million value) with a gross carbon sequestration rate of 22.8 million t C/yr (13.7–25.9 million t C/yr) (\$460 million/yr) (Nowak and Crane, 2002). The estimated carbon storage by urban trees in United States is equivalent to the amount of carbon emitted from US population in about 5.5 months. National annual carbon sequestration by urban trees is equivalent to US population emissions over a 5-day period (Nowak and Crane, 2002). Carbon storage within cities ranges from 1.2 million t C in New York City and Atlanta to 19,300 t C in Jersey City, NJ (Table 2). The US national average urban forest carbon storage density is 25.1 t C/ha, which compares to 53.5 t C/ha in ex-urban forest stands (Nowak and Crane, 2002).

Stream flows and water quality

To determine the effects of urban trees on water quality, it is important to accurately quantify the effects

Table 2. Estimated carbon storage, gross and net annual sequestration, number of trees, and percent tree cover for 14 cities

City	Storage (tC)		Annual sequestration				No. trees ($\times 10^3$)		Tree cover (%)	
			Gross (tC/yr)		Net (tC/yr)					
	Total	SE	Total	SE	Total	SE	Total	SE	%	SE
New York, NY	1,225,200	150,500	38,400	4300	20,800	4500	5212	719	20.9	2.0
Atlanta, GA	1,220,200	91,900	42,100	2800	32,200	4500	9415	749	36.7	2.0
Sacramento, CA ^a	1,107,300	532,600	20,200	4400	na	na	1733	350	13.0	na
Toronto, Canada ^b	900,600	124,700	36,600	3900	28,300	3700	7542	889	20.5	1.5
Chicago, IL ^c	854,800	129,100	40,100	4900	na	na	4128	634	11.0	0.2
Baltimore, MD	528,700	66,100	14,800	1700	10,800	1500	2835	605	25.2	2.2
Philadelphia, PA	481,000	48,400	14,600	1500	10,700	1300	2113	211	15.7	1.3
Washington, DC	474,000	51,000	14,600	1500	11,700	1300	1928	224	28.6	2.0
Boston, MA	289,800	36,700	9500	900	6900	900	1183	109	22.3	1.8
Beijing, China ^d	224,200	34,100	11,400	1300	na	na	2383	291	17.0	na
San Francisco, CA	176,000	32,000	4600	600	4200	600	668	98	11.9	1.2
Syracuse, NY	148,300	16,200	4700	400	3500	400	891	125	24.4	2.0
Oakland, CA ^e	145,800	4900	na	na	na	na	1588	51	21.0	0.2
Jersey City, NJ	19,300	2600	800	90	600	100	136	22	11.5	1.2

SE, standard error; na, not analyzed.

^aMcPherson (1998).^bMunicipality of Metropolitan Toronto (632 km²); Kenney et al. (2001).^cNowak (1994).^dCentral city area (301 km²); Yang et al. (2005).^eNowak (1993).

of trees on stream flows. Urban trees affect stream flow by intercepting rainfall, transpiring water, affecting evapotranspiration of surrounding areas, and by affecting soil infiltration rates. In addition, urban trees also affect water quality by intercepting atmospheric pollutants, reducing runoff, which indirectly affects water quality, and by increasing infiltration rates in pervious areas. As trees have a relatively large impact on runoff during small frequent storm events and the most water quality control benefit is derived from the treatment of small frequent storms (Department of Irrigation and Drainage, 2000), the potential impact of urban trees on water quality is likely to be significant.

To quantify the effects of urban tree and impervious surfaces on stream flow, a simulation was conducted using the UFORE-Hydro model (Wang et al., in review a, b) on the Dead Run watershed (14.3 km²) in the Baltimore, Maryland region. In the watershed, current tree cover is 13.2% with an impervious cover of 29%. Increasing tree cover in the watershed to 71% (keeping total impervious cover at 29%) is estimated to reduce total runoff in the watershed by about 5% for the simulation period of the year 2000. Increasing impervious area from 29% to 75% (keeping tree cover at 13.2%) increased total runoff by about 50%. These results are annual effects, and variation in tree effects will occur during each season of the year. These types of data can be used to simulate the effects of changes in

urban tree and impervious cover on water quality in future simulations for cities.

Urban forests and environmental programs in the United States

In the United States, there are several environmental programs or protocols where urban trees could make a contribution to improving environmental quality: State Implementation Plans (SIPs) of the Clean Air Act; Total Maximum Daily Loads (TMDL) and Stormwater Program for Municipal Separate Storm Sewer Systems of the Clean Water Act; and the Kyoto Protocols aimed at reducing greenhouse gases. The United States, although a signatory to the protocol, has neither ratified nor withdrawn from the protocol (UNFCCC, 2006a; Wikipedia, 2006).

State implementation plans

The Clean Air Act requires attainment of National Ambient Air Quality Standards (NAAQS) (US EPA, 2006a) for criteria air pollutants that cause human health impacts (e.g., ozone). Each non-attainment state must develop a SIP to attain the NAAQS by the applicable attainment deadlines. In September, 2004, the

US Environmental Protection Agency (EPA) released a guidance document titled “Incorporating Emerging and Voluntary Measures in a State Implementation Plan (SIP)” (US EPA, 2006b). This EPA guidance details how new measures, which may include “strategic tree planting,” can be incorporated in SIPs as a means to help meet air quality standards set by the EPA. Due to the new ozone standards (US EPA, 2006c), many urban areas are designated as non-attainment areas for the ozone clean air standard, and are required to reach attainment typically by 2007–2010 (but up to 2021 for Los Angeles).

As many of the standard strategies to meet clean air standards may not be sufficient to reach attainment, new and emerging strategies (e.g., tree planting, increasing surface albedo) may provide a means to help an area reach compliance with the new clean air standard for ozone. “In light of the increasing incremental cost associated with stationary source emission reductions and the difficulty of identifying additional stationary sources of emission reduction, EPA believes that it needs to encourage innovative approaches to generating emissions reductions” (US EPA, 2006b). This new emerging and voluntary measures document opens the door for urban tree programs to get credit within environmental regulations set to improve air quality (Nowak, 2005). Though this document specifically mentions trees, other environmental quality programs also have the potential to incorporate trees, though current documentation may not specifically mention trees.

TMDL and Stormwater Program for Municipal Separate Storm Sewer Systems

A TMDL specifies the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards, and allocates pollutant loadings among point and non-point pollutant sources. A TMDL is the sum of the allowable loads of a single pollutant from all contributing point and non-point sources. The Clean Water Act, section 303, establishes the water quality standards and TMDL programs. States should describe plans for implementing load allocations for non-point sources, including reasonable assurances that load allocations will be achieved, using incentive-based, non-regulatory or regulatory approaches (US EPA, 2006d).

Stormwater runoff is a leading source of water pollution and can harm surface waters such as rivers, lakes, and streams, which in turn cause or contribute to non-attainment of water quality standards. Stormwater runoff can change natural hydrologic patterns, accelerate stream flows, destroy aquatic habitats, and elevate pollutant concentrations and loadings. Residential and

commercial development substantially increases impervious surfaces where pollutants settle, thereby increasing runoff from city streets, driveways, parking lots, and sidewalks (US EPA, 2006e).

The Stormwater Program for Municipal Separate Storm Sewer Systems is designed to reduce the amount of sediment and pollution that enters surface and ground water from storm sewer systems. Stormwater discharges associated with Municipal Separate Storm Sewer Systems are regulated through the use of National Pollutant Discharge Elimination System (NPDES) permits (US EPA, 2006f). Through this permit, the owner or operator is required to develop a stormwater pollution prevention program that incorporates best management practices (US EPA, 2006e).

As trees can reduce stormwater flow and consequently improve water quality, urban forests have the potential to impact TMDLs and be incorporated in best management practices to reduce sediment and pollution from storm sewer systems. Though trees have the potential to improve water quality, the magnitude of their effect must still be quantified to determine if the effects are significant enough to warrant inclusion in these programs and to identify what types/designs of tree programs are most appropriate for optimal effects on water quality in particular instances.

Kyoto protocol

The average temperature of the earth’s surface has risen by 0.6 °C since the late 1800s and is expected to increase by another 1.4–5.8 °C by the year 2100. Major contributors of carbon dioxide, a dominant greenhouse gas, are fossil fuel emissions and deforestation. Over a decade ago, most countries joined an international treaty – the United Nations Framework Convention on Climate Change – to begin to consider what can be done to reduce global warming. In 1997, governments agreed to an addition to the treaty, called the Kyoto Protocol, which has more powerful (and legally binding) measures. The Protocol entered into force on February 16, 2005 (UNFCCC, 2006b). As urban trees can both directly sequester carbon dioxide, a dominant greenhouse gas, and reduce carbon emissions from power plants, they have the potential to help reduce greenhouse gases and be incorporated with Kyoto Protocols.

Conclusion

Urban forests can improve environmental quality in urban areas. The types and magnitude of these improvements need to be accurately quantified. If vegetation effects are demonstrated to improve environmental quality, then programs/regulations designed to

improve environmental quality can and should consider incorporating urban vegetation as a means to meeting established quality goals. Establishment of urban forestry programs to meet environmental quality standards can be a cost-effective “biotechnological” means to meet multiple standards (e.g., air and water quality, greenhouse gas emission reduction) as trees provide multiple benefits for a singular cost.

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