

Quantifying urban forest structure, function, and value: the Chicago Urban Forest Climate Project

E. GREGORY McPHERSON*

Pacific Southwest Research Station, USDA Forest Service, c/o Department of Environmental Horticulture, University of California, Davis, CA, USA

DAVID NOWAK and GORDON HEISLER

USDA Forest Service, Northeastern Forest Experiment Station, Syracuse, NY, USA

SUE GRIMMOND

Department of Geography, Indiana University, Bloomington, IN, USA

CATHERINE SOUCH

Department of Geography, Indiana University/Purdue University, Indianapolis, IN, USA

RICH GRANT

Department of Agronomy, Purdue University, West Lafayette, IN, USA

ROWAN ROWNTREE

USDA Forest Service, Pacific Southwest Research Station, Albany, CA, USA

This paper is a review of research in Chicago that linked analyses of vegetation structure with forest functions and values. During 1991, the region's trees removed an estimated 5575 metric tons of air pollutants, providing air cleansing worth \$9.2 million. Each year they sequester an estimated 315 800 metric tons of carbon. Increasing tree cover 10% or planting about three trees per building lot saves annual heating and cooling costs by an estimated \$50 to \$90 per dwelling unit because of increased shade, lower summertime air temperatures, and reduced neighborhood wind speeds once the trees mature. The net present value of the services trees provide is estimated as \$402 per planted tree. The present value of long-term benefits is more than twice the present value of costs.

Keywords: urban forests; urban ecology; urban climate; hydroclimate; air pollution; energy conservation; carbon removal; benefit-cost analysis

Urban forests are small pockets of green in a gray landscape. They are ribbons of life meandering through a largely artificial environment. They are enclaves of serenity and biological diversity tucked within suburban development and busy streets. The worldwide trend toward urbanization threatens the 'green infrastructure' of our cities, making the need to understand these ecosystems increasingly important.

In the United States, downsizing of local governments has led to drastic cuts in spending for urban

*Author to whom correspondence should be addressed.

forest management, and some management activities have shifted from government tree divisions to community service groups. As nonprofit organizations enlist support from local businesses, utilities, and neighborhoods, the notion of urban forestry has broadened from street tree to urban ecosystem management. Research quantifying the structure, function, and value of urban ecosystems is critical to sustaining healthy and productive community forests because it can be used by 1) potential partners to evaluate return on urban forest investments, 2) managers to use limited resources more cost effectively, and 3) nonprofit organizations to instruct citizens about the value of trees.

This paper reviews research concerning urban forest structure, function, and value, with emphasis on results from the Chicago Urban Forest Climate Project (CUFCP). We focus on the CUFCP because it linked a comprehensive analysis of urban forest structure to related analyses of forest functions and values (McPherson *et al.*, 1994). Because of the need for brevity, we highlight results quantifying urban forest impacts on energy conservation and net benefits of tree planting and care in Chicago, while citing other published literature for the interested reader.

Conceptual approach to structure, function, and value

The value of an urban forest is equal to the net benefits that members of society obtain from it. To estimate urban forest benefits, several relationships must be evaluated. First, relations between existing urban forest structure and associated ecological processes need to be understood. Here, 'structure' refers to the way vegetation is arrayed in relation to other objects such as buildings (Rowntree, 1984; Nowak, 1994a). For instance, urban heat island (UHI) intensity is influenced by tree canopy cover. Functional relationships consider changes in ecological processes and environmental quality. Understanding this linkage requires knowledge of how changes in forest structure influence ecological processes, which in turn affect environmental quality. Using the UHI example, increasing forest cover can modify fluxes of energy and water, thereby changing air temperatures, wind fields, and air pollution concentrations.

Value relationships consider the impact and response of receptor populations and the change in environmental quality. This relationship is interpreted differently depending on the characteristics of specific stakeholders. For instance, lower summertime air temperatures associated with UHI mitigation may be associated with reductions in air conditioning demand by electric utilities, lower medical expenses for at-risk populations, and reduced ozone pollution levels by air quality managers. Finally, impacts and responses are converted into dollar values by determining the value that the public attaches to them. The value that individuals place on changes in environmental quality is measured as their willingness to pay for them or compensation required to accept a change. Therefore, the term urban forest 'function' refers in general to goods and services that urban forests produce, such as UHI mitigation (Rowntree, 1986, 1995). 'Value' refers to the benefits and costs society derives from the urban forest. Research in urban environments is just beginning to reveal the nature of interrelationships between forest structure, function, and value.

Urban forest structure

The structure of an urban forest reflects the historic interactions between a host of cultural and ecological factors (Schmid, 1975; Lawrence, 1993; Bradley, 1995). Natural factors such as a region's climate, soils, storm patterns, and the composition of presettlement vegetation influence current forest structure and shape perceptions of desired forest structure (McBride and Jacobs, 1986; Nowak, 1993). The physical development of cities influences the space available for vegetation and its distribution (Sanders 1984). Technological advances in areas such as transportation, air conditioning, and pest control influence

attitudes regarding the value of trees, as well as their preservation and management (McPherson and Haip, 1989; McPherson and Luttinger, submitted). Historical data on the development of urban forests can be used with information on current forest structure to better understand key forces of change, current management needs, and future trends in forest health and productivity.

Traditionally, information on urban forest structure has consisted of street and park tree data collected for municipal forest management. However, the emergence of nonprofit organizations, electric utilities, riparian woodlands restoration groups, and other new partners in community forestry has increased the need for information on vegetation throughout the urban area. For example, electric utilities are interested in potential shade tree planting opportunities near residential buildings for energy conservation, whereas groups working on streams need information related to understory vegetation, tree canopy cover, species composition, and regeneration. As the notion of urban forestry broadens from street tree management to urban ecosystem management, a corresponding need exists for greater information about urban natural resources. In the next section we describe key findings of an extensive survey of vegetation on private and public property throughout the 3346 km² (1292 square mile) CUFCP study area.

Chicago's urban forest structure was determined using canopy cover analysis, ground surveys, tree-ring analysis, and sampling of foliar and woody biomass from individual trees. For structural analyses, the Chicago region was divided into three sectors: 1) Chicago, 2) Cook County (exclusive of Chicago), and 3) DuPage County. We found that the region's tree cover has increased from a presettlement level of about 13% to nearly 20% today. Canopy cover is 11% in Chicago, where dense development restricts opportunities for trees; 23% in Cook County, where older neighborhoods are well stocked; and 19% in DuPage County, where new developments are being planted (McPherson *et al.*, 1993). The distribution of tree density along a urban-rural gradient (McDonnell *et al.*, 1993) from Chicago to DuPage County parallels the pattern of tree cover. Tree density is highest in Cook (169 trees/ha) and DuPage (173 trees/ha) Counties and lowest in Chicago (68 trees/ha) (Nowak, 1994b).

Many-tree-related benefits are linked to their leaf area (e.g. interception, evapotranspiration, and shading). Leaf-area formulas were developed and applied to trees sampled in ground surveys to estimate total leaf surface area for various land uses. Trees growing on low-density (one to three families) residential land and institutional lands dominated by vegetation (e.g. parks, forest preserves, golf courses) account for 50 and 38% of total tree leaf surface area, respectively. Therefore, trees in these areas are likely to play a primary role in creating regional benefits. Forest preserves and other vacant, natural, and wild lands were generally dominated by smaller trees, whereas more intensively managed street and residential sites had a higher proportion of large trees.

Of the estimated 50.8 million trees in the Chicago region, 66% are in good or excellent condition. The diameter distributions of trees in Chicago, Cook, and DuPage Counties are relatively similar, as shown for the entire region in Fig. 1. Chicago has the highest percentage of large street trees (greater than 46 cm dbh), whereas Cook County has the highest percentage of medium street trees, and DuPage County has the highest percentage of small street trees (0–7 cm). Although street trees in the City of Chicago comprise only 10% of the city's tree population, they comprise 24% of total leaf surface area because of their relatively large size.

The most common tree in the Chicago region is buckthorn (*Rhamnus* spp.), an exotic and highly invasive species (Table 1). Buckthorn accounts for about 13% of the tree population, but only 3% of total leaf surface area because of its small size. Common native pioneer species include green/white ash (*Fraxinus pennsylvanica/americana*), boxelder (*Acer negundo*), willow (*Salix* spp.), and cottonwood (*Populus deltoides*). These relatively short-lived opportunistic species are especially abundant on vacant, institutional, and residential land uses, where they 'volunteer.' Managing urban forest stands to control the invasion and spread of trees such as buckthorn continues to be a formidable challenge.

The distribution of street tree species is less equitable than for all trees, with four species comprising

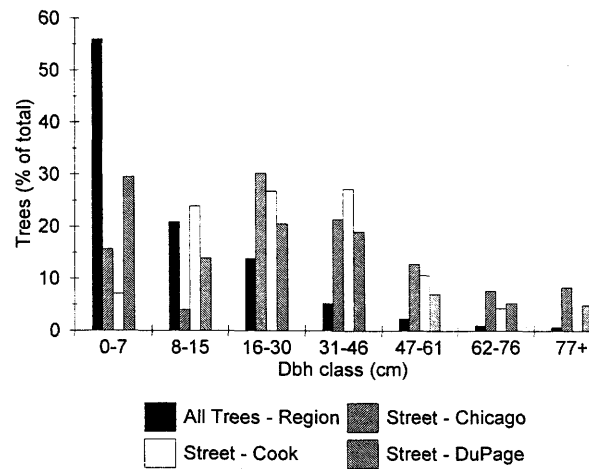


Figure 1. Small trees dominate the population of all trees in the region, whereas street trees include a higher proportion of larger trees. Chicago has the most large street trees and DuPage County has the most small street trees (from Nowak 1994b).

two thirds of the population (Table 1). Reliance on these few species suggests the need to be concerned for the population's overall stability. Introduction of a harmful disease or pest could result in significant change in the street tree population and substantial treatment, removal, and replanting costs. Personal observation indicates reduced planting of problem trees such as silver maple (*Acer saccharinum*), American elm (*Ulmus americana*), and honeylocust (*Gleditsia triacanthos*), and increased testing of disease-resistant elms and other new introductions from sources such as the Morton Arboretum.

Urban forest functions

The influence of urban forests on the physical and biological environment, as well as their socioeconomic importance has been compiled in journal articles (Rowntree, 1986, 1988; Ulrich, 1986; Oke, 1989; Dwyer *et al.*, 1992). The benefits of specific urban forest functions can be maximized by configuring vegetation in patterns that are unique to each landscape's purpose. In *Urban Forest Landscapes: Integrating Multidisciplinary Perspectives*, the authors explain the structures of landscapes designed for

Table 1. Composition of tree species on streets and all lands for the entire study area

Rank	Street tree species	%	All trees	%
1	Silver maple (<i>A. saccharinum</i>)	21.5	Buckthorn (<i>Rhamnus</i> spp.)	12.7
2	Green/white ash (<i>F. pennsylvanica/americana</i>)	19.4	Green/white ash	9.1
3	Norway maple (<i>Acer platanoides</i>)	17.9	Cherries, plums, peaches	8.1
4	Honeylocust (<i>G. triacanthos</i>)	9.0	Boxelder (<i>A. negundo</i>)	7.0
5	Cherries, plums, peaches (<i>Prunus</i> spp.)	5.4	American elm	5.7
6	Sugar maple (<i>A. saccharum</i>)	4.1	Hawthorn (<i>Crataegus</i> spp.)	5.2
7	Linden (<i>Tilia</i> spp.)	4.0	Willow (<i>Salix</i> spp.)	4.2
8	American elm (<i>U. americana</i>)	3.8	Cottonwood (<i>P. deltoides</i>)	3.8
9	Siberian elm (<i>Ulmus pumila</i>)	1.8	Silver maple	3.2
10	Red/black oak (<i>Quercus rubra/velutina</i>)	1.4	Red/black oak	2.7

specific purposes such as aesthetics, greenbelts, wildlife, energy and water conservation, and fire-hazard reduction (Bradley, 1995). Diverse management goals often result in the need for multifunctional urban landscapes. To create such landscapes designers are forced to evaluate tradeoffs and conflicts between structures and their related purposes. For instance, water conserving landscapes may not promote fire safety, energy conservation, or habitat for wildlife. By understanding each purpose and the vegetative structure necessary to accomplish that purpose, conflicts among special purpose landscapes can be avoided and net benefits maximized.

Several studies have established relationships between different urban forest structures and specific functions such as visual quality (Schroeder, 1986), energy savings (McPherson, 1993), removal of atmospheric carbon dioxide (Rowntree and Nowak, 1991), urban heat island mitigation (Huang *et al.*, 1987; Oke, 1989; McPherson, 1994a), sound reduction (Cook and Van Haverbeke, 1977), wildlife habitat (DeGraaf and Wentworth, 1986), and personal safety (Schroeder and Anderson, 1984). However, techniques for evaluating tradeoffs associated with multiple functions from a specific landscape are lacking. Key findings from the CUFCP studies which link vegetation structure with urban hydroclimate, air quality, and residential energy use for heating and cooling are described in the next section.

Hydroclimate and air quality

Hydroclimate research in Chicago by Drs. Sue Grimmond, Gordon Heisler, Rich Grant, and Catherine Souch examined how changes in urban morphology, tree cover in particular, influence local energy and water exchanges (Grimmond *et al.*, 1994; Heisler *et al.*, 1994). At a local-scale study area (13 km²), results from hydroclimatic measurements and modeling were analyzed to determine the spatial variability of land cover, land use, and other features that influence climate, evaporation, runoff, and air quality (Grimmond and Souch, 1994; Grimmond *et al.*, 1994; Grimmond and Oke, 1995). Related 'below-canopy' microclimate research examined the degree to which tree cover influences the climate surrounding people and houses (Heisler *et al.*, 1994). Measurements of wind speed, air temperature, and relative humidity were made in residential neighborhoods with differing amounts of tree canopy. The influence of tree cover on microclimate was studied by comparing differences among data recorded at residential sites and data simultaneously recorded from two fixed reference stations. For example, three residential sites were 0.28°C to 0.39°C (0.5°F to 0.7°F) warmer, on average, than the O'Hare International Airport reference site. In residential sites, a diurnal pattern of warmer nighttime temperatures and cooler daytime temperatures compared with the airport can be partially attributed to more rapid evening cooling of the open airport site and increased daytime shading by buildings and trees in the neighborhood. Wind speed at the residential sites was reduced by an average of 83 to 85% compared with the airport site during one July week. This research is producing predictive equations that can be used with building energy performance models to simulate effects of trees on energy use for heating and cooling buildings.

Air pollution and carbon removal by trees in the Chicago region was estimated for 1991 using information on local pollution concentrations, vegetation characteristics, and meteorological conditions (Nowak, 1994b,c). The region's urban forest was estimated to provide \$9.2 million dollars in air quality improvement by removing 5575 metric tons (t) of air pollutants during 1991 (Nowak, 1994c) (Fig. 2). Trees were most effective at removing O₃ (2000 t/year) and PM10 (1840 t/year). Removal rates for these two pollutants peaked during summer when trees were in leaf and air pollutant concentrations were often the highest.

Large healthy trees were estimated to remove 60 to 70 times more pollution than small trees because of their proportionately greater leaf surface area. Hence, sustaining the health and longevity of mature trees is critical to maximizing air quality benefits. Also, air quality benefits can be increased by planting pollution-tolerant species in areas where concentrations are highest. Providing ample soil volume for tree roots and adequate irrigation enhances the potential for achieving long-term benefits from transplants.

Trees throughout the region are estimated to store about 5.6 million metric tons of carbon, about 14

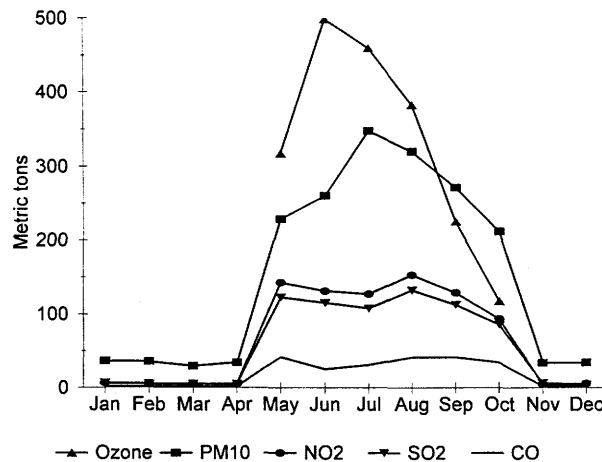


Figure 2. Monthly estimates of air pollution removal by all trees in the study area during 1991. Ozone estimates are for May through October only (from Nowak, 1994c).

to 18 t/ha (6–8 tons/acre) (Nowak, 1994d). Trees on residential and institutional lands dominated by vegetation (e.g. forest preserves, parks) account for 54 and 33% of total carbon storage, respectively. Carbon storage per hectare increases with tree density along the urban-rural gradient. Large (77+ cm dbh) and medium (31–46 cm dbh) sized trees store an average of 3186 and 399 kg of carbon, while annually sequestering 92.7 and 19.1 kg, respectively. Carbon storage by shrubs in the region is 4% of the amount stored by trees.

In summary, these findings from the CUFCP suggest that trees can improve air quality and reduce atmospheric carbon, albeit their effect is modest. Because trees are less abundant in cities than in rural forests, it is not surprising that carbon stored per hectare by live trees in the Chicago region is about 30% of carbon stored per hectare by trees in the area's rural forests (Birdsey, 1992). The amount of carbon stored in Chicago's urban forest, which has taken many years to accumulate, is equivalent to the amount emitted from the residential sector during a 5-month period. Because trees provide the benefit of avoiding emissions from power plants by conserving energy used to heat and cool buildings, there is potential to increase benefits by selecting, locating, and managing trees with their potential for energy conservation in mind.

Energy conservation

Chicago area residents spend about \$660 million annually for natural gas to heat their homes, and \$216 million for air conditioning. Approximately 93% of all households use natural gas for space heating and 78% use electricity for central and room air conditioning. Each year, the typical Chicago household with central air conditioning spends \$755 for heating (159 GJ or 151 million BTU) and \$216 for cooling (6.48 GJ or 1800 kilowatt-hours) (McPherson, *et al.* 1993).

Urban forests can mitigate urban heat island effects and conserve cooling energy by shading buildings and other heat-absorbing surfaces, as well as lowering summer air temperatures through evapotranspirational (ET) cooling (Meier, 1990/91). Trees can save space-heating energy by reducing windspeeds, thereby reducing the amount of cold outside air that infiltrates buildings (Heisler, 1986). Although the potential of these processes has not been well documented in Chicago, studies have been conducted in other cities with a similar climate (Akbari and Taha, 1992; McPherson, 1993). Objectives of this research (McPherson, 1994b) were to quantify the potential of shade trees to save residential heating and cooling energy used in Chicago and to develop guidelines for energy-efficient landscape design.

Computer simulations of microclimates and building energy performance were used to investigate the potential of shade trees to save residential heating and cooling energy use. Shading of buildings by trees was simulated with the Shadow Pattern Simulator (SPS) program (McPherson *et al.*, 1985). Effects of increased tree cover on air temperature and wind speed were based on local microclimatic measurements (Jo and McPherson, 1995) and results from other studies (Huang *et al.*, 1987; Simpson *et al.*, 1993; Souch and Souch, 1993). SPS results, weather data, and information on building thermal characteristics and occupant behavior were used by MICROPAS v. 4.0 (Enercomp, 1992) to provide hour-by-hour estimates of building energy use. Prototypical buildings included one-, two-, and three-story brick buildings similar to residences in the City of Chicago, and one- and two-story wood-frame buildings representing suburban construction. To validate the energy performance of prototypes, building performance indices of reference buildings were calculated, in some cases using whole-house metered data, and compared with indices of the prototypes.

Increasing tree cover by 10% (corresponding to about three trees per building) could reduce total heating and cooling energy use by 5 to 10% (\$50–\$90) (McPherson, 1994b). On a per-tree basis, annual heating energy can be reduced by about 1.3% (\$10, 2.1 GJ), cooling energy by about 7% (\$15, 0.48 GJ), and peak cooling demand by about 6% (90.3 kW) (Fig. 3).

Street trees are a major source of building shade within the City of Chicago. Shade from a large street tree located to the west of a typical brick residence can reduce annual air-conditioning energy use by 2 to 7% (0.50–0.74 GJ or \$17–\$25) and peak cooling demand by 2 to 6% (0.16–0.6 kW). Street trees that shade the east side of buildings can produce similar cooling savings, have a negligible effect on peak cooling demand, and slightly increase heating costs by blocking irradiance during the winter. Shade from large street trees to the south increases heating costs more than it decreases cooling costs. Planting 'solar friendly' trees (i.e. dense crown when in leaf and open crown when out of leaf) to the south and east can minimize the energy 'penalty' associated with attenuating irradiance during the heating season.

For typical suburban wood-frame residences, shade from three trees can reduce annual heating and coolings costs 10 years after planting by \$15 to \$31, and 20 years after planting by \$29 to \$50. Savings in annual and peak air-conditioning energy per tree range from 0.45 to 0.67 GJ (6–7%, \$15–\$23) and 0.9 to 1.1 kW (16–17%), assuming a 25-foot-tall tree opposite the west wall.

Features of energy-efficient residential landscapes in the Chicago area include: 1) shade trees, shrubs,

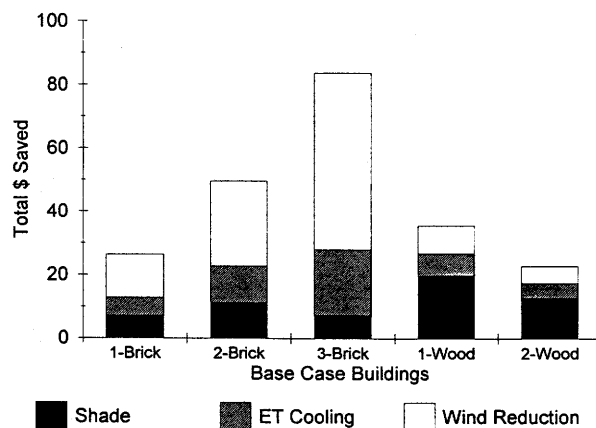


Figure 3. Simulated annual heating and cooling energy savings on a per tree basis for one-, two-, and three-story brick and wood-frame buildings that represent residential construction in the Chicago area. Shading savings are from a 25-foot tall deciduous tree opposite the west wall of each building. Reductions in ET cooling and windspeed are assumed to be associated with a 10% increase in overall neighborhood tree canopy cover (from McPherson, 1994b).

and vines located for shade on the west and southwest windows and walls; 2) solar friendly deciduous trees to shade the east and an open understory to promote penetration of cool breezes; 3) evergreen windbreaks to the northwest and west for protection from winter winds; and 4) shade on the air conditioner where feasible.

In summary, the amount and type of energy savings associated with trees is highly site specific. Potential savings are sensitive to the location of new planting sites and building characteristics. The potential for energy savings from new tree plantings is greatest in areas where tree cover is relatively low, such as public housing sites and new suburban development. Residents in public housing often spend a relatively large portion of their income for space conditioning, and these buildings seldom are energy efficient. Trees that provide mitigation of summer heat islands in Chicago also can provide savings in heating energy, especially for older buildings (Fig. 3). Tree planting could be a new type of 'weatherization' program, largely carried out by the residents themselves. In addition to direct energy savings, other social, environmental, and economic benefits would accrue to the community. Strategic landscaping for maximum shading is especially important with new construction because solar-heat gains through windows strongly influence cooling loads.

Urban forest values

The mean annual tree management budget for cities across the United States has fallen 40% since 1986 (Tschantz and Sacamano, 1994). Local governments have drastically cut spending for urban forest management. As a result, municipal foresters are less able to maintain adequate tree care programs. In some cities, responsibility for tree planting and other management activities has shifted from government tree divisions to community service groups. These nonprofit organizations created partnerships with local neighborhoods, business, and industry, enlisting their support for urban forestry. Scientific research that documented urban forest benefits and costs is critical to this effort to broaden the base of support and participation in community forestry. Science provides information to potential partners that allows them to evaluate their return on urban forest investment. Also, findings are used by managers to assess the cost effectiveness of alternative management activities, thereby optimizing the use of limited resources. Finally, research documenting the structure, function, and value of urban forests is vital to public education efforts designed to increase understanding of and appreciation for the multiple benefits of these systems. One approach to quantifying the long-term benefits and costs associated with specific urban forest landscapes was developed and applied in Chicago as part of the CUFCP.

Net benefits of tree planting and care

In Chicago and most surrounding communities, trees have long been recognized as valuable community assets. However, dwindling budgets for planting and care of street and park trees is creating new challenges for urban forestry. Urban forestry programs now must prove their cost-effectiveness.

Similarly, some residents wonder whether it is worth the trouble of maintaining street trees in front of their home or in their yard. Certain species are particularly bothersome due to litterfall, roots that invade sewers or heave sidewalks, shade that kills grass, or exudates that foul cars and other objects. Branches broken by wind, ice, and snow can damage property. Thorns and low-hanging branches can be injurious. These problems are magnified when trees do not receive regular care, or when the wrong tree was selected for planting.

The purpose of this analysis (McPherson, 1994c) was to provide initial answers to the following questions:

1. Are trees worth it? Do their benefits exceed their costs? If so, by how much?
2. In what locations do trees provide the greatest net benefits?
3. How many years does it take before newly planted trees produce net benefits in Chicago?

4. What tree-planting and management strategies will increase net benefits derived from Chicago's urban forest?

Benefit-cost analysis was used to estimate the annual dollar value of benefits and costs over a 30-year period associated with the planting and care of 95 000 new trees in Chicago. The estimated number of new trees and their management costs were based on interviews with entities responsible for much of the tree planting and care in the city.

The Cost-Benefit Analysis of Trees (C-BAT) computer model was used to calculate the present value of future management costs and environmental benefits (McPherson, 1992, 1994c). C-BAT directly connects tree size and number with the spatial-temporal flow of benefits and costs. Prices are assigned to each cost (e.g. planting, pruning, removal, irrigation, infrastructure repair, liability, waste disposal) based on reported expenditures. Benefits are based on a tree's calculated compensatory or replacement value (Miller and Sylvester, 1981; Neely, 1988). The price of benefits due to heating/cooling energy savings, air pollution/carbon removal, and reduction in storm water runoff are calculated through direct estimation and implied valuation of benefits as environmental externalities (McPherson, 1992). The difference between a tree's full compensatory value and the sum of these environmental benefits represents the 'other' benefits a tree produces (e.g. scenic quality, wildlife habitat, recreation, social empowerment, stress reduction, soil conservation, noise reduction, and biodiversity). In this analysis, green ash (*F. pennsylvanica*) was selected as the 'typical' species. Different growth and mortality rates, as well as different levels of maintenance associated with 'typical' locations, were assumed in projecting the annual flow of benefits and costs as trees mature and die. Because of incomplete information and simplifying assumptions, this study provides only an initial approximation of those benefits and costs. As our understanding of urban forest structure, function, and values increases, and we learn more about urban forestry programs and costs, these assumptions and methods will be improved.

Key findings

Are trees worth it? Findings suggest that energy savings, air-pollution mitigation, avoided runoff, and other benefits associated with trees in Chicago can outweigh planting and maintenance costs. Given the assumptions of this analysis (30 years, 7% discount rate, 95 000 trees planted), planting and maintaining trees costed \$21 million, whereas the benefits conferred by the trees was valued at \$59 million, for a net present value of \$38 million or \$402 per tree planted. A benefit-cost ratio of 2.83 indicates that the value of projected benefits is nearly three times the value of projected costs (Fig. 4).

In what locations do trees provide the greatest net benefits? Benefit-cost ratios were projected to be positive for plantings at park, yard, street, highway, and public housing locations at discount rates ranging from 4 to 10%. Assuming a 7% discount rate, ratios were largest for trees in residential yard and public housing (3.5) sites. Trees in these locations were relatively inexpensive to establish, had low mortality rates, showed vigorous growth, and accrued large energy savings. Because of their prominence in the landscape and existence of public programs for their management, street and park trees frequently receive more attention than yard trees. By capitalizing on the many opportunities for yard-tree planting in Chicago, residents can gain additional environmental, economic, social, and aesthetic benefits. Residents on whose property such trees are located receive direct benefits (e.g. lower energy bills, increased property value), yet benefits accrue to the community as well. In the aggregate, private trees improve air quality, reduce storm water runoff, remove atmospheric CO₂, enhance the local landscape, and produce other benefits that extend well beyond the site where they grow.

How many years does it take before trees produce net benefits in Chicago? Payback periods vary with the species planted, planting location, and level of care that trees received. C-BAT findings suggest that discounted paybacks periods for trees in Chicago can range from 9 to 18 years (Fig. 4). Shorter payback periods were obtained at lower discount rates, whereas higher rates delayed the payback dates.

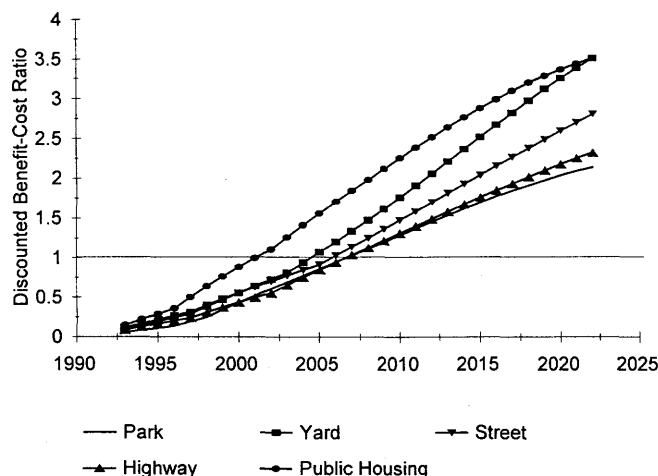


Figure 4. Discounted payback periods are depicted as the number of years before the discounted benefit-cost ratios exceed 1.0. This analysis assumes a 30-year planning period and 7% discount rate (from McPherson 1994c).

What tree planting and management strategies will increase net benefits derived from Chicago's urban forest? Findings from the C-BAT simulations suggest several strategies to maximize net benefits from investment in Chicago's urban forest, as well as communities outside Chicago.

Select the right tree for each location and reduce initial costs. Because tree planting and establishment costs often account for 80% or more of discounted total costs, investing in trees that are well suited to their sites can pay dividends. Matching tree to site should incorporate local knowledge of the tolerances of various tree species. Also, reducing up-front costs will increase cost effectiveness. Strategies include the use of trained volunteers, smaller tree sizes, and follow-up care to increase survival rates. When growing conditions are likely to be favorable it may be most cost effective to use smaller, inexpensive stock. However, in highly urbanized settings, money may be well spent creating growing environments that improve the long-term performance of trees.

Plan for long-term tree care. Benefits from trees increase as they grow, especially if systematic pruning and maintenance result in a healthy tree population (Miller and Sylvester, 1981). The costs of providing regular tree care are small compared with the value of benefits forgone when maturing trees become unhealthy and die (Abbott *et al.*, 1991). Efficiently delivered tree care can more than pay for itself by improving health, increasing growth, and extending longevity.

A healthy urban forest can produce long-term benefits that all residents can share. To improve the health and increase the productivity of Chicago's urban forest will require increased support from agencies and local residents. Information on the value of some of these benefits, as well as the costs, could be part of public education programs aimed at making more residents aware of the value their trees add to the environment in which they live.

Challenges and opportunities in urban forest research

The species composition, age, structure, health, and geographic distribution of urban vegetation have profound impacts on the benefits we derive and the costs we pay to manage urban forests. The relations between urban forest structure, function, and value need to be better understood so that tree planting and management decisions will maximize net benefits for city residents over the long term. Communities are trying to 'do more with less,' but resources for urban forestry programs are dwindling. Cities are

competing to attract new businesses, create jobs, and bolster local economies. Some policy makers recognize that healthy and productive urban forests can mitigate certain environmental impacts associated with economic development. Also, by increasing community attractiveness and sense of place, urban forests enhance quality of life and improve a city's ability to attract new business. Urban forest science is fundamental to the pressing need to manage economic growth and environmental quality so that human settlements are both prosperous and healthy. To apply ecotechnologies successfully in our cities we require a better understanding of ecological processes in urban environments.

Unfortunately, relatively little ecological research has been directed at urban environments; therefore theories and methodologies are not fully developed. Because urban systems are complex and dynamic it is difficult to maintain control plots, identify 'typical' or reference sites, and limit effects of confounding variables. The need for integrated analyses that successfully marry socioeconomic and biotic components, the contrasting scales of measurement by which variables are assessed, and the difficulty of analyzing some behavioral and societal variables pose additional challenges to urban forest research (Platt *et al.*, 1994; Bradley, 1995). Fortunately, recent studies that apply ecological paradigms to urban settings are strengthening the scientific underpinnings for future work (McDonnell *et al.*, 1993).

Urban forest research has the opportunity to advance science by increasing our awareness of people's relationship with the land. Because urban forests are largely created and maintained by people, urban research is inevitably people oriented. Urban forest research and monitoring programs can train, educate, and include people in their studies. Science and environmental education programs can be integrated to reach urban populations that otherwise have little contact with natural resources.

The CUFCP and other studies (Aston, 1977; Boyden, 1977; Newcombe *et al.*, 1978; Douglas, 1983) have increased our knowledge of urban ecosystems. Continued air quality studies and data analysis will yield additional information from the CUFCP. Knowledge from the CUFCP is already being applied in cities such as Baltimore, Maryland and Sacramento, California. As policy makers and the public embrace 'science-based' ecosystem management applied to both urban and wildland regions, we can expect increasing demand and opportunity for integrated urban forest research.

Acknowledgments

This project would not have been possible without the assistance of many individuals and organizations. We are indebted to all those who provided their assistance and to Nina Luttinger, who reviewed an earlier version of this paper. We especially thank Dr John Dwyer, Dr Rich Guldin, and the City of Chicago Department of Environment and Bureau of Forestry for providing the research team with the support that was so crucial to this endeavor.

References

- Abbott, R. E., Luley, C., Buchannan, E., Miller, K., and Joehlin, K. (1991) The importance of large tree maintenance in mitigating global climate change, National Arborist Association, Urbana, IL, International Society of Arboriculture, Research Report, Amherst, NH.
- Akbari, H., and Taha, H. (1992) The impact of trees and white surfaces on residential heating and cooling energy use in four Canadian cities. *Energy* **17**, 141-9.
- Aston, A. (1977) Water resources and consumption in Hong Kong. *Urban Ecol.* **2**, 327-53.
- Birdsey, R. (1992) *Carbon Storage and Accumulation in United States Forest Ecosystems*, General Technical Report No. WO-59, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA.
- Boyden, S. V. (1977) Integrated ecological studies of human settlements. *Impact Sci. Soc.* **27**, 159-69.

- Bradley, G. (1995) Integrating multidisciplinary perspectives. In *Urban Forest Landscapes: Integrating Multidisciplinary Perspectives* (G. Bradley, ed), pp. 3–11. University of Washington Press, Seattle.
- Cook, D. I., and Van Haverbeke, D. F. (1977) *Suburban Noise Control with Plant Materials and Solid Barriers*, Research Bulletin EM 100, U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.
- DeGraaf, R. M., and Wentworth, J. M. (1986) Avian guild structure and habitat associations in suburban bird communities. *Urban Ecol.* **9**, 399–412.
- Douglas, I. (1983) *The Urban Environment*, Edward Arnold, Baltimore, MD.
- Dwyer, J., McPherson, E., Schroeder, H., and Rowntree, R. (1992) Assessing the benefits and costs of the urban forest. *J. Arboricult.* **18**, 227–34.
- Enercomp (1992) *Micropas4 v4.0 User's Manual*, Enercomp, Inc., Sacramento, CA.
- Grimmond, C. S. B., and Souch, C. (1994) Surface description for urban climate studies: A GIS based methodology. *Geocarta Int.* **9**, 47–59.
- Grimmond, S., Souch, C., Grant, R., and Heisler, G. (1994) Local scale energy and water exchanges in a Chicago neighborhood. In *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*, pp. 41–62. General Technical Report No. NE-186, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experimental Station, Radnor, PA.
- Grimmond, C. S. B. and Oke, T. R. (1995) Comparison of heat fluxes from summertime observations in the suburbs of four North American cities. *J. Appl. Meteorol.* **34**, 873–89.
- Heisler, G. M. (1986) Energy savings with trees. *J. Arboricult.* **12**, 113–25.
- Heisler, G. M., Grimmond, S., Grant, R. H., and Souch, C. (1994) Investigation of the influence of Chicago's urban forests on wind and air temperature. In *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project* (E. G. McPherson, D. J. Nowak, and R. A. Rowntree, eds), pp. 19–40. General Technical Report No. NE-186, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA.
- Huang, J., Akbari, H., Taha, H., and Rosenfeld, A. (1987) The potential of vegetation in reducing summer cooling loads in residential buildings. *J. Climate Appl. Meteorol.* **26**, 1103–16.
- Jo, H. K., and McPherson, E. G. (1995) Carbon storage and flux in urban residential greenspace. *J. Environ. Manage.* **45**, 109–33.
- Lawrence, H. W. (1993) The neo-classical origins of modern urban forests. *Forest Conserv. Hist.* **37**, 26–36.
- McBride, J. R., and Jacobs, D. F. (1986) Presettlement forest structure as a factor in urban forest development. *Urban Ecol.* **9**, 245–66.
- McDonnell, M. J., Pickett, S. T. A., and Pouyat, R. V. (1993) The application of the ecological gradient paradigm to the study of urban effects. In *Humans as Components of Ecosystems: Subtle Human Effects and the Ecology of Populated Areas* (M. J. McDonnell and S. T. A. Pickett, eds.), pp. 175–89. Springer-Verlag, New York.
- McPherson, E. G. (1992) Accounting for benefits and costs of urban greenspace. *Landscape Urban Plann.* **22**, 41–51.
- McPherson, E. G. (1993) Evaluating the cost effectiveness of shade trees for demand-side management. *Electricity J.* **6**, 57–65.
- McPherson, E. G. (1994a) Cooling urban heat islands with sustainable landscapes. In *The Ecological City, Preserving and Restoring Urban Biodiversity* (R. H. Platt, R. A. Rowntree, and P. C. Muick, eds.), pp. 151–71. University of Massachusetts Press, Boston, MA.
- McPherson, E. G. (1994b) Energy saving potential of trees in Chicago. In *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project* (E. G. McPherson, D. J. Nowak, and R. A. Rowntree, eds), pp. 95–114. General Technical Report No. NE-186, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA.
- McPherson, E. G. (1994c) Benefits and costs of tree planting and care in Chicago. In *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project* (E. G. McPherson, D. J. Nowak, and R. A. Rowntree, eds), pp. 115–34. General Technical Report No. NE-186. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA.
- McPherson, E. G., Brown, R., and Rowntree, R. A. (1985) Simulating tree shadow patterns for building energy analysis. In *Solar 85—Proceedings of the National Passive Solar Conference* (A. T. Wilson, and W. Glennie, eds), pp. 378–82. American Solar Energy Society, Boulder, CO.
- McPherson, E. G., and Haip, R. A. (1989) Emerging desert landscape in Tucson. *Geograph. Rev.* **79**, 435–49.

- McPherson, E. G., and Luttinger, N. (submitted) From nature to nurture: The history of Sacramento's urban forest. *Geograph. Rev.*
- McPherson, E., Nowak, D. J., and Rowntree, R. A. (1994) *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*, General Technical Report No. NE-186, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Radnor, PA.
- McPherson, E. G., Nowak, D. J., Sacamano, P. L., Prichard, S. E., and Makara, E. M. (eds) (1993) *Chicago's Evolving Urban Forest: Initial Report of the Chicago Urban Forest Climate Project*, General Technical Report No. NE-169, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA.
- Meier, A. (1990/91) Strategic landscaping and air-conditioning savings: a literature review. *Energy Buildings* **15**–**16**, 479–86.
- Miller, R. H., and Sylvester, W. A. (1981) An economic evaluation of the pruning cycle. *J. Arboricult.* **7**, 185–91.
- Neely, D. (ed) (1988) *Valuation of Landscape Trees, Shrubs, and Other Plants*, International Society of Arboriculture, Urbana, IL.
- Newcombe, K., Kalma, J. D., and Aston, A. R. (1978) The metabolism of a city: The case in Hong Kong. *Ambio* **7**, 3–15.
- Nowak, D. (1993) Historical vegetation change in Oakland and its implications for urban forest management. *J. Arboricult.* **19**, 313–19.
- Nowak, D. J. (1994a) Understanding the structure of urban forests. *J. Forestry*. **92**, 36–41.
- Nowak, D. J. (1994b) Urban forest structure: The state of Chicago's urban forest. In *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project* (E. G. McPherson, D. J. Nowak, and R. A. Rowntree, eds), pp. 3–18. General Technical Report No. NE-186, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA.
- Nowak, D. J. (1994c) Air pollution removal by Chicago's urban forest. In *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project* (E. G. McPherson, D. J. Nowak, and R. A. Rowntree, eds), pp. 63–82. General Technical Report No. NE-186, U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Radnor, PA.
- Nowak, D. J. (1994d) Atmospheric carbon dioxide reduction by Chicago's urban forest. In *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project* (E. G. McPherson, D. J. Nowak, and R. A. Rowntree, eds), pp. 83–94. General Technical Report No. NE-186, U.S. Department of Agriculture, Northeastern Forest Experiment Station, Radnor, PA.
- Oke, T. R. (1989) The micrometeorology of the urban forest. *Philos. Trans. R. Soc. Lond.* **324**, 335–49.
- Platt, R. H., Rowntree, R. A., and Muick, P. C. (eds) (1994) *The Ecological City, Preserving and Restoring Urban Biodiversity*, University of Massachusetts, Boston, MA.
- Rowntree, R. A. (ed) (1984) Ecology of the urban forest—part I: Structure and composition. *Urban Ecol.* **8**, 1–178.
- Rowntree, R. A. (ed) (1986) Ecology of the urban forest—part II: Function. *Urban Ecol.* **9**, 227–440.
- Rowntree, R. A. (ed) (1988) Ecology of the urban forest—part III: Values. *Landscape Urban Plann.* **15**, 1–200.
- Rowntree, R. A. (1995) Shifts in the core and the context of urban forest ecology. In *Urban Forest Landscapes: Integrating Multidisciplinary Perspectives* (G. Bradley, ed), pp. 43–59. University of Washington Press, Seattle, WA.
- Rowntree, R., and Nowak, D. J. (1991) Quantifying the role of urban forests in removing atmospheric carbon dioxide. *J. Arboricult.* **17**, 269–75.
- Sanders, R. A. (1984) Some determinants of urban forest structure. *Urban Ecol.* **8**, 13–28.
- Schmid, J. A. (1975) Urban vegetation, Ph.D. Dissertation, University of Illinois, Chicago, IL.
- Schroeder, H. W. (1986) Estimating park tree density to maximize landscape aesthetics. *J. Environ. Manage.* **23**, 325–33.
- Schroeder, H. W., and Anderson, L. M. (1984) Perception of personal safety in urban recreation sites. *J. Leisure Res.* **16**, 178–94.
- Simpson, J. R., McPherson, E. G., and Sacamano, P. (1993) *Impact of Urban Heat Island on Cooling and Environment: A Demonstration Project*, City of Phoenix, Energy Conservation Section, Phoenix, AZ.
- Souch, C. A., and Souch, C. (1993) The effects of trees on summertime below canopy urban climates: A case study. *J. Arboricult.* **19**, 303–12.
- Tschantz, B. A., and Sacamano, P. L. (1994) *Municipal Tree Management in the United States*. International Society of Arboriculture Research Trust, Savoy, IL.
- Ulrich, R. S. (1986) Human responses to vegetation and landscapes. *Landscape Urban Plann.* **13**, 29–44.