The Interactions between Urban Forests and Global Climate Change

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INTRODUCTION

Increasing levels of atmospheric carbon dioxide (CO_2) and other "greenhouse" gases (i.e., methane (CH_4), chlorofluorocarbons, nitrous oxide (N_2O), and tropospheric ozone (O_3)) are thought by many to be contributing to an increase in atmospheric temperatures by the trapping of certain wavelengths of heat in the atmosphere. Some chemicals, though, may be reducing atmospheric temperatures (e.g., sulfur dioxide, particulate matter, stratospheric ozone) (Graedel and Crutzen, 1989; Hamburg et al., 1997). Globally averaged air temperature at the Earth's surface has increased between 0.3 and 0.6°C since the late 1800's. The current best estimate of the expected rise in average surface air temperature globally is between 1 to 3.5°C by the year 2100 (Hamburg et al., 1997). Increased atmospheric CO_2 is attributable mostly to fossil fuel combustion (about 80-85% percent) and deforestation (Schneider 1989; Hamburg et al., 1997). Atmospheric carbon is estimated to be increasing by approximately 2.6 billion metric tons annually (Sedjo, 1989).

Urban forests are comprised of all trees within urban areas (Nowak, 1994a). These trees, whether found individually or in stands, can affect global climate change by affecting the urban atmosphere and various chemical emissions. Urban vegetation, because of its close proximity to numerous emissions sources, can have increased impacts on global climate change through both direct (e.g., removal of greenhouse gases) and indirect (e.g., altering nearby emissions) effects. Conversely, changes in urban climate associated with climate change can affect the urban forest. The purpose of this paper is to explore the numerous ways that urban forests and global climate change interact and thereby affect urban and global environmental quality.

URBAN FORESTS

Urban areas[1] (e.g., cities, towns, villages, etc.) currently occupy 3.5% (281,000 km^2) of the conterminous United States and contain approximately 80% of the U.S. population (Dwyer et al., in press).

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[1] urban areas are defined as the area occupied by the union of three census-defined urban designations (U.S. Department of Commerce, Bureau of the Census, 1994): 1) urbanized areas (population of 50,000 or more and a minimum population density of 384 people per square kilometer), 2) places (concentrations of people in incorporated or census-designated areas that have a name, are locally recognized, and are not part of any other place) that contain some urbanized areas within their boundaries, and 3) urban places (places with at least 2,500 people and located outside of urbanized areas). Areas totally surrounded by urbanized areas but not within an urbanized area or place boundary were also considered to be an urban area (Dwyer et al., in press).

Table 1. Estimates of number of trees and tree density (trees/ha) fo cities analyzed with the Urban Forest Effects (UFORE) model (Nowak and Crane, in press; Nowak et al., in review). Estimates of percent tree cover are based on satellite images or sampling of aerial photographs. Data from Oakland, CA (Nowak, 1991) and Chicago, IL (Nowak, 1994b) were not analyzed with UFORE (SE = standard error).

City	Number of trees		Tree density		Tree cover (%)	
	Total	SE	Mean	SE	Mean	SE
Atlanta, GA	9,420,000	749,000	276	22	32.9	na
New York, NY	5,220,000	719,000	65	9	16.6	0.3
Chicago, IL	4,130,000	634,000	68	10	11.0	0.2
Baltimore, MD	2,600,000	406,000	109	17	18.9	na
Philadelphia, PA	2,110,000	211,000	62	6	21.6	0.4
Oakland, CA	1,590,000	51,000	120	4	21.0	0.2
Boston, MA	1,180,000	109,000	83	8	21.2	0.4
Brooklyn, NY	610,000	75,000	33	4	11.4	0.5

na = not analyzed; base data for Atlanta from American Forests; base data for Baltimore from Grove (1996).

Urban areas in the United States are increasing, doubling in size between the late 1960's and early 1990's, with continued projected growth in urban areas globally in the future. Tree canopies cover 27% of U.S. urban areas (Dwyer et al., in press) with cities developed in forested areas having the highest percent canopy cover (31%), followed by cities developed in grasslands (19%) and deserts (10%) (Nowak et al., 1996). Overall, there are an estimated 3.8 billion urban trees in the conterminous United States, with the states with the most urban trees being Georgia (233 million), Alabama (206 million), and Ohio (191 million) (Dwyer et al, in press). Tree cover and tree population totals vary among cities (Table 1).

Within cities, land uses that dominate the landscape are residential (41% of city area), followed by vacant (24%), commercial/industrial (13%), other (agriculture, transportation and miscellaneous) (12%), institutional (6%), and parks (5%) (Nowak et al., 1996). In cities developed in forests, park and vacant land had the highest percent tree cover; in grassland and desert cities, percent tree cover was highest on park and residential lands. Surrounding ecoregion and land use distribution are two dominant factors that determine the amount of trees and canopy cover in urban areas (Nowak et al., 1996).

In addition to differences exhibited in tree cover both among and within cities, differences in tree species composition and sizes are also exhibited (Nowak, 1991, 1994b; Nowak et al., in review; McPherson, 1998). Urban forests tend to have higher species richness and diversity than natural forests due to multiple land managers and introduced plants into urban areas. In Oakland, CA, over 350 tree species were identified with a Shannon-Weiner diversity index value of 5.1 (Nowak, 1993a). In Brooklyn, NY, 57 tree species were sampled with a diversity index value of 3.4 (Nowak et al., in press). Natural forests in the eastern United States typically have diversity index values from approximately 1.7 to 3.1 (Barbour et al., 1980).

These data on the urban forest reveal that it is a significant resource with variability in the amount and type of vegetation both within and among urban areas. The urban forest, because of its close proximity to people and numerous emission sources, currently affects global climate change and has the potential for greater beneficial effects through proper design and management. Due to the diversity of the resource, actual and potential effects of the urban forest will vary among urban areas.

URBAN FOREST EFFECTS ON GLOBAL CLIMATE CHANGE

There are four main ways that urban forests can affect global climate change: 1) by removing various atmospheric chemicals (e.g., CO_2); 2) by emitting various atmospheric chemicals either directly from the vegetation or indirectly through vegetation maintenance practices; 3) by altering urban microclimates (e.g., air temperature reductions); and 4) by altering building energy use and consequently emissions from power plants (Nowak, 1995). Greenhouse gases that are most affected by urban forests and urban forest management are CO_2, tropospheric O_3, and SO_2.

Chemical Removal. Trees, through their growth process, remove CO_2 from the atmosphere and sequester the carbon within their biomass. In addition, trees offer a large leaf surface area upon which particles can be deposited and various gases removed, primarily via leaf stomata (Smith, 1990). For the most part, the net carbon sequestered from afforestation or reforestation programs is the carbon sequestered by the first generation of trees. Future generations of trees sequester back the carbon lost through decomposition of previous generations. Thus, the net carbon storage in a given area with a given tree composition will cycle through time as the population grows and declines (Figure 1). When

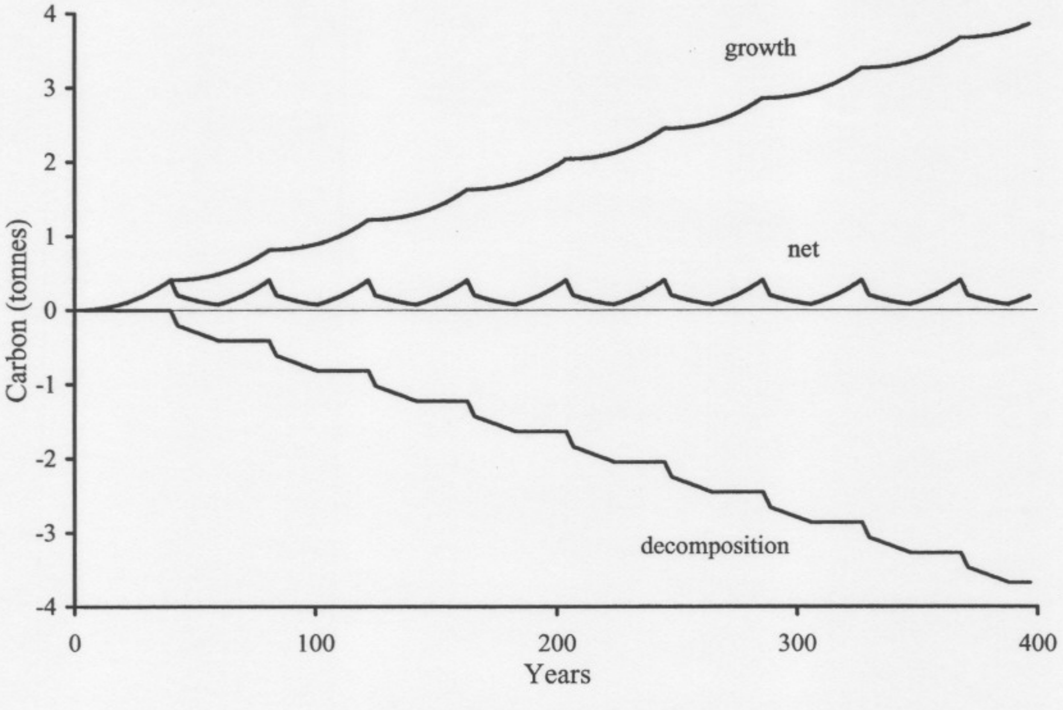

Figure 1. Cumulative annual carbon sequestration (growth), cumulative annual carbon emission due to decomposition (mulching of tree at removal), and net annual carbon effect (sequestration - emission) for a red maple with a 40-year life span with a similar tree replanted immediately following tree removal. After a tree is removed, the tree eventually decomposes and the carbon stored in that tree is emitted back to the atmosphere. The maximum amount of carbon stored at one individual tree site through time is equal to the amount stored by one tree at maturity. All carbon sequestered by subsequent trees grown on that same individual tree site will be offset by carbon emissions due to decomposition of the tree previously on the site. Thus, if fossil-fuels are not used in managing the vegetation, net carbon sequestered at a site cycles through time but remains positive (Nowak et al., in preparation).

forest growth (carbon accumulation) is greater than decomposition, net carbon storage increases.

Net carbon storage in the entire ecosystem may increase slightly through time if the soil environment reduces the decomposition rate. A reduction in decomposition will allow carbon from past generations of trees to accumulate in the forest ecosystem, thereby increasing the net long-term carbon storage of the forest. However, there will be no net gain in soil carbon storage when soil decomposition rates approach the rate of carbon input into the soil. For non-urban forest ecosystems in the United States, 61% of the total carbon is stored in the soil environment (Birdsey and Heath, 1995). The amount of carbon from trees that is retained in urban soils, its residence time, and the amount of carbon currently stored in these soils remain to be investigated. It is likely, however, that urban soils contain less carbon per hectare than forest soils due to lower carbon inputs and increased soil decomposition rates due to warmer air and soil temperatures (e.g., Pouyat et al., 1997).

When forests are removed, the net carbon storage will diminish through time as accumulated carbon in both trees and soil will convert back to CO_2 through decomposition. Various management practices can be used to help enhance the long-term impacts of forests on atmospheric carbon. Utilization of tree biomass into long-term products, or disposing of biomass in locations that reduce decomposition (e.g., landfills), will delay carbon releases for long periods. In addition, utilizing trees for energy production can reduce carbon emissions from fossil fuels by reducing use of these fuels for energy use (Nowak et al., in preparation).

Carbon storage by trees in urban forests nationally has been estimated at between 660 to 990 million tonnes (Nowak, 1994c). Carbon storage in individual urban forests ranges between 145,800 tonnes (11 tC/ha) in Oakland to 854,800 tonnes (14.1 tC/ha) in Chicago (Table 2). Total carbon storage by trees in Chicago, which took years to sequester, is equivalent to carbon emissions from the residential sector of Chicago during a 5-month period (Nowak, 1994c). Carbon storage in Brooklyn (152,200 tonnes) is equivalent to the amount of carbon emitted from Brooklyn's population in about 4 days based on average per capita emission rates (Nowak et al., in review). Annual estimated gross sequestration rates for trees in individual cities are 4,700 tonnes in Brooklyn (0.3 tC/ha/yr) and 40,100 tonnes (0.7 tC/ha/yr) in Chicago (Table 2). The gross sequestration rates compare with 2.6 t/ha/yr for a 25-year-old loblolly pine plantation with genetically improved stock on a high yield site, and 1.0 t/ha/yr for a 25-year-old natural regeneration spruce-fir forest on an average site (Birdsey, 1996). Net annual sequestration (gross sequestration minus estimated carbon emissions due to mortality [decomposition]) are estimated as 14,400 tonnes for Chicago (Nowak, 1994c) and -3,300 tonnes for Brooklyn (Nowak et al., in review).

Table 2. Estimated carbon storage (above- and belowground), gross annual sequestration, and net annual sequestration (gross sequestration minus carbon losses due to tree mortality [decomposition]) by trees in Brooklyn, NY; Chicago, IL, and Oakland, CA (Nowak, 1993b; Nowak 1994c; Nowak et al., in review).

	Total Storage		**Gross Sequestration**		**Net Sequestration**	
City	**(tC)**	**(tC/ha)**	**(tC/yr)**	**(tC/ha/yr)**	**(tC/yr)**	**(tC/ha/yr)**
Chicago, IL	854,800	14.1	40,100	0.7	14,400	0.2
Brooklyn, NY	152,200	8.3	4,700	0.3	-3,300	-0.2
Oakland, CA	145,800	11.0	na	na	na	na

na - not analyzed

Based on data from five cities, pollution removal by urban forests ranges between 255 t/yr in Brooklyn and 1,821 t/yr in New York City (Table 3). Factors affecting the amount of pollution removed by an urban forest include amount of tree cover, leaf area index, length of growing season, meteorology (e.g., air temperature, wind speed, precipitation), and pollution concentration (Nowak et al., 1998).

Chemical emissions. Urban forests lead to the emission or formation of various greenhouse gases in two ways: 1) emission of various trace gases by plants, and 2) emission of gases due to urban tree maintenance (e.g., from vehicles, chain saws, backhoes, etc.). Plants emit varying amounts of chemicals, which include volatile organic compounds (VOCs) and sulfur compounds (Sharkey et al., 1991). VOC emissions by trees vary with species, air temperature, and other environmental factors (e.g., Tingey et al., 1991; Guenther et al., 1994). VOCs contribute to the formation of ozone and carbon monoxide (Brasseur and Chatfield, 1991), and eventually CO_2. However, because the carbon used to form the VOCs originally comes from CO_2, VOC emissions should not be considered as contributing to increasing CO_2 concentrations.

Table 3. Total estimated pollution removal (tonnes) by trees during nonprecipitation periods (dry deposition) for New York, NY[a], Atlanta, GA[b], Chicago, IL[c], Baltimore, MD[d], and Brooklyn, NY[e]. Estimates are for ozone (O_3), particulate matter less than 10 microns (PM10), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO). Numbers in parentheses represent expected range of values (no range determined for CO or Chicago).

Pollutant	New York	Atlanta	Chicago	Baltimore	Brooklyn
O_3	506	514[f]	191	180	76[g]
	(124-631)	(101-604)		(42-221)	(20-114)
PM10[h]	470	406	212	137	68
	(182-834)	(157-706)		(53-239)	(26-106)
NO_2	510	145	89	115	63
	(216-593)	(72-165)		(48-134)	(30-92)
SO_2	238	95	84	55	33
	(117-358)	(42-137)		(26-85)	(17-58)
CO	97	35	15	13	15
Total	**1,821**	**1,196**	**591**	**499**	**255**
	(736-2,514)	**(407-1,648)**		**(181-692)**	**(108-385)**

[a] 800 km^2; 16.6% tree cover; assumed leaf area index of 6; 1994 pollution and meteorological data (Nowak and Crane, in press)

[b] 341 km^2; 32.9% tree cover; assumed leaf area index of 6; 1994 pollution and meteorological data (Nowak and Crane, in press)

[c] 603 km^2; 11.0% tree cover; measured leaf area index of 6; 1991 pollution and meteorological data (Nowak, 1994d)

[d] 209 km^2; 18.9% tree cover; assumed leaf area index of 6; 1994 pollution and meteorological data (Nowak and Crane, in press)

[e] removal by both trees and shrubs; 182 km^2; 11.2% tree cover; 3.1% shrub cover; measured tree leaf area index of 4.2; measured shrub leaf area index of 2.4; 1994 pollution and meteorological data (Nowak et al., in review)

[f] Average national O_3 monthly trend data were used to estimate missing data for Jan., Feb., and Dec.

[g] Average national O_3 monthly trend data were used to estimate missing data for Jan. and Feb.

[h] Assumes 50% resuspension of particles.

Because urban tree management often uses relatively large amounts of energy, primarily from fossil fuels, to maintain the vegetation structure, the emissions from maintenance / management activities need to be considered in determining the ultimate net effect of urban forests on global climate change. Various types of equipment are used to plant, maintain, and remove vegetation in cities. This equipment includes vehicles for transport or maintenance, chain saws, back hoes, leaf blowers, chippers, and shredders. The use and combustion of fossil fuels to power this equipment leads to the emission of CO_2 (approximately 0.7 kg/l of gasoline, including manufacturing emissions; Graham et al., 1992) and other chemicals such as VOCs, carbon monoxide, nitrogen and sulfur oxides, and particulate matter (USEPA, 1991).

Though the total emission of atmospheric chemicals due to maintenance activities is currently unknown, they could significantly reduce the possible beneficial effects of urban forests on global climate change. If trees are maintained using fossil fuels and secondary tree effects do not exist (e.g., trees in locations away from emission sources), urban forests will ultimately be net emitters of carbon to the atmosphere as at some point in the future, carbon emissions due to maintenance activities will exceed the total storage capacity of the tree or stand (Figure 2). The number of years until carbon emissions exceed the carbon capacity of the site vary by tree species, tree density and maintenance intensity. For maintained trees that do not survive the first few years of establishment, carbon deficits can occur from the onset because the carbon return from the trees is less than the initial carbon inputs invested into planting the trees (Nowak et al., in preparation).

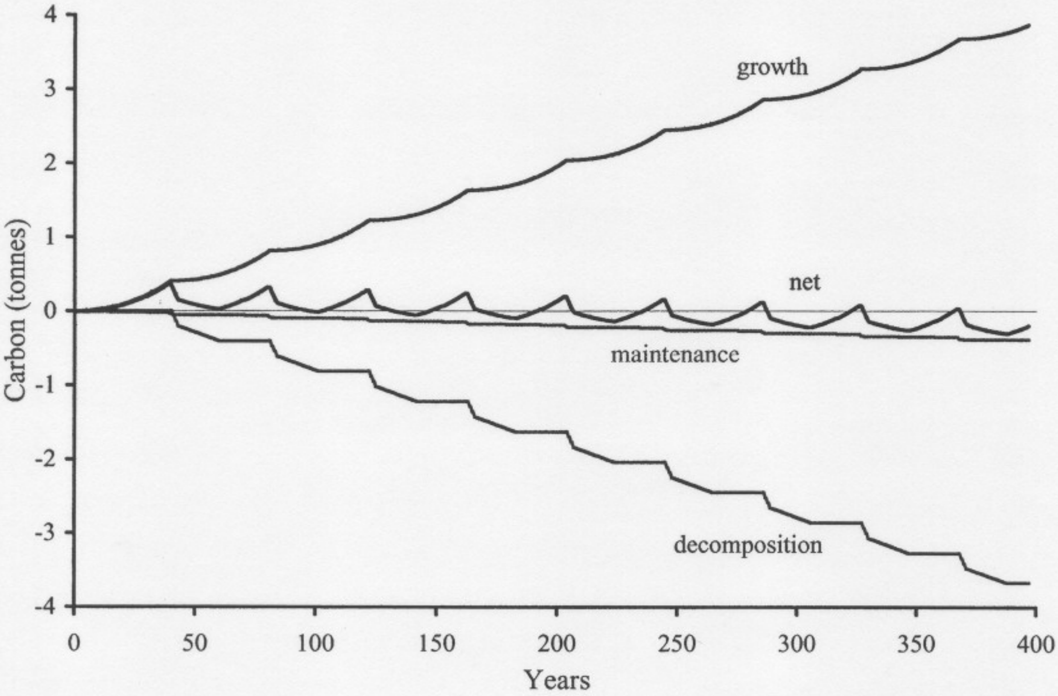

Figure 2. Cumulative annual carbon sequestration (growth), cumulative annual carbon emission due to decomposition (mulching of tree at removal), cumulative annual carbon emissions due to tree maintenance (planting; 15 year pruning cycle; tree removal), and net annual carbon effect (sequestration - decomposition emission - maintenance emission) for a red maple with a 40-year life span with a similar tree replanted immediately following tree removal. When fossil fuels are used to manage or maintain vegetation, the carbon emissions will offset the carbon gains through time and eventually more carbon will be emitted due to maintenance activities than will be sequestered by a tree. This point when carbon emissions become greater than carbon sequestered is referred to as the "break-even point" and will vary depending on tree species, maintenance activities, and disposal/utilization of removed trees. The larger the break-even point, the more beneficial the species and/or management activities are for reducing atmospheric carbon (Nowak et al., in preparation).

Urban Microclimates. 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 (e.g., Heisler et al., 1995; Berman et al., 1997). Maximum mid-day air temperature reductions due to trees are in the range of 0.04°C (Sailor et al., 1992) to 0.2°C (Taha et al., 1991) per percent canopy cover increase (Simpson, 1998). Below individual and small groups of trees over grass, midday air temperatures at 1.5 m above ground are 0.7°C to 1.3°C cooler than in an open area (e.g., Souch and Souch, 1993). Although trees usually contribute to cooler summer air temperatures, their presence can increase air temperatures in some instances (Myrup et al., 1991). In areas with scattered tree canopies, radiation can reach and heat 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).

Changes in urban microclimate can affect pollution emission and formation, particularly the formation of ozone. Cardelino and Chameides (1990) revealed that a 20 percent loss in the Atlanta area forest due to urbanization could have led to a 14 percent increase in O_3 concentrations for the modeled day. 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 O_3 chemistry such that concentrations of O_3 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 boundary layer heights, which, in turn, affect ozone concentrations (Nowak et al., in press).

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

Building energy use. Planting trees in energy-conserving locations around buildings (e.g., Heisler, 1986) can reduce building energy use and consequently chemical emissions from power plants. In a simulation of planting 10 million trees annually in energy conserving locations over a 10-year period with 100% survival rates, carbon storage by these trees at year 50 was estimated to be 77 million tonnes of carbon, with carbon avoidance from power plants at 286 million tC (Nowak, 1993b). In this case, the potential carbon avoidance was four times greater than the direct carbon sequestration rate. The total carbon stored and avoided by the 100 million trees (363 million tC) is less than 1% of the estimated amount of carbon emitted in the United States over the same 50-year period. Increasing fuel efficiency of passenger automobiles by 0.5 km/l over 50 years would also produce the same carbon effects as the 100 million trees (Nowak, 1993b).

Although carbon storage in urban trees is only a fraction (4-5%) of carbon storage in trees in all forests of the United States (Birdsey, 1992), the relatively high secondary effects of reducing carbon emissions (e.g., energy conservation, reduced air temperatures) gives urban trees a greater per tree effect on reducing greenhouse gas concentrations than non-urban trees. These secondary effects are likely more important than the primary effects of direct carbon sequestration as most carbon stored by trees will eventually be released back to the atmosphere through decomposition after the tree dies, though a fraction of the carbon can be retained in the soil. Secondary tree effects that avoid carbon emissions are of permanent benefit to reducing global climate change.

Tree species and size effects. Tree species selection within urban forests can influence the overall forest effect on global climate change. In addition to choosing species that are well-adapted to the site to reduce maintenance needs and increase longevity, tree species characteristics can influence chemical removal, chemical emissions, urban microclimate, and building energy conservation.

To enhance transpirational cooling, and thereby reduce air temperatures and temperature dependent VOC emissions, trees with relatively high leaf surface areas and transpiration rates should be used. Besides location around buildings, tree size, transpiration, and leaf and branching density can also influence building energy use (Heisler, 1986; McPherson, 1994).

Large trees (with healthy leaf surface area) will increase carbon sequestration and pollution removal rates. Large healthy trees greater than 77 cm in diameter sequester approximately 90 times more carbon and remove 70 times more air pollution annually than small healthy trees less than 8 cm in diameter (Nowak, 1994c,d) (Figure 3). Large trees also store approximately 1,000 times more carbon than small trees (Figure 4). Tree species with relatively long life spans will have the greatest overall positive effect on carbon dioxide as carbon emissions due to tree planting and removal will happen less frequently (Nowak et al., in preparation).

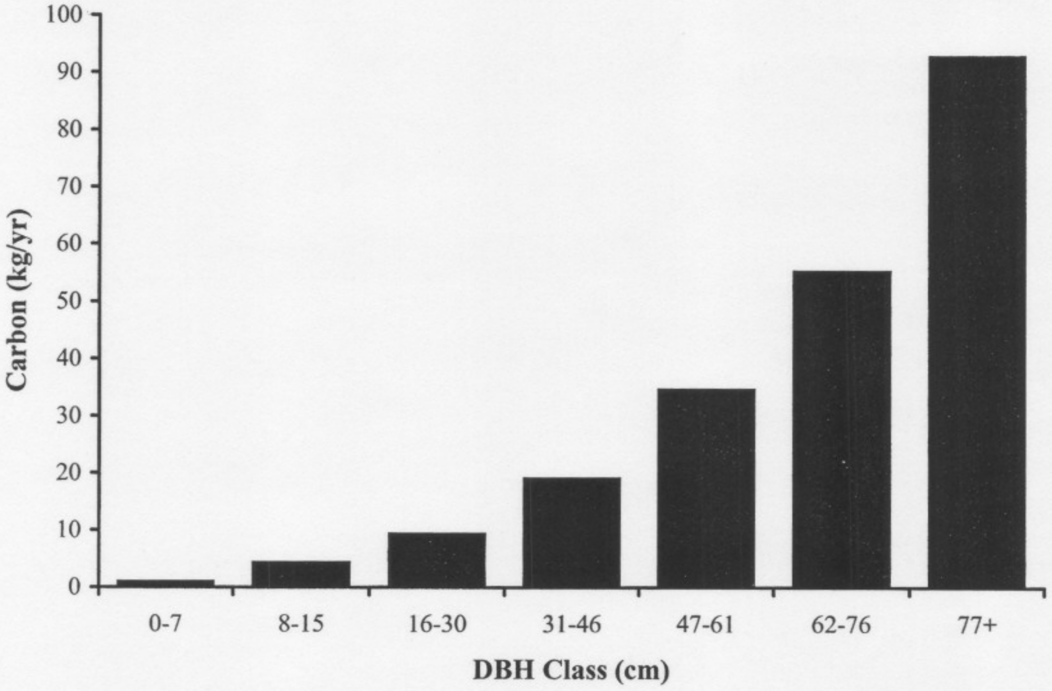

Figure 3. Estimated average annual carbon sequestration by an individual urban tree by diameter (dbh) class (Nowak, 1994c).

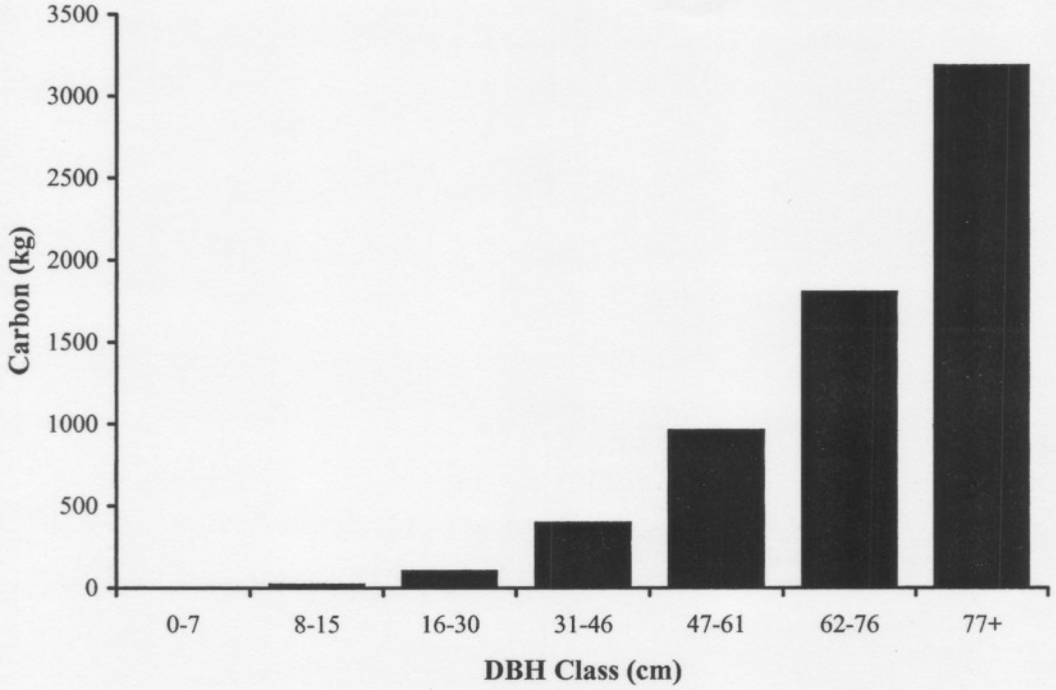

Figure 4. Estimated average carbon storage by an individual urban tree by diameter (dbh) class (Nowak, 1994c).

VOC emission rates also vary by species. Nine genera that have the highest standardized isoprene emission rate (70 μgC/g leaf wt/hr standardized to 30°C and 1,000 μmol/m^2/s (Geron et al., 1994; Geron, pers. comm., 1999; Nowak et al., in review)), and therefore the greatest relative effect among genera on increasing ozone, are: beefwood (*Casuarina* spp.), *Eucalyptus* spp., sweetgum (*Liquidambar* spp.), black gum (*Nyssa* spp.), sycamore (*Platanus* spp.), poplar (*Populus* spp.), oak (*Quercus* spp.), black locust (*Robinia* spp.), and willow (*Salix* spp.). However, due to the high degree of uncertainty in atmospheric modeling, and the complexities and variations of modeling individual city conditions, 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, NY, 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., in review).

GLOBAL CLIMATE CHANGE EFFECTS ON THE URBAN FOREST

Global climate change is projected to increase average surface air temperature globally between 1 to 3.5°C by the year 2100, increase the frequency and duration of extreme events such as heavy rains and droughts, and decrease the available soil moisture for plants during the summer (Hamburg et al., 1997). As urban areas typically have warmer air temperatures (due to the urban heat island effect), lower humidity, and increased precipitation than rural environs (Oke, 1978; Landsberg, 1981), forest stands in urban areas offer a potential laboratory for studying the effects of global climate change and urbanization (e.g., increased air pollution) on forest stand structure and function (e.g., McDonnell et al., 1993).

As urban areas already exhibit climatic differences compared to rural environs, due in part to the multiple artificial surfaces and high level of fossil fuel combustion, climate change impacts may be exacerbated in these areas. These environmental changes can affect urban forest structure and functions in multiple ways.

Tree stress and/or decline may be increased due to elevated air temperatures, possible increased air pollution concentrations due to temperature change, limited moisture, and intensified storm damage. Conversely, some trees/plants may benefit from increased air temperatures (e.g., trees planted in cooler environments than in their native range; xerothermic plants) (e.g., Sukopp and Werner, 1983), increased air pollutants (e.g., sulfur and nitrogen) that can have a fertilizing effect (NAPAP, 1991), and/or increased CO_2 levels that may enhance growth rates (McGuire and Joyce, 1995).

If the environmental plant stresses induced by global climate change affect plant functioning by reducing tree growth and transpiration, then urban forest carbon sequestration and air pollution removal could decrease, and urban air temperatures rise even higher. Loss of these tree effects could feedback into an increase in urban chemical emissions and global climate change.

However, if plant functioning is not, or only minimally, diminished by climate change in cities (e.g., via supplemental watering and/or fertilization), then carbon sequestration and pollution removal by trees may be enhanced with increased concentrations of CO_2 and air pollutants (e.g., McGuire and Joyce, 1995; Baldocchi et al., 1987). If pollutant concentrations become so high that plant function is affected (e.g., stomata close) (e.g., Saxe, 1991), increased pollution concentrations may decrease the effectiveness of trees in removing air pollution.

Increased plant stress/decline and/or storm damage frequency/intensity has the potential to increase tree maintenance activities needed to sustain healthy tree cover, thereby increasing associated fossil fuel emissions. In addition, if tree stress/mortality increases in urban areas, it is likely that management will respond with changes in species composition toward species better adapted to the new urban environment. These potential changes in species composition will consequently affect such forest attributes as biodiversity, wildlife habitat, and human preferences/attitudes towards urban vegetation.

Along with changes in urban forest structure due to humans, natural changes may occur in unmanaged areas as species compositions shift with altered environments (e.g., Iverson and Prasad, 1998; Iverson et al., 1999). Insect and disease compositions and prevalence may also be altered in urban areas due to global climate change. These potential changes in pest populations may lead to changes in management activities (i.e., fossil fuel emissions) and species health and composition.

The degree to which global climate change will affect urban forest structure and function is dependent upon the degree to which urban environments change, how the diverse plant population responds to the changes, and the degree to which tree maintenance activities can or do mitigate the effects of the changes. Due to the relatively high degree of maintenance / management activities in urban areas, effects of global climate change may be accelerated or reduced in cities depending upon whether managers tend to alter plant populations toward better adapted species or attempt to minimize the impact of global climate change through enhanced maintenance activities (e.g., watering, fertilization).

CONCLUSION

Urban forests can help mitigate global climate change, though the effects are relatively minimal compared to total emissions from urban areas. Carbon and pollutant emissions associated with tree maintenance can detract from the total forest carbon and pollution benefits. However, urban trees offer some of the greatest per tree benefits for reducing global climate change because of their secondary effects on urban emissions that are yielded due to the forest's proximity to numerous emission sources. In addition, the forest's close proximity to a large portion of the U.S. population enhances the forest's ability to offer numerous other benefits to enhance human health and environmental quality. Urban forests also offer a potential laboratory to help study the potential impacts of global climate change and urbanization on forest ecosystems.

Urban forest management strategies to help mitigate global climate change include:

- Increase the number of healthy trees (increases pollution removal and carbon sequestration)
- Sustain existing tree cover (maintains current carbon storage and pollution removal levels)
- Maximize use of low VOC-emitting trees (reduces ozone and carbon monoxide formation)
- Sustain large, healthy trees (large trees have greatest per tree effects)
- Use long-lived trees (forestalls carbon emissions from decomposition)
- Use low-maintenance trees (reduces pollutants emissions from maintenance activities)
- Reduce fossil fuel use in maintaining vegetation (reduces chemical emissions)
- Plant trees in energy-conserving locations (reduces chemical emissions from power plants)
- Plant trees to shade parked cars (reduces vehicular VOC emissions)
- Supply ample water to vegetation (enhances pollution removal and temperature reduction)
- Plant trees in polluted areas or heavily populated areas (maximizes tree effects)
- Avoid pollutant-sensitive species (increases tree health)
- Utilize evergreen trees for particulate matter reduction (year-round removal of particles)
- Utilize wood for long-term products (forestalls carbon emissions from decomposition)
- Utilize tree materials for energy production (reduces chemical emissions from power plants)

As urbanization continues to increase on a global scale, the effects of urban forests and proper urban forest management will become increasingly important to enhance human health and global environmental quality.

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GLOBAL CLIMATE CHANGE

& The Urban Forest

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GCRCC, U.S. Federal Building, Baton Rouge, LA 70821-4292
Franklin Press, Inc. • 1391 Highland Road • Baton Rouge, LA 70802

GLOBAL CLIMATE CHANGE & The Urban Forest

Production supervision and interior design: Franklin Press, Inc.

Photos: Eyewire Studios, White House Office of Science and Technology Policy (OSTP) , American Forests (AF), and United States Department of Agriculture, Forest Service (USDA-FS)

Editors: Kamran K. Abdollahi, Zhu Hua Ning and Alexander Appeaning

Printed / Published in 2000 by Franklin Press, Inc and GCRCC.

ISBN 1-930129-62-9

Library of Congress Card Number : 00-103362
Catalog record available from the Library of Congress.

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Direct all inquiries to GCRCC, U.S. Federal Building, Baton Rouge, LA 70821-4292

International Standard Book Number (ISBN) 1-930129-62-9
Printed in the United States of America by Franklin Press, Inc
10 9 8 7 6 5 4 3 2 1 .