# Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project

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Results of the 3-year Chicago Urban Forest Climate Project indicate that there are an estimated 50.8 million trees in the Chicago area of Cook and DuPage Counties; 66 percent of these trees rated in good or excellent condition. During 1991, trees in the Chicago area removed an estimated 6,145 tons of air pollutants, providing air cleansing valued at $9.2 million dollars. These trees also sequester approximately 155,000 tons of carbon per year, and provide residential heating and cooling energy savings that, in turn, reduce carbon emissions from power plants by about 12,600 tons annually. Shade, lower summer air temperatures, and a reduction in windspeed associated with increasing tree cover by 10 percent can lower total heating and cooling energy use by 5 to 10 percent annually ($50 to $90 per dwelling unit). The projected net present value of investment in planting and care of 95,000 trees in Chicago is $38 million ($402 per planted tree), indicating that the long-term benefits of trees are more than twice their costs. Policy and program opportunities to strengthen the connection between city residents and city trees are presented.

*Retrevial Terms:* urban climate, air pollution, urban forestry, energy conservation, carbon dioxide, urban ecosystem

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## Contents

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The Chicago Urban Forest Climate Project (CUFCP) was a 3-year study to quantify the effects of urban vegetation on the local environment and help city planning and management organizations increase the net environmental benefits derived from Chicago's urban forest. The CUFCP study area consists of three sectors: Chicago, Cook County (exclusive of Chicago), and DuPage County (Figure 1). This report presents study results as well as information on continuing urban-forest research in the Chicago area. Numerous interrelated studies in the Chicago region were completed as part of the CUFCP, ranging from region-wide analyses of urban-forest ecosystems to investigations of individual trees and leaves. Research results can be summarized in the following five research topics.

## I. Chicago's Urban Forest Ecosystem and its Effect on Air Quality and Atmospheric Carbon Dioxide

Information on the structure of Chicago's urban forest (e.g., species composition, tree leaf-surface area) provides the basis for understanding the functions of the urban forest that affect the city and its inhabitants. There are currently 4.1 million trees in the City of Chicago, with an estimated 50.8 million trees across the Chicago area of Cook and DuPage Counties. Most of these trees are small and on institutional, residential, and vacant lands. Relatively short-lived pioneer species contribute significantly to the Chicago area's urban forest, are most prevalent on land uses with minimal or naturalistic management (e.g., forest stand conditions), and may constitute an even more important component of the Chicago area's urban forest structure in the future. The most common trees in the Chicago area are buckthorn, green/ white ash, *Prunus* spp., boxelder, and American elm.

Field sampling of leaves of urban trees was used to develop equations to estimate leaf-surface area, the plant surface where atmospheric gases are actively exchanged. The most dominant species in leaf area in the Chicago area are silver maple, green/white ash, white oak, American elm, and boxelder. These species likely have the greatest effect on the environment in the Chicago area.

Street trees are a significant part of Chicago's landscape, accounting for 10 percent of the city's trees and 24 percent of the total leaf-surface area. Street trees are less significant in more suburban or rural areas. The most common ground surfaces in the study area are maintained grass, tar, herba-
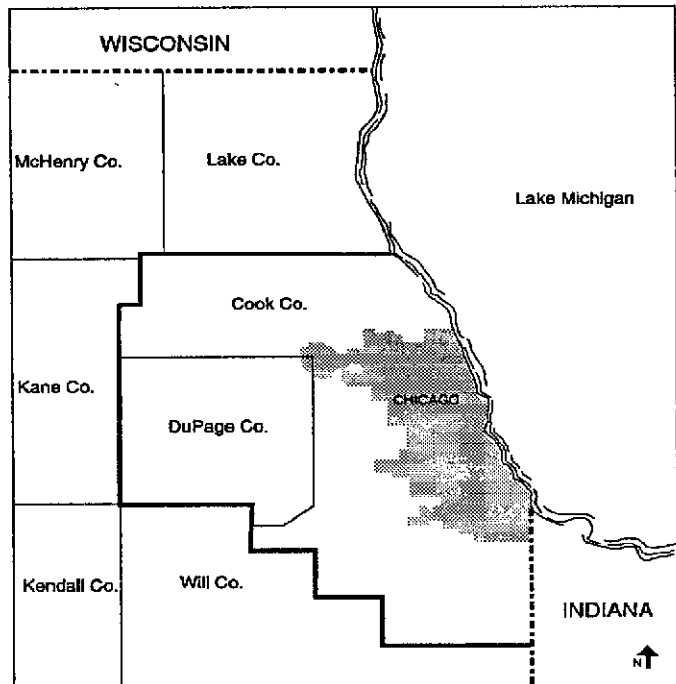


Figure 1. —The Chicago Urban Forest Climate Project study area includes the City of Chicago, and Cook and DuPage Counties.

ceous cover (e.g., crops), and buildings. Information on the structure of the Chicago urban forest ecosystem was used to help quantify the ecosystem functions of air pollution removal and carbon dioxide sequestration by urban trees.

### Removal of Air Pollution

Air pollution is a multibillion dollar problem nationally that affects most major U.S. cities. Air pollution affects human health, damages vegetation and various anthropogenic materials, and reduces visibility. Trees can remove air pollution by intercepting particulates and absorbing gaseous pollutants (Figure 2). In 1991, trees in Chicago removed an estimated 15 metric tons (t) (17 tons) of carbon monoxide (CO), 84 t (93 tons) of sulfur dioxide ($SO_2$), 89 t (98 tons) of nitrogen dioxide ($NO_2$), 191 t (210 tons) of ozone ($O_3$), and 212 t (234 tons) of particulate matter less than 10 microns (PM10). Across the Chicago area, trees (in-leaf season) removed an average of 1.2 t/day (1.3 tons/day) of CO, 3.7 t/day (4.0 tons/day) of $SO_2$, 4.2 t/day (4.6 tons/day) of $NO_2$, 8.9 t/day
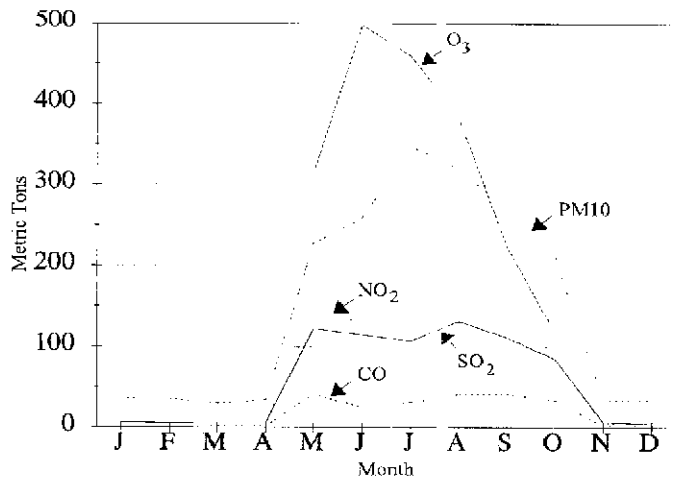
Figure 2. —Monthly estimates of pollution removal by trees in study area in 1991. Ozone removal estimates are for May-October only. PM10 estimates assume 50 percent resuspension of particles.

(9.8 tons/day) of PM10 and 10.8 t/day (11.9 tons/day) of $O_3$. The estimated value of pollution removal in 1991 was $1 million for trees in Chicago and $9.2 million for trees across the Chicago area. Average hourly improvement (in-leaf season) in air quality due to all trees in the Chicago area ranged from 0.002 percent for CO to 0.4 percent for PM10. Maximum hourly improvement was estimated at 1.3 percent for $SO_2$, though localized improvements in air quality can reach 5 to 10 percent or greater in areas with relatively high tree cover, particularly under stable atmospheric conditions during the daytime of the in-leaf season. Large, healthy trees remove an estimated 60 to 70 times more pollution than small trees.

## Sequestration of Carbon Dioxide

Increasing levels of atmospheric carbon dioxide ($CO_2$) and other "greenhouse" gases are thought by many to be leading to increased atmospheric temperatures through the trapping of certain wavelengths of heat in the atmosphere. In terms of reducing atmospheric $CO_2$, trees in urban areas offer the double benefit of direct carbon storage and the avoidance of $CO_2$ production by fossil-fuel power plants through energy conservation from properly located trees. Trees in Chicago store an estimated 855,000 t of carbon (942,000 tons), and trees throughout the Chicago area store approximately 5.6 million t (6.1 million tons). Carbon storage by shrubs is approximately 4 percent of the amount stored by trees. Total carbon storage and annual sequestration are greatest on 1-3 family residential lands, institutional lands dominated by vegetation (e.g., parks, forest preserves) and vacant lands. The estimated net sequestration of carbon in the Chicago area is 140,600 t (155,000 tons). Carbon storage by urban forests nationally likely is between 400 and 900 million t (440 and 990 millions tons).

Carbon storage by individual trees is up to 1,000 times greater in large than in small trees, with sequestration rates up to 90 times greater for healthy large than healthy small trees. Estimated carbon emissions avoided annually due to energy conservation from existing trees throughout the Chicago area is 11,400 t (12,600 tons). Total carbon stored by trees in the Chicago area, which took years to store, is equivalent to the amount of carbon emitted from the residential sector in the Chicago area during a 5-month period. Net annual sequestration equals the amount of carbon emitted from transportation use in the Chicago area in 1 week. The amount of carbon sequestered annually by one tree less than 8 cm (3 inches) in trunk diameter (d.b.h.) equals the amount emitted by one car driven 16 km (10 miles). Reasonable additional tree planting in conjunction with efforts to sustain existing tree cover could increase carbon storage in the Chicago area by another 1.2 million t (1.3 million tons), or the amount of carbon emitted by transportation use in the Chicago area in less than 2 months.

## II. Effect of Urban Trees on Wind and Air Temperature

By transpiring water, blocking winds, shading surfaces, and modifying the storage and exchanges of heat among urban surfaces, trees affect local climate and consequently energy use in buildings, human thermal comfort, and air quality. Models that accurately estimate the effect of urban trees on local windspeed and air temperature at the height of people and residential buildings are lacking, partly because of the complexity of the multiple surfaces in urban areas.

To develop models for estimating the effect of trees on urban microclimates, measurements of windspeed, air temperature, and humidity were taken at 39 sites in and near residential neighborhoods in Chicago over an 11-month period (July 1992 to June 1993). Equations to predict the influence of trees on local climate are being developed by analyzing the interrelationships among climatic variables and local urban morphology (e.g., tree and building attributes).

Preliminary analyses for a 1-week summer period indicate that residential morphology (buildings and trees combined) reduced windspeeds by an average of 46 to 85 percent (relative to an open field site at O'Hare International Airport) depending on the specific neighborhood morphology. The reductions in wind speed were significantly related to indicators of urban morphology. Residential air temperatures generally were warmer than the open-field site due to the predominance of building surfaces which tend to warm the local environment. Continuing work is quantifying the specific effect of urban trees on local windspeed, air temperature, and humidity.

## III. Local-Scale Energy and Water Exchanges

The complex mix of anthropogenic surfaces (e.g., buildings, roads) and natural surfaces (e.g., trees, grass) in urban areas affects how energy and water are partitioned and cycled through the urban system (Figure 3). The replacement of natural surfaces with anthropogenic surfaces alters the thermal and moisture properties of the area, thereby modifying the local atmosphere and generating an "urban climate" that is commonly characterized by increased air
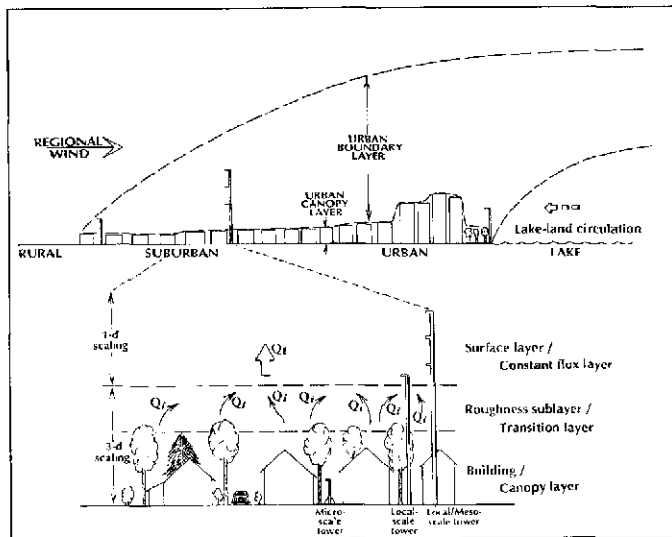
Figure 3.—Schematic representation of spatial scales and atmospheric processes in urban areas (adapted from Oke 1984; Oke et al. 1989).

temperatures and poorer air quality. Extensive climatic measurements across the north-side of Chicago and intensive measurements of a predominantly residential area in and around Chicago were conducted to quantify how urban morphologies affect local energy and water exchanges. Intensive observations consisted of direct measurements of sensible and latent heat flux, and net all-wave radiation. Convective fluxes were quantified using eddy-correlation techniques which seek to measure the flux directly by sensing properties of eddies as they pass through a measurement level on an instantaneous basis.

Calculation of the Bowen ratio for a period during July 1992 indicates that more energy (available from the sun and earth) was going to drying surfaces (latent heat flux) than to warming the air (sensible heat flux). This result is different from that observed in the summer in Tucson, Arizona, and in Sacramento and Los Angeles, California. However, the results for Chicago are realistic considering the meteorological conditions of July 1992 (i.e., relatively high frequency of rainfall). Of the net available energy from solar and earth radiation during the daytime, 32 percent went to heating the air, 38 percent to evaporating water, and 30 percent to heating urban surfaces. Work is in progress to correlate the latent and sensible heat fluxes with tree cover. This correlation will reveal the effect of trees on flux partitioning and help determine to what degree trees cool the local environment. Numerical models are being developed to predict the effect of different tree-planting scenarios on local-scale energy and water exchanges.

## IV. Potential Building Energy Savings from Urban Trees

Trees can reduce building energy use by lowering summertime temperatures, shading buildings during the summer,

and blocking winter winds. However, trees also can increase building energy use by having their branches shade buildings during the winter, and can increase or decrease building energy use by blocking summertime breezes. Computer simulations of microclimates and building energy performance were used to investigate the potential of shade trees to reduce the use of residential heating and cooling energy in Chicago. Increasing tree cover by 10 percent (or about three trees located in optimal energy-conserving locations per building) could reduce total heating and cooling energy use by 5 to 10 percent ($50 to $90). On a per-tree basis of this mass planting, annual heating energy use can be reduced by about 1.3 percent ($10, 2 MBtu), cooling energy use by about 7 percent ($15, 125 kWh), and peak cooling demand by about 6 percent (0.3 kW). Benefit-cost ratios of 1.40 for trees planted around typical two-story buildings and 1.96 for trees near energy-efficient wood frame buildings indicate that a utility-sponsored shade tree program could be cost-effective for both existing and new construction in Chicago.

Street trees are a major source of building shade in Chicago. Shade from a large street tree located to the west of a typical brick residence can reduce the annual use of air-conditioning energy by 2 to 7 percent ($17 to $25, 138 to 205 kWh) and peak cooling demand by 2 to 6 percent (0.16 to 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 can slightly increase heating costs. Shade from large street trees to the south increase heating costs more than they decrease cooling costs. Planting "solar friendly" trees to the south and east can minimize the energy penalty associated with blocking irradiance during the heating season. Design guidelines and recommended tree species for energy-efficient landscapes are presented.

## V. Benefits and Costs of Urban Tree Planting and Care

Benefit-cost analysis was used to estimate the net present value, benefit-cost ratio, and discounted payback periods of proposed tree plantings in Chicago. A "typical" tree species, green ash, was located in "typical" park, residential yard, street, highway, and public housing sites. The 30-year stream of annual costs and benefits associated with the planting of 95,000 trees was estimated. Assuming a 7-percent discount rate, a net present value of $38 million, or $402 per planted tree, was projected. Projected benefit-cost ratios were largest for trees planted in residential yards and public housing sites (3.5), and least for parks (2.1) and highways (2.3). Discounted payback periods ranged from 9 to 15 years (Figure 4). Expenditures for planting alone accounted for over 80 percent of projected costs except at public housing sites, while the largest benefits were attributed to "other" benefits (e.g., scenic, social, economic values) and energy savings. Findings indicate that despite the expense of planting and caring for trees in Chicago, with time the benefits that healthy trees produce can exceed their costs.

Several policies and programs could expand the current role of residents, businesses, utilities, and governments in the planning and management of Chicago's future urban forest.
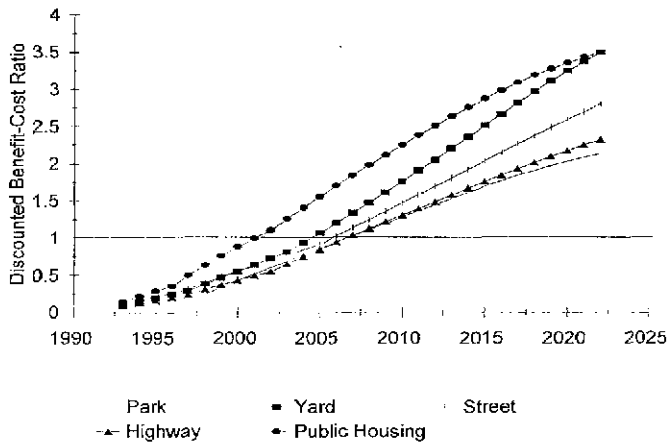
Figure 4. —Discounted payback periods depict the number of years before the benefit-cost ratio exceeds 1.0. This analysis assumes a 30-year planning period and 7-percent discount rate.

Potential new policies and programs include developing a comprehensive set of urban-forest planning principles which address such issues as job training opportunities, conservation education, neighborhood revitalization, mitigation of heat islands, and energy conservation; partnerships to enhance tree planting and care in public and low-income housing areas; an urban-forest stewardship program to provide financial assistance for professional care of existing trees; a yard-tree planting program to reduce building energy use that is sponsored by local utility companies; and a public education program that informs residents about the benefits of healthy and productive urban forests in ways to strengthen the connection between city residents and city trees.

## Acknowledgments

# Chapter 1
# The Role of Vegetation in Urban Ecosystems

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## Abstract

The Chicago Urban Forest Climate Project (CUFCP) evaluates the role of trees and other vegetation in the regional urban forest ecosystem. Ecosystem analysis provides an effective approach to planning and controlling the distribution of benefits and costs associated with ecological effects. The flow of energy, water, carbon, and pollutants through the ecosystem can be changed by changing the amount and spatial distribution of trees. Continuing research in Chicago and collaborating cities will refine the information needs for urban ecosystem management.

## Purpose of this Study

The goal of this research is to add to our knowledge of how vegetation in and near cities affects the human environment. This report summarizes the 3-year Chicago Urban Forest Climate Project which examined how trees and plants of the Chicago area affect selected components of the regional urban ecosystem.

Vegetation is part of the region's infrastructure, woven into a complex network of power lines, roads, aqueducts, and sewers that together help to sustain human health and quality of life. Yet, little is known about how this green infrastructure creates benefits and costs for people. In fact, most of the world's cities have scant information about the composition and geography of their urban forest.

Urban forest is now a common term that means all of the vegetation and soils of an urban region. For this study, we occasionally substitute the term "urban forest ecosystem" to emphasize the ecological approach the scientific team has taken in conducting the research. This approach proceeds from the assumption that the Chicago region operates as a result of multiple interactions among vegetation, soils, water, insects, wildlife, climate, anthropogenic surfaces, and people. The goal is to manage that operation so that benefits far exceed costs.

The initial report of this research project, "Chicago's Evolving Urban Forest," describes the history of vegetation and changes in the urban forest in the Chicago region since the beginning of urbanization (McPherson et al. 1993) Because research is continuing into 1995, a book will be published in the next several years updating our knowledge about Chicago's urban forest ecosystem.

## Manipulating Vegetation to Guide Ecosystem Operation

Some elements of the urban ecosystem can be readily manipulated and others cannot. Vegetation is one element of the ecosystem that can be manipulated in a planned and cost-effective way. Vegetation is renewable and has the potential to yield a wide range of important benefits. The body of knowledge about the role of vegetation in the urban ecosystem and for enhancing human well being is inadequate for managers to make informed decisions about how much to invest, when and where, and for what outcomes. This weak technical foundation has plagued decisionmakers over the last decades in the face of increasing public interest in urban afforestation and urban forestry.

Planners and managers must know what vegetation does, because it affects nearly every other component of the regional urban ecosystem. Herbs, shrubs, and trees change the temperature and humidity of the air. They intercept rainfall and capture air pollutants. Vegetation mediates chemical exchanges between the soil and the atmosphere. The urban forest provides habitat for local and migratory birds. Therefore, to effectively manage the ecological processes in an urban region, we must manage the vegetation. To do that, we must understand its structure and function.

The ecosystem concept has been used for many years to understand how portions of natural landscapes function. The standard approach is first to describe the main components of the system. The second task is to understand how energy, water, and matter (e.g., nutrients) move through the ecosystem. In this study of the Chicago region, we follow this same sequence. First we quantified the structure of the vegetation. Then the research team examined how vegetation affected the flux, or flow, of energy, water, and air pollution through the ecosystem in ways that produce benefits or costs.

## Managing an Urban Region Using the Ecosystem Approach

Today, federal and state land-management agencies are using ecosystem management to bring a science-based approach to caring for complex landscapes. This study is one of the first to approach the analysis of an *urban* landscape with an eye toward employing ecosystem management in the future. The research takes the first steps towards building a model that can support ecosystem management of an urban region by stewarding vegetation.

Given the complexity of ecological and socioeconomic processes in an urban region, ecosystem management is the most effective approach for the following reasons:

(1) *Ecosystem management requires documentation of all components and potential relationships.* No factor is left off the list. The level of documentation and understanding will vary among the components. For example, as a result of this research we know much more about Chicago's urban forest, but our understanding of how the forest cools summer air masses is relatively weak. A survey of how much we know about each component and each potential relationship provides managers with a map of their technical strengths and weaknesses. They can make decisions accordingly and request more technical information where it is needed.

(2) *Ecosystem management views processes that generate benefits and costs at different but related scales of time and space.* Management decisions can be assessed in the context of long-term processes such as changes in tree cover over time. For example, in this report we offer a method for spreading the distribution of benefits and costs of tree planting over future years. This method allows the decisionmaker to see what has been invested and what benefits have been generated at any point in time. Small-scale (in both time and space) processes, such as neighborhood tree planting events, can be assessed in the framework of long-term afforestation programs that will have a spectrum of associated benefits and costs. Thus, a resident planting a tree is seen not as an isolated event but as influencing larger-scale (in both time and space) meteorological, energy, and air-pollution processes. Simply, ecosystem management gives the planner, policymaker, and manager an accounting system and map that aggregates small events into larger processes, and disaggregates large, complex processes into simpler elements.

(3) *Ecosystem management is responsible for inter-regional and inter-generational effects.* Because of the expanded time and space scale cited, this approach makes the management of each ecosystem responsible for how it affects adjacent and distant but related ecosystems. And, ecosystem management is responsible for how future generations of people will be affected. While this may seem to place a greater burden on those who manage an ecosystem, this approach—if applied uniformly across all ecosystems—will result in lower costs and greater benefits for all of society.

(4) *Ecosystem management brings private and public land owners and managers together for a common purpose.* Once it is understood how the ecosystem operates, landowners can see how their actions influence processes that generate benefits and costs. Most ecosystems are made up of private and public land managed for a range of purposes, from parks to supermarkets. When individual land owners and agency officials understand the systemwide effects of their actions, they will be able to better manage their land.

In summary, the information requirements for managing urban ecosystems are high, but the short-, medium-, and long-term benefits far exceed the investment. This is recognized in many cities and urban areas, and citizens and organizations are seeking ways of taking the next step toward ecosystem management in their area.

## Transferring the Chicago Ecosystem Model to Other Cities

The Chicago study was conducted with federal funds by a team of USDA Forest Service researchers, in cooperation with several university colleagues, to provide knowledge for future stewardship of the Chicago region, but also to act as a model for other cities in the United States and around the world. Already, several cities are making preparations to conduct similar studies of their ecosystems to determine precisely the role of vegetation. It is the research team's hope that the concepts, methods, and procedures developed in Chicago will be tested and streamlined in the next few years so that cities can do this work themselves with scientists serving only as technical advisors.

## Acknowledgments

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# Chapter 2
# Urban Forest Structure:
# The State of Chicago's Urban Forest

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## Abstract

Information on urban forest structure (species composition, tree size and location, etc.) provides the basis for understanding the urban forest functions that affect urban inhabitants and for improving management to maximize the environmental and social benefits of urban forests. There are an estimated 4.1 million trees in the City of Chicago, with an estimated 50.8 million trees across the study area of Cook and DuPage Counties. Most of these trees are small and on institutional, residential, and vacant lands.

Relatively short-lived pioneer species contribute significantly to the Chicago area urban forest. The invasive buckthorn is the most common tree, accounting for 12.7 percent of the total tree population but only 2.9 percent of total leaf-surface area. Other common trees are green/white ash, *Prunus* spp., boxelder, and American elm. The most dominant species in leaf area are silver maple, green/white ash, white oak, American elm, and boxelder. Native pioneer tree species (e.g., boxelder, green ash, willow, cottonwood) and buckthorn are most prevalent on land uses with minimal or naturalistic management (e.g., forest stand conditions) and may constitute an even more important component of the Chicago area's urban forest structure in the future.

Streets trees are a significant part of Chicago's landscape, accounting for 10 percent of the city's trees and 24 percent of the total leaf-surface area. Street trees are less significant in more suburban or rural areas. Common ground surfaces in the study area are maintained grass, tar, herbaceous cover (e.g., crops) and buildings. This paper presents formulas for estimating the leaf-surface area of urban trees and discusses the importance of urban forest structure, particularly leaf-surface area, and how managers and planners can direct urban forest structure to a desired outcome.

## Introduction

Urban forest structure is the three-dimensional spatial arrangement of vegetation in urban areas (species composition, tree size and health, number and location of trees, etc.). Information on this structure provides the basis for understanding the urban forest functions that affect urban inhabitants (air temperature modifications, human stress reduction, air pollution mitigation, improved sense of community, etc.) and for improving management to maximize the environmental and social benefits of urban forests.

Urban forest structure is determined by three broad factors: urban morphology, which creates the spaces available for vegetation; natural factors, which influence the amounts and types of biomass likely to be found within cities; and human management systems, which account for intraurban variations in biomass configurations according to land use distributions (Sanders 1984). There are significant variations in urban forest structure both within and among cities. Aerial photographic analyses of urban tree canopy cover reveal that tree cover varies between 5 and 60 percent among land-use types within four eastern U.S. cities, while overall urban tree cover ranged from 24 to 37 percent among the cities (Rowntree 1984).

There has been little ground-based research evaluating the urban forest structure of an entire city. Many researchers have evaluated the street-tree component of the urban forest (Impens and Delcarte 1979; Richards and Stevens 1979; Dawson and Khawaja 1985; Talarchek 1985; Jim 1986; Stevens and Richards 1986; McPherson and Rowntree 1989) or limited portions of non-street tree urban forests (e.g., Derrenbacher 1969; Schmid 1975; Whitney and Adams 1980; Airola and Buchholz 1982; Boyd 1983; Buhyoff et al. 1984; Dorney et al. 1984; McBride and Froehlich 1984; Miller and Winer 1984; Richards et al. 1984; Schroeder and Green 1985; Schroeder and Cannon 1987; Profous et al. 1988, Profous and Rowntree 1993), but ground-based urban forest structural analyses of an entire urban area have been conducted only for the Los Angeles Basin (Horie et al. 1991) and Oakland, California (Nowak 1991). The Los Angeles study focused on leaf biomass and volatile organic emissions from vegetation. The Oakland study focused on variations in urban forest structure and its overall effect on forest compensatory value, atmospheric carbon storage and volatile organic emissions from vegetation (Nowak 1993a,b).

Since many environmental functions are related to leaf-surface area (e.g., reductions in air temperature, air pollution removal, volatile organic emissions, carbon dioxide sequestration), understanding the leaf-area contribution of various tree species is important to urban-forest researchers, managers and planners. The measure of tree-species dominance reflects the relative contribution of a species to the overall leaf-surface area of the forest. Species with the greatest proportion of leaf-surface area are the most dominant and likely have the greatest influence on the local environment. Many social benefits of trees also may be related to leaf-surface area. For example, large trees contribute more scenic beauty than smaller ones (Buhyoff et al. 1984; Schroeder and Cannon 1987).

Leaf-area indices (LAI) are another common means of comparing the relative contribution of leaf area among different areas or tree species on an equal-area basis. LAI is the total leaf area (one surface only) divided by the ground area occupied by the plant. A LAI of 4 means that for every square meter of ground below the tree canopy, 4 m$^2$ of leaves lie above it. Net primary productivity (individual plant growth) of forests is greatest at a LAI of approximately 4. However, the yield (growth) per unit of ground area is low in such open stands (LAI < 4). Maximum gross productivity usually occurs at LAI values of 8 to 10 (Kramer and Kozlowski 1979); LAI varies with plant size, age, spacing, species, and site characteristics.

Typical LAI's are 10 to 11 for tropical rain forests, 5 to 8 for deciduous forests, and 9 to 11 for boreal coniferous forests (Barbour et al. 1980). The LAI of some Piedmont hardwood forests range from 4.5 to 7.4 (Hedman and Binkley 1988), and LAI's of a subalpine Sierra Nevada forest range from 3.6 to 11.7 (Peterson et al. 1988). Little research has been conducted on the LAI of urban trees. Data from individual urban trees and shrubs in Warsaw, Poland, show LAI's for individual trees ranging from 1 to 15 with an average LAI of individual trees for various areas in Warsaw of 3.5 to 4.8 (Gacka-Grzesikiewicz 1980).

Because information is scarce on the variation in forest structure within urban areas, on how urban forest structure combines to create an urban forest ecosystem, and on leaf-surface area of urban trees, the objectives of this study were to: 1) quantify urban forest structure and its variation by land-use type in the Chicago area; and 2) measure the leaf-surface area of individual open-grown urban trees and develop predictive equations of leaf-surface area to estimate tree species dominance in the Chicago area. This information will be used to reveal key urban forest characteristics and aid in quantifying various environmental functions (see Nowak 1994a,b: Chapters 5 and 6, this report).

# Methods

## Study Area

The study area encompasses Cook and DuPage Counties (3,350 km$^2$; 1,292 mi$^2$) and contains nearly six million people. To reveal regional variation within the Chicago area, the study area was subdivided into the City of Chicago, Cook County exclusive of Chicago (hereafter referred to as suburban Cook County), and DuPage County (Figure 1). Chicago is the most densely populated sector, accounting for 18 percent of the entire study area and 47 percent of the total population. Suburban Cook County contains 56 percent of the study area and 40 percent of the total population, and many of the older suburban communities in the Chicago region. DuPage County is the least densely populated, most agricultural, and most rapidly urbanizing sector within the study area. It contains 13 percent of the population and occupies 26 percent of the study area. Tree crowns cover an average of 11 percent of the land area in Chicago, 23 percent in suburban Cook County, and 19 percent in DuPage County (McPherson et al. 1993). Crown cover also varies by individual land-use types within each sector (Table 1).
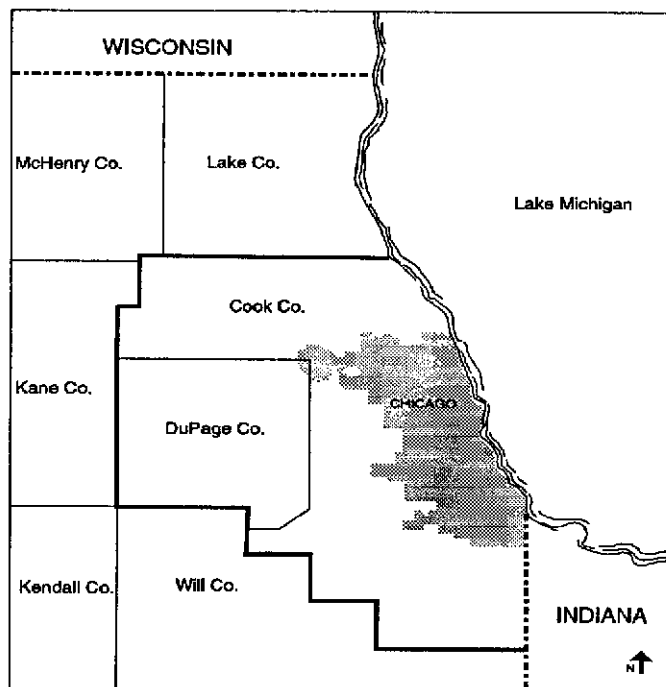


Figure 1. — Study area includes City of Chicago, suburban Cook County, and DuPage County.

## Ground Sampling of Vegetation

Urban vegetation and other surface data were collected on 652 randomly located plots established as a sample of grid points (213 plots in Chicago, 222 in suburban Cook County and 217 in DuPage County). Because the focus of this study is on urban trees, the number of sample plots allocated to each land-use type was proportional to the estimated tree cover in the land use.[1]

Plot structure varied by land-use type.[2] Residential plots were subdivided into smaller ground units, whose area was measured to aid in estimating ground-surface cover (to the nearest 5 percent). Building size on each residential plot was measured and building-surface characteristics were noted. The amount of ground area occupied by various materials (tar, cement, buildings, small structures, other impervious material, maintained or unmaintained grass, shrubs, soil, herbaceous, rock, duff, water, wood) was measured or estimated on each plot.

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[1] Overall, 249 plots were located on 1-3 family residential lands, 26 plots on multifamily residential lands (apartments with four or more units), 194 plots on institutional lands dominated by vegetation (e.g., parks, cemeteries, golf courses, forest preserves), 22 plots on institutional lands dominated by buildings (e.g., schools, churches), 52 plots on commercial/industrial lands, 45 plots on vacant lands, 39 plots on transportational lands (e.g., airports, freeways), and 25 plots on agricultural lands.

[2] On 1-3 family residential lands, the entire residential lot (mid-road to mid-alley) was measured. For other land use types, 0.04-hectare (ha) (0.1-acre) plots were measured.

Table 1. —Mean percent tree cover and standard error by land-use type in Chicago, suburban Cook County, DuPage County, and entire study area

| Land use | Chicago Mean | Chicago SE | Cook Co. Mean | Cook Co. SE | DuPage Co. Mean | DuPage Co. SE | Study area Mean | Study area SE |
|---|---|---|---|---|---|---|---|---|
| Transportation (freeway) | 3.8 | 0.8 | 0.5 | 0.5 | 0.0 | 0.0 | 1.1 | 0.3 |
| Transportation (other) | 1.8 | 0.3 | 2.1 | 1.0 | 2.4 | 2.0 | 2.1 | 0.7 |
| Large commercial/industrial | 2.9 | 0.3 | 2.4 | 0.5 | 1.4 | 0.6 | 2.3 | 0.3 |
| Small commercial/industrial[a] | 1.8 | 0.3 | 3.5 | 1.2 | 1.4 | 1.3 | 2.6 | 0.6 |
| Agriculture | 0.0 | 0.0 | 4.1 | 0.6 | 2.4 | 0.5 | 2.9 | 0.4 |
| Institutional (building)[b] | 7.1 | 0.7 | 6.4 | 1.2 | 9.9 | 1.9 | 7.3 | 0.8 |
| Multiresidential[c] | 6.6 | 0.5 | 8.9 | 1.7 | 10.2 | 2.7 | 8.1 | 0.8 |
| Commercial (landscaped)[d] | 12.1 | 7.7 | 15.6 | 6.8 | 6.3 | 6.1 | 11.5 | 4.5 |
| Institutional (vegetation)[e] | 26.4 | 1.0 | 16.7 | 1.6 | 20.4 | 2.2 | 19.7 | 1.1 |
| Residential[f] | 15.0 | 0.4 | 24.4 | 0.7 | 25.3 | 1.0 | 22.8 | 0.5 |
| Vacant | 19.6 | 1.5 | 39.2 | 1.9 | 31.7 | 2.3 | 33.7 | 1.2 |
| Forest preserve | 53.8 | 3.2 | 66.6 | 1.4 | 75.2 | 2.7 | 70.0 | 1.2 |
| Total | 11.0 | 0.2 | 22.5 | 0.4 | 18.6 | 0.5 | 19.4 | 0.3 |

[a] Small street-front commercial stores, etc.

[b] Dominated by buildings (e.g., schools, churches).

[c] Apartments with four or more units.

[d] Hereafter incorporated in the commercial/industrial land-use class in subsequent tables and analyses.

[e] Dominated by vegetation (e.g., parks, cemeteries, golf courses). This land-use class includes forest preserves in subsequent tables and analyses.

[f] 1-3 family residential units.

SE - denotes the standard error of the corresponding estimate.

The size and species of individual shrub masses were recorded (length, width, height). On every 10th plot measured, stem diameters of individual shrubs at 15 cm (6 inches) above groundline were measured. Data were collected on 8,996 trees and shrubs that were growing in tree form (i.e., relatively large open-grown individuals). The data included species, trunk diameter at breast height (d.b.h. - diameter at 1.37 m or 4.5 ft), total tree height, height to base of crown, crown width, crown shape, percent of crown occupied by leaves, tree location (street-tree locations between sidewalk and road, or on median, were noted), and condition. Estimates of tree condition were based on foliage characteristics. Trees were rated as excellent if less than 5 percent of the crown showed dieback or leaf discoloration. Other ratings were good (5 to 25 percent dieback or discoloration), moderate (26 to 50 percent), poor (51 to 75 percent), dying (76 to 99 percent), and dead (no leaves).

Plot information was combined to produce aggregate estimates on vegetation and other urban-forest attributes by land-use type in each sector of the study area (Gerald Walton, USDA Forest Service, 1992, pers. commun.).

## Leaf Area of Urban Trees

To estimate leaf-surface area of urban trees, data were collected from 54 healthy, open-grown park trees in Chicago that were selected specifically for their excellent condition (10 American elm, 10 green ash, 10 hackberry, 10 honeylocust, and 14 Norway maple). The crown height (base of crown to crown top) of sampled trees ranged from 3.4 to 9.1 m (11.2 to 29.9 ft); crown width ranged from 4.1 to 12.0 m (13.5 to

39.4 ft) and individual LAI's ranged from 0.7 to 12.5. The volume of each tree crown was mapped (including areas devoid of leaves) using a telescoping pole.[3] Crown height and distance from the tree base were measured at crown boundary points every 1.5 m (5 ft) vertically and at every 45° angle radially (i.e., eight points around the tree at every 1.5 m vertically). Ten 0.4 m3 (14.1 ft3) samples of foliage were collected from random points within the tree crown using a high-lift truck.[4] The number of leaves per sample were counted and approximately 30 leaves were randomly subsampled for analysis of leaf area. For samples with 50 leaves or less, all leaves were analyzed for leaf area. Individual leaf areas were measured with a leaf-area meter (CID Inc., Conveyor Area Meter CI251). Average sample leaf area (one-surface only) per unit crown volume (m2/m3) was extrapolated using the total crown volume (m3) to estimate total leaf area for each tree. Following leaf-area analyses, all leaves were dried at 65°C (149°F) for 24 hours and then weighed.

Total leaf-surface area for smaller urban trees was obtained from Gacka-Grzesikiewicz (1980). Data from 34 trees (12 species) that ranged in crown height (H) from 0.7 to 12.8 m (2.3 to 42.0 ft) and in crown width (D) from 0.5 to 4.6 m (1.6 to 15.1 ft) were combined with field data on leaf-surface area

[3] A sliding pole that displays the height at the top of the pole.

[4] A computer program was written to map the measured tree-crown dimensions and calculate crown volume. Random distances along x, y, and z coordinates from the tree base were selected to determine sampling locations within each tree crown. Sample locations in the tree crown were approached with the high-lift truck bucket so as not to disturb the sample prior to leaf collection.

of individual trees to produce equations for estimating total leaf-surface area of individual urban trees based on crown parameters. Other variables included in the predictive equations were a factor for leaf-surface area based on the outer surface of the tree crown $(S= \pi D(H + D)/2)$ (Gacka-Grzesikiewicz 1980) and average shading coefficients for individual species (percent sunlight intercepted by foliated tree crowns) (McPherson 1984).

Least-squares linear regression was used to produce two regression equations for estimating total leaf area of individual urban trees. One equation included shading coefficients, the other excluded shading coefficients to aid in estimating leaf area of species for which shading coefficients are unknown (40 percent of the total population). Because logarithmic equations slightly underestimate leaf area (Crow 1988) a correction factor of one-half of the estimated variance of the estimate was added to the untransformed value $(y = e^x + var(x)/2)$ for each equation (G. Walton, 1993, pers. commun.).

The regression formula estimated for log-leaf area of trees with measured shading coefficients was:

$\ln Y = -4.3309 + 0.2942H + 0.7312D +$
$\qquad 5.7217Sh - 0.0148S \quad (r^2 = 0.91),$

where Y = total leaf area $(m^2)$, H = crown height (m), D = crown diameter (m), Sh = shading coefficient (Appendix A, Table 1), and $S=\pi D(H + D)/2$. The correction factor (0.1159), added to the untransformed estimate, resulted in the following estimate for leaf area:

$Y = e^{-4.3309 + 0.2942H + 0.7312D + 5.7217Sh - 0.0148S} + 0.1159$

For trees for which shading coefficients are unknown, the estimated log-leaf area relationship was:

$\ln Y = 0.6031 + 0.2375H + 0.6906D - 0.0123S \quad (r^2 = 0.86)$

The correction factor added to the untransformed estimated value was 0.1824.

Total leaf area, derived from trees in excellent condition, was adjusted according to the condition class of the tree. Estimates of total leaf area were multiplied by 1 for trees in excellent condition, by 0.85 for trees in good condition, by 0.625 for moderate trees, by 0.375 for poor trees, by 0.125 for dying trees, and by 0 for dead trees.

For trees with characteristics outside the range of conditions under which the regression equations were derived (H > 12 m, D > 12 m, H/D > 3, S > 500 or S < 1; n = 759, 8.4 percent of the sample), leaf area was estimated using a volumetric approach. The volume of individual crowns occupied by leaves (foliated-crown volume) was estimated based on measured crown height, width, shape, and percent of crown occupied by leaves. Average leaf dry weight $(g/m^3)$ was calculated based on measured data and information from the literature on individual tree species (Winer et al. 1983; Nowak 1991). Factors for average leaf dry weight were applied to the foliated-crown volume to estimate total leaf dry weight of the tree. This estimate was converted to leaf area using conversion factors $(m^2/g)$ calculated from measured data and from the literature (McLaughlin and Madgwick 1968; Monk et al. 1970; Gacka-Grzesikiewicz 1980; Box 1981;

Shelton and Switzer 1984; Bacon and Zedaker 1986; Vose and Allen 1988; Reich et al. 1991; Cregg 1992). If no conversion data were found for an individual species, the genera average was substituted; if no genera data were found, the average conversion value for the hardwood or conifer group was used.

Relative dominance of a tree species was calculated as the total leaf-surface area of all trees of one species as a percentage of the total leaf-surface area of trees of all species. Reliable estimates of error of leaf area estimates could not be made because it was not possible to determine the amount of error regarding factors associated with estimates of leaf area, for example, regression formula transformations, conversions used in the volumetric approach, and adjustments for crown condition. Thus, standard errors are not reported for estimates of species dominance.

Average LAI's for individual trees were calculated by dividing the sum of leaf-surface areas by the sum of crown projections (individual ground area = $\pi D^2/4$). The total LAI for the study area was calculated by dividing the estimate of the total leaf-surface area in the study area by the total area occupied by trees (from aerial photograph interpretation) (McPherson et al. 1993). Ground projections based on aerial photographs account for the multiple layering effect of trees (combined effect of overstory and understory trees).

## Results

There are approximately 50.8 million trees in the study area, with 4.1 million trees in Chicago, 31.8 million in suburban Cook County, and 14.9 million in DuPage County (Table 2). The largest proportion of trees (49 percent) is on institutional lands dominated by vegetation (e.g., parks, forest preserves, cemeteries, golf courses), followed by 1-3 family residential land (25 percent), and vacant land (21 percent) (Table 2). These land uses also have the highest tree densities with institutional lands dominated by vegetation having 563 trees/ ha (228 trees/acre). Vacant lands have 488 trees/ha (197 trees/acre) and 1-3 family residential lands have 93 trees/ha (38 trees/acre) (Table 3). Overall tree density is highest in DuPage County at 173 trees/ha (70 trees/acre), followed by suburban Cook County with 169 trees/ha (68 trees/acre) and Chicago with 68 trees/ha (28 trees/acre) (Table 3). Most of the estimated leaf-surface area (87.5 percent) is on 1-3 family residential lands and institutional lands dominated by vegetation (Table 4).

Cottonwood and green/white ash are the most common species in Chicago. Buckthorn and green/white ash are most common in suburban Cook County, and willow and boxelder are the most common species in DuPage County (Table 5; Appendix A, Tables 2-6). Species that dominate in leaf area are cottonwood and green/white ash in Chicago, silver maple and American elm in suburban Cook County, and white oak and silver maple in DuPage County (Table 5; Appendix A, Tables 2-6). Composition and leaf-area dominance of tree species by land-use type for each sector of the study area are given in Appendix A, Tables 7-14.

Table 2. —Estimated number of trees (in thousands) by land-use type in Chicago, suburban Cook County, DuPage County, and entire study area

| Land use | Chicago Total | Chicago SE | Cook County Total | Cook County SE | DuPage County Total | DuPage County SE | Study area Total | Study area SE |
|---|---|---|---|---|---|---|---|---|
| Institutional (bldg.) | 73 | 55 | 0 | 0 | 57 | 27 | 130 | 61 |
| Transportation | 225 | 175 | 0 | 0 | 28 | 28 | 253 | 178 |
| Agriculture | 0 | 0 | 0 | 0 | 442 | 342 | 442 | 342 |
| Multiresidential | 199 | 134 | 232 | 89 | 153 | 31 | 584 | 164 |
| Commercial/indust. | 33 | 33 | 1,021 | 873 | 81 | 30 | 1,136 | 874 |
| Vacant | 494 | 248 | 3,863 | 1,455 | 6,443 | 2,406 | 10,799 | 2,822 |
| Residential | 1,258 | 180 | 6,712 | 586 | 4,529 | 647 | 12,500 | 892 |
| Institutional (veg.) | 1,845 | 505 | 19,978 | 3,300 | 3,163 | 706 | 24,985 | 3,412 |
| Total | 4,128 | 634 | 31,806 | 3,758 | 14,897 | 2,612 | 50,830 | 4,620 |

Table 3.—Tree density (no. trees/ha) by land-use type in Chicago, suburban Cook County, DuPage County, and entire study area (divide by 2.471 to convert stems/ha to stems/acre)

| Land use | Chicago Total | Chicago SE | Cook County Total | Cook County SE | DuPage County Total | DuPage County SE | Study area Total | Study area SE |
|---|---|---|---|---|---|---|---|---|
| Institutional (bldg.) | 25 | 19 | 0 | 0 | 20 | 9 | 9 | 4 |
| Agriculture | 0 | 0 | 0 | 0 | 26 | 20 | 12 | 10 |
| Transportation | 40 | 31 | 0 | 0 | 13 | 13 | 15 | 10 |
| Commercial/indust. | 2 | 2 | 32 | 27 | 10 | 3 | 21 | 16 |
| Multiresidential | 34 | 23 | 56 | 21 | 70 | 14 | 48 | 13 |
| Residential | 52 | 7 | 91 | 8 | 124 | 18 | 93 | 7 |
| Vacant | 256 | 128 | 315 | 119 | 810 | 303 | 488 | 127 |
| Institutional (veg.) | 332 | 91 | 674 | 111 | 345 | 77 | 563 | 77 |
| Overall | 68 | 10 | 169 | 20 | 173 | 30 | 152 | 14 |

Table 4. —Percentage of land area, total number of trees (tree population), and total leaf area within the study area, by land-use type

| Land use | Land area | Tree population | Leaf area |
|---|---|---|---|
| Institutional (bldg.) | 4.1 | 0.3 | 0.6 |
| Transportation | 5.2 | 0.5 | 1.0 |
| Agriculture | 10.6 | 0.9 | 0.4 |
| Multiresidential | 3.7 | 1.1 | 1.3 |
| Commercial/indust. | 16.3 | 2.2 | 0.8 |
| Vacant | 6.6 | 21.2 | 8.4 |
| Residential | 40.2 | 24.6 | 49.7 |
| Institutional (veg.) | 13.3 | 49.2 | 37.8 |
| Total | 100.0 | 100.0 | 100.0 |

Table 5. —Tree-species composition in Chicago, suburban Cook County, DuPage County, and entire study area; includes top 20 species in number and percentage of trees and species dominance based on percentage of total leaf-surface area in each sector

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| **CHICAGO** | | | | | | |
| Cottonwood | 535,900 | 303,100 | 13.0 | 1 | 15.8 | 1 |
| Green/white ash | 495,500 | 132,100 | 12.0 | 2 | 12.9 | 2 |
| American elm | 297,100 | 167,200 | 7.2 | 3 | 4.3 | 6 |
| *Prunus* spp. | 268,200 | 103,100 | 6.5 | 4 | 2.4 | 11 |
| Hawthorn | 259,500 | 105,500 | 6.3 | 5 | 1.9 | 17 |
| Buckthorn | 232,100 | 101,100 | 5.6 | 6 | 0.9 | 27 |
| Honeylocust | 189,000 | 43,800 | 4.6 | 7 | 3.4 | 8 |
| Boxelder | 178,900 | 86,700 | 4.3 | 8 | 2.0 | 15 |
| Mulberry | 166,600 | 49,600 | 4.0 | 9 | 2.3 | 13 |
| Silver maple | 124,700 | 26,800 | 3.0 | 10 | 7.2 | 3 |
| Norway maple | 122,600 | 30,900 | 3.0 | 11 | 6.7 | 5 |
| Yew | 112,000 | 87,700 | 2.7 | 12 | 1.6 | 20 |
| Ash (other) | 107,500 | 58,100 | 2.6 | 13 | 1.5 | 21 |
| Ailanthus | 89,200 | 29,900 | 2.2 | 14 | 4.2 | 7 |
| Crabapple | 77,700 | 28,500 | 1.9 | 15 | 1.9 | 18 |
| Elm (other) | 64,900 | 49,000 | 1.6 | 16 | 1.0 | 23 |
| Hackberry | 62,100 | 33,200 | 1.5 | 17 | 2.3 | 12 |
| Chinese elm | 60,000 | 30,000 | 1.5 | 18 | 0.9 | 26 |
| Blue spruce | 58,900 | 25,200 | 1.4 | 19 | 1.6 | 19 |
| White oak | 49,600 | 29,700 | 1.2 | 20 | 7.0 | 4 |
| Swamp white oak | 47,500 | 34,100 | 1.2 | 21 | 2.3 | 14 |
| Red/black oak | 29,000 | 26,000 | 0.7 | 27 | 2.5 | 9 |
| Basswood | 26,800 | 13,600 | 0.6 | 28 | 1.9 | 16 |
| Linden | 18,600 | 8,900 | 0.5 | 31 | 2.5 | 10 |
| **SUBURBAN COOK COUNTY** | | | | | | |
| Buckthorn | 4,601,600 | 1,430,800 | 14.5 | 1 | 2.9 | 12 |
| Green/white ash | 3,181,900 | 745,300 | 10.0 | 2 | 9.6 | 3 |
| *Prunus* spp. | 2,619,300 | 660,100 | 8.2 | 3 | 4.0 | 9 |
| American elm | 2,126,400 | 741,700 | 6.7 | 4 | 9.8 | 2 |
| Boxelder | 1,757,800 | 447,200 | 5.5 | 5 | 4.6 | 6 |
| Hawthorn | 1,715,600 | 440,100 | 5.4 | 6 | 3.6 | 10 |
| Alder | 1,337,200 | 1,130,400 | 4.2 | 7 | 0.5 | 33 |
| Silver maple | 1,220,200 | 287,900 | 3.8 | 8 | 10.9 | 1 |
| Red/black oak | 1,044,100 | 328,200 | 3.3 | 9 | 5.2 | 4 |
| Poplar (other) | 841,400 | 527,800 | 2.6 | 10 | 1.3 | 21 |
| Black locust | 831,000 | 618,200 | 2.6 | 11 | 0.4 | 38 |
| Slippery elm | 732,900 | 582,800 | 2.3 | 12 | 1.2 | 23 |
| Cottonwood | 715,700 | 352,600 | 2.3 | 13 | 3.0 | 11 |
| Sugar maple | 590,400 | 507,600 | 1.9 | 14 | 1.4 | 20 |
| White oak | 540,100 | 236,200 | 1.7 | 15 | 4.5 | 7 |
| Crabapple | 490,800 | 100,300 | 1.5 | 16 | 1.8 | 15 |
| Honeylocust | 430,400 | 81,200 | 1.4 | 17 | 1.7 | 16 |
| Mulberry | 414,500 | 132,200 | 1.3 | 18 | 1.2 | 22 |
| Bur oak | 408,000 | 211,400 | 1.3 | 19 | 1.6 | 18 |
| Norway maple | 407,900 | 110,700 | 1.3 | 20 | 4.3 | 8 |
| Willow | 317,400 | 99,800 | 1.0 | 26 | 5.0 | 5 |
| Swamp white oak | 123,100 | 55,100 | 0.4 | 38 | 2.5 | 14 |

Table 5. —continued

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| **DUPAGE COUNTY** | | | | | | |
| Willow | 1,819,400 | 1,754,000 | 12.2 | 1 | 2.3 | 15 |
| Boxelder | 1,630,900 | 454,500 | 10.9 | 2 | 6.2 | 3 |
| Buckthorn | 1,619,400 | 572,600 | 10.9 | 3 | 3.7 | 8 |
| *Prunus* spp. | 1,253,100 | 333,100 | 8.4 | 4 | 4.3 | 7 |
| Green/white ash | 950,200 | 381,400 | 6.4 | 5 | 5.2 | 5 |
| Cottonwood | 658,600 | 442,500 | 4.4 | 6 | 3.4 | 10 |
| Hawthorn | 650,900 | 175,000 | 4.4 | 7 | 1.2 | 22 |
| Shagbark hickory | 520,700 | 295,800 | 3.5 | 8 | 2.6 | 13 |
| American elm | 458,200 | 168,300 | 3.1 | 9 | 4.5 | 6 |
| Mulberry | 299,300 | 88,300 | 2.0 | 10 | 2.5 | 14 |
| Red/black oak | 299,100 | 131,100 | 2.0 | 11 | 1.9 | 16 |
| Blue spruce | 295,700 | 92,900 | 2.0 | 12 | 1.9 | 17 |
| Silver maple | 286,800 | 47,900 | 1.9 | 13 | 9.4 | 2 |
| Bur oak | 275,700 | 109,700 | 1.9 | 14 | 5.7 | 4 |
| Basswood | 243,500 | 144,400 | 1.6 | 15 | 1.3 | 20 |
| Black locust | 236,900 | 157,300 | 1.6 | 16 | 0.9 | 25 |
| Jack pine | 234,300 | 169,800 | 1.6 | 17 | 0.2 | 39 |
| White oak | 218,200 | 66,900 | 1.5 | 18 | 17.3 | 1 |
| Crabapple | 211,200 | 28,900 | 1.4 | 19 | 1.6 | 19 |
| Walnut | 190,100 | 121,100 | 1.3 | 20 | 3.4 | 9 |
| Norway maple | 161,700 | 31,100 | 1.1 | 22 | 3.1 | 11 |
| Pin oak | 112,200 | 41,600 | 0.8 | 25 | 2.8 | 12 |
| Honeysuckle | 98,800 | 54,500 | 0.7 | 30 | 1.7 | 18 |
| **STUDY AREA** | | | | | | |
| Buckthorn | 6,453,100 | 1,544,400 | 12.7 | 1 | 2.9 | 11 |
| Green/white ash | 4,627,500 | 847,600 | 9.1 | 2 | 8.7 | 2 |
| *Prunus* spp. | 4,140,600 | 746,500 | 8.1 | 3 | 3.9 | 9 |
| Boxelder | 3,567,600 | 643,500 | 7.0 | 4 | 4.8 | 5 |
| American elm | 2,881,700 | 778,700 | 5.7 | 5 | 7.6 | 4 |
| Hawthorn | 2,626,000 | 485,300 | 5.2 | 6 | 2.7 | 13 |
| Willow | 2,144,600 | 1,756,800 | 4.2 | 7 | 3.6 | 10 |
| Cottonwood | 1,910,200 | 641,900 | 3.8 | 8 | 4.6 | 6 |
| Silver maple | 1,631,600 | 293,100 | 3.2 | 9 | 10.0 | 1 |
| Red/black oak | 1,372,200 | 354,400 | 2.7 | 10 | 3.9 | 8 |
| Alder | 1,340,700 | 1,130,400 | 2.6 | 11 | 0.3 | 41 |
| Black locust | 1,073,000 | 637,900 | 2.1 | 12 | 0.5 | 35 |
| Poplar (other) | 885,600 | 528,200 | 1.7 | 13 | 1.0 | 25 |
| Mulberry | 880,300 | 166,500 | 1.7 | 14 | 1.7 | 17 |
| Shagbark hickory | 864,600 | 384,800 | 1.7 | 15 | 1.2 | 22 |
| Slippery elm | 841,100 | 588,200 | 1.7 | 16 | 0.9 | 28 |
| White oak | 807,800 | 247,300 | 1.6 | 17 | 8.5 | 3 |
| Crabapple | 779,700 | 108,200 | 1.5 | 18 | 1.8 | 15 |
| Honeylocust | 753,100 | 96,700 | 1.5 | 19 | 1.7 | 18 |
| Norway maple | 692,300 | 119,000 | 1.4 | 20 | 4.2 | 7 |
| Bur oak | 690,200 | 238,300 | 1.4 | 21 | 2.7 | 12 |
| Siberian elm | 332,800 | 86,100 | 0.7 | 31 | 1.4 | 20 |
| Norway spruce | 265,400 | 56,300 | 0.5 | 32 | 1.9 | 14 |
| Walnut | 264,100 | 127,100 | 0.5 | 33 | 1.4 | 19 |
| Swamp white oak | 171,700 | 64,800 | 0.3 | 41 | 1.8 | 16 |

Common and/or dominant species that contribute the most leaf area on a per-tree basis are white oak, swamp white oak, Norway spruce, silver maple, and Norway maple (Table 6). Species that contribute the most large-diameter trees to the study area are silver maple, white oak, American elm, bur oak, and cottonwood (Table 7). Common small-diameter tree species are buckthorn, *Prunus* spp., green/white ash, boxelder, and willow (Table 8).

Fifty-six percent of the trees in the study area are less than 7 cm (3 inches) in diameter and 76.9 percent are less than 15 cm (6 inches) d.b.h. (Table 9). Chicago has the highest proportion of large trees greater than 46 cm (18 inches) d.b.h. (7.5 percent). Land uses with the highest proportion of large trees are institutional land dominated by buildings (29 percent) and 1-3 family residential land (10 percent) (Appendix A, Table 15).

About 55 percent of the trees in the study area were rated in good condition and 10.5 percent were rated as dead or dying (Table 10). Land uses with the highest proportion of dead and dying trees are institutional land dominated by vegetation (16 percent), followed by institutional lands dominated by buildings (11 percent), and vacant land (9.5 percent) (Appendix A, Table 16).

The average LAI of individual trees is 4.3 in Chicago, 4.2 in suburban Cook County, 4.5 in DuPage County and 4.3 in the study area. The maximum LAI calculated using the regression equations for an individual tree was 18.1 with only 0.05 percent of the estimated LAI's for individual trees greater than 15. The estimated LAI for the entire study area, which accounts for the multiple layering of trees, is 6.3. The overall LAI may be slightly overestimated because of a likely conservative estimate of tree cover in Chicago. The large amount and size of buildings in Chicago tend to obscure small trees. This obstruction likely results in an underestimation of tree

Table 6. —Average leaf-surface area (m$^2$) per tree for top 20 species (in number and species dominance) in entire study area (index value is average species leaf area per tree divided by average leaf area per tree for entire population (81 m$^2$))

| Species | Leaf area per tree | Index value |
| --- | --- | --- |
| White oak | 436 | 5.4 |
| Swamp white oak | 422 | 5.2 |
| Norway spruce | 292 | 3.6 |
| Silver maple | 253 | 3.1 |
| Norway maple | 253 | 3.1 |
| Walnut | 219 | 2.7 |
| Siberian elm | 171 | 2.1 |
| Bur oak | 162 | 2.0 |
| Red oak | 117 | 1.4 |
| American elm | 109 | 1.3 |
| Cottonwood | 100 | 1.2 |
| Crabapple | 94 | 1.2 |
| Honeylocust | 91 | 1.1 |
| Mulberry | 79 | 1.0 |
| Green/white ash | 77 | 1.0 |
| Willow | 70 | 0.9 |
| Shagbark hickory | 60 | 0.7 |
| Boxelder | 55 | 0.7 |
| Poplar (other) | 48 | 0.6 |
| Slippery elm | 43 | 0.5 |
| Hawthorn | 42 | 0.5 |
| *Prunus* spp. | 38 | 0.5 |
| Black locust | 20 | 0.2 |
| Buckthorn | 19 | 0.2 |
| Alder | 10 | 0.1 |

Table 7. —Most common large trees given as percentage of total number of trees larger than 46 cm (18 inches) d.b.h.

| Species | Percent |
| --- | --- |
| Silver maple | 14.2 |
| White oak | 12.3 |
| American elm | 8.0 |
| Bur oak | 6.8 |
| Cottonwood | 6.7 |
| Willow | 5.5 |
| Siberian elm | 4.6 |
| Green/white ash | 4.6 |
| Red oak | 4.6 |
| Honeylocust | 4.6 |
| Norway maple | 2.5 |
| Mulberry | 2.2 |
| *Prunus* spp. | 1.5 |
| Boxelder | 1.5 |
| Hawthorn | 1.5 |

Table 8. —Most common small trees given as percentage of total number of trees less than 7 cm (3 inches) d.b.h.

| Species | Percent |
| --- | --- |
| Buckthorn | 18.7 |
| *Prunus* spp. | 8.9 |
| Green/white ash | 7.5 |
| Boxelder | 6.8 |
| Willow | 6.7 |
| American elm | 5.1 |
| Hawthorn | 4.6 |
| Alder | 4.4 |
| Cottonwood | 3.7 |
| Black locust | 2.5 |
| Shagbark hickory | 2.3 |
| Red oak | 2.2 |
| Slippery elm | 2.2 |
| Sugar maple | 1.8 |
| Silver maple | 1.5 |
| Mulberry | 1.4 |

Table 9. —Distribution of tree diameters in Chicago, suburban Cook County, DuPage County, and entire study area

| D.b.h. class (cm) | Chicago | | Cook County | | DuPage County | | Study area | |
|---|---|---|---|---|---|---|---|---|
| | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE |
| 0-7 | 41.3 | 4.6 | 58.5 | 2.2 | 54.5 | 5.2 | 56.0 | 2.1 |
| 8-15 | 22.2 | 1.8 | 20.2 | 1.2 | 22.2 | 3.0 | 20.9 | 1.2 |
| 16-30 | 19.9 | 2.1 | 12.7 | 1.2 | 15.0 | 2.3 | 13.9 | 1.0 |
| 31-46 | 9.1 | 1.1 | 5.1 | 0.6 | 4.3 | 0.5 | 5.2 | 0.4 |
| 47-61 | 3.5 | 0.7 | 2.2 | 0.3 | 2.4 | 0.4 | 2.3 | 0.2 |
| 62-76 | 1.9 | 0.4 | 0.7 | 0.2 | 1.3 | 0.2 | 1.0 | 0.1 |
| 77+ | 2.1 | 0.8 | 0.6 | 0.2 | 0.4 | 0.1 | 0.7 | 0.1 |
| All classes | 100.0 | | 100.0 | | 100.0 | | 100.0 | |

[a] Percentage of population

Table 10. —Distribution of trees by condition in Chicago, suburban Cook County, DuPage County, and the entire study area

| Condition class | Chicago | | Cook County | | DuPage County | | Study area | |
|---|---|---|---|---|---|---|---|---|
| | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE |
| Excellent | 9.4 | 1.2 | 9.4 | 1.1 | 14.6 | 1.8 | 10.9 | 0.9 |
| Good | 50.5 | 3.5 | 56.0 | 2.4 | 53.1 | 4.4 | 54.7 | 2.0 |
| Moderate | 25.9 | 2.4 | 17.8 | 1.3 | 15.3 | 2.4 | 17.7 | 1.1 |
| Poor | 7.9 | 1.3 | 5.2 | 0.7 | 8.0 | 1.7 | 6.2 | 0.7 |
| Dying | 1.4 | 0.2 | 2.2 | 0.5 | 2.4 | 0.6 | 2.2 | 0.3 |
| Dead | 5.0 | 1.0 | 9.4 | 1.2 | 6.6 | 1.3 | 8.3 | 0.8 |
| All classes | 100.0 | | 100.0 | | 100.0 | | 100.0 | |

[a] Percentage of population

cover and consequently a slight overestimation of the overall LAI. Thus, an overall LAI of 6.0 is probably more likely for the Chicago area. Conifers account for 6 percent of the leaf-surface area in the study area.

## Populations of Street Trees

There are an estimated 1,463,700 street trees in the study area (SE = 151,900), with 416,000 in Chicago (SE = 48,500), 854,300 in suburban Cook County (SE = 139,400), and 193,400 in DuPage County (SE = 35,700). Norway maple and honeylocust are the most common street trees in Chicago, silver maple and green/white ash in suburban Cook County, and green/white ash and Norway maple in DuPage County (Table 11). Street trees in the study area tend to be larger than trees in general— 51.5 percent of all street trees are 16 to 46 cm (6 to 18 inches) d.b.h. (Table 12). Chicago has the highest proportion of large street trees with 28.7 percent larger than 46 cm d.b.h. (Table 12).

Most street trees in the study area were rated as good (46 percent) or excellent (34 percent) (Table 13). Only 0.5 percent were rated as dead or dying. No dead or dying street trees

were found in Chicago or suburban Cook County. Street trees account for only 2.9 percent of the total tree population but 9.5 percent of the total leaf-surface area (Table 14). Street trees are most significant in Chicago where they account for 10.1 percent of the total population and 24 percent of total leaf-surface area. Dominance of street trees varies by land-use type with the greatest proportion occurring on residential lands in Chicago where street trees account for 27.9 percent of the trees and 43.7 percent of leaf-surface area (Table 14).

## Urban Ground Cover

The most common ground surfaces in the study area are maintained grass, tar, and herbaceous plants; common surfaces in Chicago are tar, maintained grass, and buildings (Table 15). Ground cover varied by land-use type with maintained grass the most common ground cover type on institutional and 1-3 family residential lands, tar most common on commercial/industrial and transportational lands, herbaceous cover most abundant on agricultural and vacant lands, and building cover most common on multifamily residential lands (Appendix A, Table 17).

Table 11. —Top 25 street tree species in study area by sector

| Species | Chicago | | | Cook County | | | DuPage County | | | Study area | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Percent[a] | SE | Rank | Percent[a] | SE | Rank | Percent[a] | SE | Rank | Percent[a] | SE | Rank |
| Silver maple | 13.1 | 4.0 | 3 | 26.5 | 9.1 | 1 | 17.0 | 6.8 | 3 | 21.5 | 5.5 | 1 |
| Green/white ash | 12.1 | 4.0 | 4 | 22.1 | 11.3 | 2 | 23.1 | 6.9 | 1 | 19.4 | 6.8 | 2 |
| Norway maple | 22.2 | 5.4 | 1 | 14.7 | 5.0 | 3 | 22.5 | 10.5 | 2 | 17.9 | 3.6 | 3 |
| Honeylocust | 22.0 | 6.5 | 2 | 3.2 | 3.0 | 8 | 7.0 | 4.2 | 4 | 9.0 | 2.6 | 4 |
| *Prunus* spp. | 0.0 | 0.0 | -- | 8.9 | 7.1 | 4 | 1.3 | 1.3 | 14 | 5.4 | 4.1 | 5 |
| Sugar maple | 2.1 | 1.5 | 10 | 5.1 | 2.9 | 6 | 4.1 | 4.1 | 7 | 4.1 | 1.8 | 6 |
| Linden | 3.2 | 2.0 | 6 | 4.2 | 2.4 | 7 | 5.1 | 3.6 | 6 | 4.0 | 1.6 | 7 |
| American elm | 1.0 | 1.0 | 16 | 5.7 | 3.2 | 5 | 1.5 | 1.5 | 11 | 3.8 | 1.9 | 8 |
| Chinese elm | 6.3 | 6.3 | 5 | 0.0 | 0.0 | -- | 0.0 | 0.0 | -- | 1.8 | 1.8 | 9 |
| Red/black oak | 0.0 | 0.0 | -- | 2.4 | 1.7 | 9 | 0.0 | 0.0 | -- | 1.4 | 1.0 | 10 |
| Siberian elm | 0.6 | 0.6 | 19 | 1.8 | 1.8 | 10 | 0.0 | 0.0 | -- | 1.2 | 1.0 | 11 |
| Hackberry | 0.6 | 0.6 | 18 | 1.6 | 1.6 | 11 | 0.0 | 0.0 | -- | 1.1 | 1.0 | 12 |
| Pear | 0.0 | 0.0 | -- | 0.3 | 0.3 | 15 | 6.9 | 5.0 | 5 | 1.1 | 0.7 | 13 |
| Maple (other) | 0.0 | 0.0 | -- | 1.6 | 1.6 | 12 | 0.0 | 0.0 | -- | 0.9 | 0.9 | 14 |
| Catalpa | 2.8 | 2.0 | 7 | 0.0 | 0.0 | -- | 0.0 | 0.0 | -- | 0.8 | 0.6 | 15 |
| Ailanthus | 2.8 | 2.0 | 8 | 0.0 | 0.0 | -- | 0.0 | 0.0 | -- | 0.8 | 0.6 | 16 |
| Norway spruce | 2.7 | 2.7 | 9 | 0.0 | 0.0 | -- | 0.0 | 0.0 | -- | 0.8 | 0.8 | 17 |
| Golden-rain tree | 2.1 | 2.1 | 12 | 0.0 | 0.0 | -- | 0.0 | 0.0 | -- | 0.6 | 0.6 | 19 |
| Basswood | 2.1 | 2.1 | 11 | 0.0 | 0.0 | -- | 0.0 | 0.0 | -- | 0.6 | 0.6 | 18 |
| Hawthorn | 0.0 | 0.0 | -- | 1.0 | 1.0 | 13 | 0.0 | 0.0 | -- | 0.6 | 0.6 | 20 |
| Pin oak | 0.0 | 0.0 | -- | 0.8 | 0.8 | 14 | 0.0 | 0.0 | -- | 0.5 | 0.5 | 21 |
| Red maple | 0.0 | 0.0 | -- | 0.0 | 0.0 | -- | 3.4 | 2.4 | 8 | 0.4 | 0.3 | 22 |
| Horsechestnut | 1.3 | 1.3 | 13 | 0.0 | 0.0 | -- | 0.0 | 0.0 | -- | 0.4 | 0.4 | 23 |
| White birch | 1.2 | 1.2 | 14 | 0.0 | 0.0 | -- | 0.0 | 0.0 | -- | 0.3 | 0.3 | 24 |
| Oak (other) | 0.0 | 0.0 | -- | 0.0 | 0.0 | -- | 2.4 | 2.4 | 9 | 0.3 | 0.3 | 25 |
| All species | 100.0 | | | 100.0 | | | 100.0 | | | 100.0 | | |

[a] Percentage of population

Table 12. —Diameter distribution of street trees in Chicago, suburban Cook County, DuPage County, and entire study area

| D.b.h. class (cm) | Chicago Percent[a] | SE | Cook County Percent[a] | SE | DuPage County Percent[a] | SE | Study area Percent[a] | SE |
|---|---|---|---|---|---|---|---|---|
| 0-7 | 15.7 | 5.6 | 7.1 | 3.4 | 29.5 | 11.6 | 12.5 | 3.0 |
| 8-15 | 4.0 | 2.2 | 24.0 | 12.5 | 13.9 | 5.8 | 17.0 | 7.4 |
| 16-30 | 30.3 | 6.6 | 26.8 | 6.8 | 20.5 | 6.5 | 27.0 | 4.5 |
| 31-46 | 21.4 | 4.7 | 27.2 | 6.5 | 19.0 | 9.7 | 24.5 | 4.2 |
| 47-61 | 12.8 | 3.8 | 10.6 | 3.5 | 7.0 | 4.9 | 10.7 | 2.4 |
| 62-76 | 7.6 | 3.0 | 4.3 | 2.6 | 5.2 | 3.1 | 5.4 | 1.8 |
| 77+ | 8.3 | 5.3 | 0.0 | 0.0 | 4.9 | 2.9 | 3.0 | 1.5 |
| All classes | 100.0 | | 100.0 | | 100.0 | | 100.0 | |

[a] Percentage of population

Table 13. —Distribution of street trees by condition in Chicago, suburban Cook County, DuPage County, and entire study area

| Condition class | Chicago Percent[a] | SE | Cook County Percent[a] | SE | DuPage County Percent[a] | SE | Study area Percent[a] | SE |
|---|---|---|---|---|---|---|---|---|
| Excellent | 18.8 | 4.8 | 41.7 | 13.8 | 30.3 | 12.2 | 33.7 | 8.3 |
| Good | 52.5 | 9.3 | 41.2 | 9.3 | 55.0 | 11.0 | 46.2 | 6.2 |
| Moderate | 26.0 | 6.9 | 14.7 | 4.9 | 8.2 | 3.7 | 17.0 | 3.5 |
| Poor | 2.7 | 1.6 | 2.4 | 1.7 | 3.0 | 2.1 | 2.6 | 1.1 |
| Dying | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Dead | 0.0 | 0.0 | 0.0 | 0.0 | 3.6 | 2.7 | 0.5 | 0.4 |
| All classes | 100.0 | | 100.0 | | 100.0 | | 100.0 | |

[a] Percentage of population

Table 14. —Street trees as a percentage of total tree population (%POP) and percentage of total leaf-surface area (%LSA) in Chicago, suburban Cook County, DuPage County, and entire study area

| Land use | Chicago %POP | %LSA | Cook County %POP | %LSA | DuPage County %POP | %LSA | Study area %POP | %LSA |
|---|---|---|---|---|---|---|---|---|
| Agriculture | NA | NA | NA | NA | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (bldg.) | 0.0 | 0.0 | NA | NA | 0.0 | 0.0 | 0.0 | 0.0 |
| Vacant | 1.0 | 0.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 |
| Institutional (veg.) | 0.7 | 6.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.6 |
| Multiresidential | 10.3 | 8.5 | 11.1 | 10.1 | 3.2 | 1.1 | 8.8 | 7.6 |
| Residential | 27.9 | 43.7 | 10.2 | 19.7 | 3.8 | 5.9 | 9.7 | 18.0 |
| Transportation | 11.5 | 5.5 | NA | NA | 0.0 | 0.0 | 10.3 | 3.8 |
| Commercial/indust. | 0.0 | 0.0 | 14.2 | 18.5 | 20.0 | 41.0 | 14.2 | 25.8 |
| Total | 10.1 | 24.0 | 2.7 | 9.5 | 1.3 | 3.6 | 2.9 | 9.5 |

Table 15. —Distribution of ground-surface materials in Chicago, suburban Cook County, DuPage County, and entire study area

| Surface type | Chicago | | Cook County | | DuPage County | | Study area | |
|---|---|---|---|---|---|---|---|---|
| | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE |
| Grass (maintained) | 20.4 | 1.4 | 30.7 | 2.0 | 32.6 | 1.8 | 29.3 | 1.2 |
| Tar | 21.3 | 2.6 | 13.3 | 1.8 | 11.5 | 1.2 | 14.3 | 1.1 |
| Herbaceous | 3.4 | 0.7 | 12.6 | 1.5 | 20.1 | 2.0 | 12.9 | 1.0 |
| Building | 16.5 | 2.1 | 9.1 | 1.3 | 8.0 | 1.2 | 10.1 | 0.9 |
| Cement | 12.2 | 1.2 | 5.8 | 0.7 | 3.7 | 0.5 | 6.4 | 0.5 |
| Soil | 4.5 | 0.6 | 7.5 | 1.4 | 4.1 | 1.2 | 6.1 | 0.8 |
| Shrub | 2.4 | 0.5 | 6.2 | 0.7 | 6.4 | 0.7 | 5.5 | 0.5 |
| Grass (unmaintained) | 2.5 | 0.8 | 3.4 | 0.7 | 7.7 | 1.8 | 4.3 | 0.6 |
| Other structure | 4.2 | 0.4 | 3.5 | 0.9 | 1.9 | 0.2 | 3.2 | 0.5 |
| Rock | 4.9 | 1.4 | 2.8 | 0.7 | 1.3 | 0.2 | 2.8 | 0.5 |
| Other impervious | 5.8 | 2.0 | 1.4 | 1.0 | 0.3 | 3.0 | 1.9 | 1.0 |
| Duff | 1.2 | 0.4 | 1.9 | 0.4 | 1.4 | 0.3 | 1.6 | 0.3 |
| Water | 0.3 | 0.2 | 1.8 | 1.0 | 1.0 | 0.3 | 1.3 | 0.6 |
| Wood | 0.3 | 0.2 | 0.1 | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 |
| All surfaces | 100.0 | | 100.0 | | 100.0 | | 100.0 | |

[a] Percentage of population

# Discussion

## Urban Forest Structure in the Chicago Area

The Chicago area's urban forest is composed mostly of small trees less than 15 cm d.b.h. (76.9 percent). Small trees also account for the majority of trees in other cities. In Shorewood, Wisconsin, and Oakland, California, 67 percent and 60.9 percent of the trees are less than 15 cm d.b.h., respectively (Dorney et al. 1984; Nowak 1993a). However, the distribution of tree sizes varies among and within land-use types depending on the duration and intensity of vegetation management. Less-managed (e.g., vacant) or naturalistically managed lands (e.g., forest preserves) had the highest proportion of small trees. Highly managed areas, particularly those managed for a relatively long period (e.g., street trees, residential areas), tend to have a higher proportion of large trees. However, there are some large old remnant trees throughout the Chicago area, particularly in forest preserves.

Most of the trees in the study area were classified as being in good condition. Ratings on tree condition are affected by urban-environmental stresses (e.g., salt, soil compaction, vandalism, injury), plant competition (related to tree density) and natural aging processes (tree size), all of which tend to increase crown discoloration and dieback (e.g., Nowak and McBride 1991). Consequently, relatively few trees were rated as excellent. Most of the dead and dying trees are in areas with minimal maintenance, naturalistic management, or in areas with more large trees that are not intensively managed (institutional land dominated by buildings). Dead and dying trees tend to be removed in the more intensively managed areas.

### Species Composition

The most common species is the exotic and highly invasive buckthorn, accounting for 12.7 percent of the tree population.

Seven of the 10 most common trees are native; three are genera of both native and exotic species. Four of the eight most common species are native pioneer species: green ash, boxelder, willow, cottonwood. These species have a propensity to colonize sites but have a shorter lifespan than more shade-tolerant species (Spurr and Barnes 1980; Burns and Honkala 1990). These species are common on all land uses but most common on vacant lands where they account for 47 percent of the population. Buckthorn is common on the three land uses that contain 95 percent of the trees (institutional lands dominated by vegetation, 1-3 family residential, and vacant lands). These land uses include many areas with relatively low maintenance (e.g., tree stands), which facilitates invasion by buckthorn. The most common ornamental species, exclusive of major pioneer species, planted on residential lands are silver maple, *Prunus* spp., blue spruce, crabapple, mulberry, Norway maple, arborvitae, honeylocust, American elm, and junipers.

The most common trees in Chicago are cottonwood and green/white ash, which make up 25 percent of the city's tree population. Green/white ash, both a pioneer and common ornamental tree, is common on most land uses in Chicago and accounts for 12 percent of all trees in the city. Cottonwood, which generally is not planted as an ornamental species, is the most common tree on vacant lands and institutional lands dominated by vegetation in Chicago. These land uses contain many low maintenance sites which facilitate invasion by cottonwood.

### Species and Individual Tree Dominance

The most dominant species in total leaf area are silver maple, green/white ash, white oak, and American elm. These four species most likely have the greatest impact on the surrounding environment and constitute 34.8 percent of total leaf-surface area. Institutional lands dominated by vegetation

are dominated by American elm, white oak, green/white ash, and red/black oak (39.8 percent of total leaf-surface area); 1-3 family residential areas are dominated by silver maple, green/white ash and white oak (31.7 percent); and vacant lands are dominated by the pioneer species of cottonwood, boxelder, willow, and poplar (other) (50.7 percent). Although buckthorn is the most common tree in the study area, it accounts for only 2.9 percent of total leaf-surface area due to its relatively small size.

The greatest average leaf-surface area on a per-tree basis occurs on white oak, swamp white oak, Norway spruce, silver maple, and Norway maple. Management activities should be directed toward preserving dominant individuals in a healthy condition so that their large environmental and social benefits, relative to smaller trees, are sustained (e.g., Schroeder and Cannon 1987; Nowak 1994a,b).

Diameter-growth rates of individual open-grown urban trees are relatively high (Nowak 1994b) and these growth rates are explained partially by the average LAI of individual trees in the study area (4.3), which is near the index level of maximum net growth. The overall urban tree LAI of 6.0 is at the low end of the normal range of LAI's exhibited for deciduous forests (Barbour et al. 1980). This relatively low index level is understandable considering the relative lack of lower level canopy (understory trees) in some urban areas that are common in deciduous forests. The urban forest understory of more intensively managed land uses often is occupied by grass or impervious surfaces.

### Street Trees
Street trees in Chicago constitute 1 of every 10 trees overall and 1 of every 4 trees in 1-3 family residential areas. Chicago's street trees contribute 24 percent of the total city leaf-surface area, and 44 percent of total leaf area on 1-3 family residential lands. Street trees play a less important role in less urbanized areas, but can still contribute significantly to the street-corridor environment (Schroeder and Cannon 1987).

In suburban Cook County, street trees constitute 1 of every 37 trees (9.5 percent of total leaf-surface area) and 1 of every 10 trees on residential land. In the least urbanized sector, DuPage County, street trees account for 1 of every 77 trees (3.6 percent of total leaf-surface area) and 1 of every 26 trees on residential land. Thus, street trees become a more important component of the urban forest in more urbanized areas as artificial surfaces and land-use activities compete for tree space.

A high percentage of street trees in the Chicago area are greater than 46 cm d.b.h. (Chicago: 28.7 percent; suburban Cook County: 14.9 percent; DuPage County: 17.1 percent). There is a 4 to 6 times higher percentage of large street trees than non-street trees. Large trees are important to the urban environment, contributing significantly more air quality and carbon dioxide sequestration benefits than small trees (see Nowak 1994a,b: Chapters 5 and 6, this report).

### Urban Ground Surfaces
Besides trees, a wide range of other urban surfaces interact with the surrounding environment and affect local gas and

energy exchanges, visual quality, human stress, etc. The most abundant urban ground surfaces in the study area are maintained grass, tar, herbaceous plants (e.g., agriculture crops) and buildings. Impervious surfaces cover 60 percent of Chicago, 33 percent of suburban Cook County, and 25 percent of DuPage County. Tar generally is the most common ground-surface cover of commercial/industrial and transportation lands. Maintained grass often is the most abundant surface on residential and institutional lands. Converting non-essential impervious surfaces (e.g., abandoned parking lots) to more pervious surfaces (e.g., soil) could facilitate the formation of vegetation and reduce surface runoff. Understanding how various urban surfaces interact to affect the local environment and city inhabitants remains to be investigated.

## Factors Influencing Current Vegetation Patterns
Vegetation within urban and urbanizing areas changes through time and space. Land use is one of the most significant factors affecting local vegetation patterns and distribution. In conjunction with its associated patterns of buildings and other artificial surfaces, land use influences the space available for trees and to some extent whether those spaces will be filled with trees and how they will be managed. Most of the nearly 51 million trees in Cook and DuPage Counties are on institutional lands dominated by vegetation, 1-3 family residences, and vacant land. This distribution pattern is similar to that for trees in Oakland, California (Nowak 1993a). These land uses generally are the most amenable to tree growth in urban areas and are likely where most of the trees exist in U.S. cities. Management plans should consider differences in tree distribution among land-use types to optimize tree configurations across the entire urban area. By understanding tree variations among land-use types, managers could focus planting efforts in areas typically lacking trees and direct species composition in more heavily-treed areas to meet specific management objectives and enhance the local environment.

In regions such as the Chicago area where trees are readily established through natural seeding, available planting space that is not filled with trees often has been actively managed to prohibit trees (e.g., mowing, use of herbicides, planting of herbs, selective tree removal). Such activities are necessary for land uses such as agriculture, airports, prairies, and sporting fields, but uses such as residential, commercial, and some transportation corridors could be used to increase tree cover if desired.

Tree cover can be increased through education and other promotional efforts that support tree planting and maintenance and/or encourage reducing management activities that prohibit trees and thereby allow trees to become established on the site naturally. Natural tree establishment can facilitate the development of invasive species so management activities should be directed toward altering species composition if certain invasive species are deemed undesirable.

The intensity of urban development also influences the amount of trees in a city, with tree density generally decreasing with urbanization. Average tree density in the Chicago area ranged from 68 trees/ha (28 trees/acre) in Chicago to 173 trees/ha

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(70 trees/acre) in DuPage County. There are two primary reasons for the decrease in tree density with increased urbanization. First, in more heavily urbanized areas, more of the land is occupied by uses that preclude tree establishment (e.g., commercial/industrial, transportation).[5] Second, tree space tends to be more limited in highly urban areas (i.e., residential lots tend to be smaller; impervious surfaces occupy a higher proportion of the ground area).

Tree density on residential and commercial land in Chicago is comparable to those in Shorewood, Wisconsin, for the same land uses (Dorney et al. 1984). Tree density from other urban areas are 120 trees/ha (49 trees/acre) in Oakland, California (Nowak 1993a) and 373 and 40 trees/ha (151 and 16 trees/acre) for portions of South Lake Tahoe and Menlo Park, California, respectively (McBride and Jacobs 1986). By contrast, the average live tree density on timberland in Illinois is 1,186 trees/ha (480 trees/acre) (Raile and Leatherberry 1988).

Besides affecting management and various environmental functions, tree density affects visual quality of a landscape. Optimal foreground density for aesthetic quality in municipal parks has been estimated at approximately 125 trees/ha (51 trees/acre) (Schroeder and Green 1985). High tree densities and large trees are also preferred along streets (Schroeder and Cannon 1987).

Most of the differences in vegetation patterns within the study area are due to differences in land-use distribution, intensity of urbanization, and age of development. Chicago is the oldest, most urbanized area while DuPage County is the most suburban to rural area with newer residential developments and the highest proportion of agricultural areas.

### Directing Future Urban Forest Structure in the Chicago Area

The future urban forest in the Chicago area, as indicated by the distribution of tree species less than 7 cm d.b.h., is likely to be dominated by green/white ash, boxelder, willow, cottonwood, black locust, and shagbark hickory. Other common species (buckthorn, *Prunus* spp., hawthorns, alders) in this smallest d.b.h. class generally do not reach a dominating size. American elm also is a common small tree, but sanitation programs and/or the planting of cultivars that resist Dutch elm disease must be continued or utilized if American elms are to maintain a dominant position in the Chicago area's urban forest.

This probable future forest will mean a shift from silver maple and white oak that codominate today toward more invasive pioneer species. While silver maple, white oak, and bur oak account for one-third of the trees greater than 46 cm d.b.h., they make up only 3.3 percent of the trees less than 7 cm d.b.h. However, planners and managers can alter or direct future species composition and structure (Nowak 1993c).

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[5] Rural areas also can have land uses where low tree densities are typical (e.g., agriculture, vacant land in desert areas).

Education and management can influence the amount, type, and location of urban vegetation (e.g., tree planting in backyards and parking lots) and thereby direct future urban forest structure to a desirable outcome. Trees are not appropriate in all locations or land uses. However, where trees are desirable, planning and management can facilitate proper urban forest structure. The more space available for tree planting that is not inhibited by the existing land use, the more the natural environment and local planning and management can influence vegetation structure (e.g., vacant lands, parks).

Management plans should consider directing current urban forest structure toward a future structure that enhances healthy, functional leaf-surface area and optimizes species composition to maximize both social and environmental benefits of trees. Management plans should be developed to meet specific local needs, for example, enhancing the scenic beauty of a park or reducing air pollution in a certain area. Managing for one need or to maximize one benefit may reduce some other benefits derived from urban trees, so local and regional management priorities and plans must be developed. Besides preserving large trees, multilayer forest structures (stand conditions) should be sustained where appropriate, and healthy canopies should be maintained to maximize many tree benefits. Also, ample water should be supplied to trees to optimize benefits that are linked with transpiration (e.g., removal of gaseous pollutants and reduced air temperatures).

### Implications for Research

The equations developed to predict the leaf-surface area of individual urban trees appear to yield reasonable estimates when applied within the bounds in which the regression equations were developed. However, more work is needed on developing shading coefficients and leaf-area predictions for individual species, particularly for large trees and coniferous species. Also needed is additional research on urban-forest structure and its link to various functions for other U.S. cities to help clarify and determine existing urban-forest patterns and processes. Finally, researchers need to investigate changes in urban forest structure and functions through time to better predict and understand the dynamics of these ecosystems, and to determine how urban surfaces interact in affecting the local environment and inhabitants.

## Conclusion

Urban forest planning and management can direct urban forest structure toward a desired outcome. One of the first steps in properly directing urban forest structure is to understand if, and what, changes are necessary by analyzing the existing urban forest structure. By understanding forest structure and determining the relationships between structure and forest functions, various social and environmental benefits can also be quantified. The Chicago area urban forest contains 50.8 million trees, approximately 9 trees per resident. Most of the trees are small and predominantly found on institutional, residential and vacant lands.

The current pattern of urban vegetation has been formed through both present and past human and environmental factors. Education of both the public and private sectors can facilitate directing future urban forest structure toward desired results as dictated by urban forest management plans. However, the urban environment (e.g., land uses) presents many constraints on urban forest structure that managers and planners must consider.

Relatively short-lived pioneer species contribute significantly to the Chicago area urban forest and are most prevalent on land uses with minimal or naturalistic management (e.g., forest stand conditions). Street trees are also important elements of the urban forest, particularly in the City of Chicago. Trees are just one of many surfaces that interact to influence the urban environment; other prominent ground surfaces include tar and grass.

# Acknowledgments

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# Chapter 3

# Investigation of the Influence of Chicago's Urban Forests on Wind and Air Temperature Within Residential Neighborhoods

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## Abstract

Ongoing research is examining the degree to which climate that surrounds people and houses in residential neighborhoods in the City of Chicago and adjacent communities is influenced by trees. The general research approach is to use windspeed, air temperature, and humidity at the nearest airport as reference conditions to compare differences in these climate variables between points in residential neighborhoods. Regression analysis is used to develop models to relate climate differences to measures of urban structure. The climate variables were measured for about 11 months at O'Hare International Airport, at two other reference locations, and in residential neighborhoods. The measurements in neighborhoods were made with four portable meteorological systems that were moved to sample 39 locations during the study period. Preliminary analyses indicate that it is possible to derive equations to predict the effect of buildings on windspeed separately from the effects of trees. The practical application of this is that, upon completion of the analysis, equations will be available to indicate the effect on wind within a neighborhood if the numbers or sizes of trees are changed. A goal of the study is to derive similar equations for tree effects on air temperature. Over three summertime days, temperatures in residential neighborhoods were higher on average than at the airport, though they were sometimes lower and sometimes higher than at the airport, depending largely of the net radiation balance. In the middle of a day with clear skies and bright sun, temperatures were slightly higher in a narrow space between two buildings than in a front yard near street trees. The relationships between climate and urban structure will apply best in the Chicago area, but extrapolation to other areas with a similar general climate and urban structure should be possible. These relationships are necessary for predicting effects of trees on energy use in buildings, human thermal comfort, and air quality.

## Introduction

In this paper we describe ongoing research that is examining the degree to which climate at the height of people and houses in the Chicago area is influenced by trees. The general approach is to measure windspeed, air temperature, and humid-ity and then to develop equations to relate differences in these climate variables to measures of urban structure. By urban structure or morphology, we mean here the three-dimensional pattern of buildings, trees, and ground-surface characteristics (paved, grass, water, bare soil, etc.). The degree of success that we have in developing the relational equations will largely determine our ability to evaluate the effects of trees on climate within the urban area. The equations or models must be able to separate tree effects from building effects. Average windspeed and air temperature are the climate variables for primary consideration, though possible influences of tree distribution on humidity will also be examined.

Trees can have a major impact on the human environment in residential neighborhoods (Heisler 1986a; Oke 1989). For example, tree influences on wind (Heisler 1990a), air temperature and humidity (Grant 1991), and solar and long-wave radiation influence energy use in buildings (Heisler 1986a, 1990b; McPherson 1994; McPherson et al. 1988), human thermal comfort, air quality (Nowak 1994a), growth of smaller vegetation, and insect distribution (Heisler and Dix 1991). The influence of trees on solar radiation is directly related to geometrical factors that, although complex, have been studied sufficiently to provide at least approximate quantification of tree influences (e.g., Heisler 1986b, 1991). However, considering either a point in a residential neighborhood or the neighborhood generally, few tree effects on below-canopy air—its motion, temperature, humidity, and polluting constituents—can be estimated with sufficient accuracy for planning purposes. Below-canopy refers to the space below the general level of the tallest trees or buildings.

There have been few measurements of wind within residential neighborhoods (Heisler 1990a), and most available study reports, though containing valuable information, are for one season of the year or for a small number of sampling points (e.g., McGinn 1983). The general pattern of analysis in this study follows that used in a previous study in central Pennsylvania that showed a strong relationship between tree cover in the upwind direction and reductions in average windspeed in several neighborhoods that were typical of suburban developments (Heisler 1990a). Earlier studies with measurements in Dayton, Ohio, initially demonstrated the feasibility of developing prediction equations by statistical methods to relate windspeed at street level to building dimensions in the central business district (Grant et al. 1985; Heisler and Grant 1987).

Many studies have investigated the influence of urbanization on air temperature in both the above- and below-canopy space. Air temperatures have been related to land use, and clear distinctions in spatial and temporal patterns of air temperature have been observed between, for example, parks with many trees and surrounding building areas. The parks generally are cooler. However, such studies do not indicate the separate effects of buildings and trees. For example, given park land with 30-percent tree cover, it does not follow that a nearby neighborhood with streets and houses will have a similar temperature pattern if tree cover there also is 30 percent.

In discussions of tree effects on energy use, the potential of trees to save air conditioning costs through reductions in air temperature by evapotranspiration is often mentioned and incorporated in models (e.g., Huang et al. 1987). However, trees influence air temperature through other important aerodynamic and thermodynamic effects. For example, the trees throughout a neighborhood influence wind flow, which in turn influences exchange of the air below the general level of tree crowns with the air above. Some measurements (McGinn 1983) suggest that with moderate tree cover in a residential neighborhood, air temperatures may tend to be higher than with either more or less tree cover. This could be the result of the trees in the moderate-cover neighborhood reducing the air exchange while allowing most of the solar radiation to penetrate to ground level. In a forest with a complete canopy, there is little exchange of air between above- and below- canopy layers, but little solar radiation penetrates to heat the ground and below-canopy air. A complete forest may be approximated by the trees in a neighborhood with high tree cover, whereas with moderate tree cover, the trees cause significant reductions in below- to above-canopy air exchange but relatively small reductions in penetration of solar radiation to below-canopy species. Though solar radiation penetration may be greater in neighborhoods with low than with moderate tree cover, air exchange may be sufficient in the low tree density neighborhoods to keep them cooler at the height of people and buildings than in the neighborhoods with moderate cover.

Analogies can be made between the effects of the aggregate of trees in residential neighborhoods and traditional tree row windbreaks (Heisler and DeWalle 1988, McNaughton 1989). In the protected zone close behind windbreaks, air temperatures tend to be higher during the day, than upwind or farther downwind. At night, air temperatures in the near lee behind windbreaks may be relatively low because there are large losses of heat from the ground by long-wave radiation and relatively little mixing between the sheltered air and air flowing above the windbreak. Of course, in residential neighborhoods the situation is more complex because of interactive effects of trees and buildings on wind flow, heat storage, and radiation exchanges.

This study was carried out in conjunction with two other meteorological studies in the Chicago Urban Forest Climate Project. One study includes a description of the relationship between general weather patterns and air-flow fields over the city of Chicago (Grant 1993). That work is essential for interpreting meteorological observations in this study. The general area for meteorological data collection (Figure 1) was identical to that described in the study of local-scale energy and water exchange (Grimmond et al. 1994: Chapter 4, this report); data from the fixed meteorological measurement points at O'Hare Airport, the tall tower (ISPT3), and the Belmont Harbor light tower provide the reference conditions for this study. The land-use database described in Chapter 4 provides information for quantifying the urban structure in this study.

A general assumption is that climate variables at the airport site, which is in the middle of a large open area, are uninfluenced by trees and buildings. For purposes of developing the predictive models in this study, the differences that we are seeking to model generally are those between the hourly averages of windspeed and air temperature at points in residential neighborhoods and the reference point at O'Hare Airport. These differences form the dependent variables in the analysis. Descriptors of the structure of trees and buildings around the climate sample points in the residential neighborhoods form the independent variables. Some of the descriptors are derived from plat maps and aerial photographs and analyzed via a geographical information system (GIS); others are derived from analysis of hemispherical photographs taken from the climate sample points. An important objective of this study is to evaluate the efficiency with which descriptors can be developed by the different methods.

If the predictive model building is successful, the models will provide research tools to answer such questions as: What happens to wind and air temperature at specified kinds of sites or generally in a neighborhood configuration if we add a given number of trees of given sizes? The models will apply most directly to Chicago residential neighborhoods that have building and tree cover densities within the range of those included in this study. With this same constraint on range of cover densities, the models could be extrapolated to other cities with similar climates. The minimum input required to use the models would be some quantification of existing building and tree structure and general weather data for the period of interest. Weather data could be in the form of averages for each hour of a typical year. These data sets are available for over 200 cities in the United States (National Climate Center 1981).

Windspeed, wind direction, air temperature, and humidity were measured with 10 sets of sensors that operated almost continuously for nearly 11 months. The sensors were distributed among the three reference points and 39 below-canopy locations in residential neighborhoods (Figure 2). In this paper we describe the methods of data collection and the methods being used in the analysis of the entire data set. That analysis is not yet complete, but a partial analysis for a sample of the total meteorological and urban structural data is presented here to illustrate the methods.

## METHODS

### Meteorological Instrumentation

The meteorological sensors measured averages of windspeed, wind direction, air temperature, and humidity along with associated maximum and minimum values and standard deviations from July 16, 1992, to June 14, 1993. The wind, temperature, and humidity sensors were mounted perma-
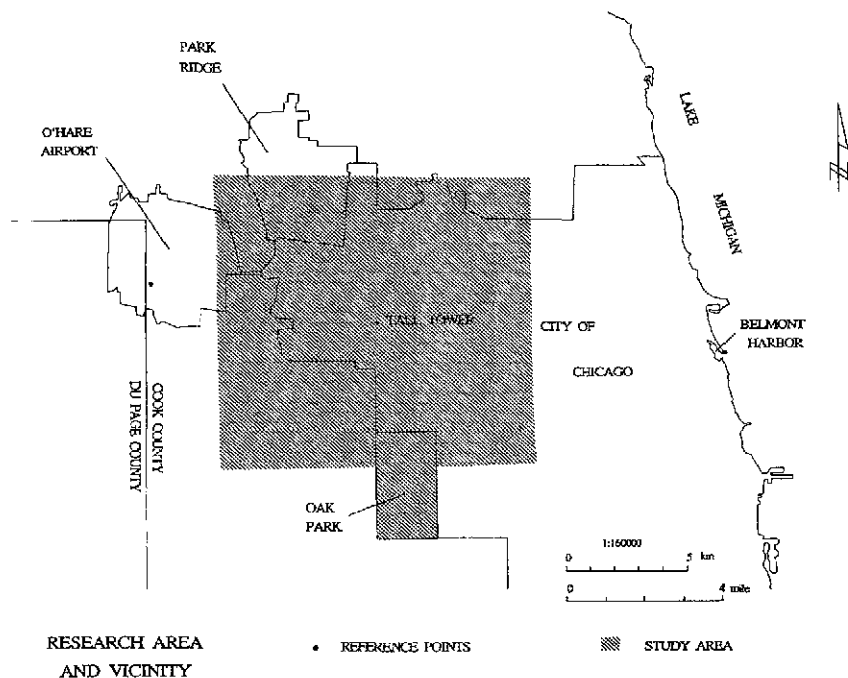
Figure 1.—Research area and meteorological reference points in and near Chicago.
The tall tower is ISPT3 in Grimmond et al. (1994: Chapter 4,this report). The large
portion of the shaded study area is bordered by Touhy Avenue on the north, Pulaski
Road on the east, Chicago Avenue on the south, and Mannheim Road on the west.

nently at three reference locations: 1) within 8 feet (2.4 m) of the ground about 50 feet (15 m) from the National Weather Service instrument tower at O'Hare Airport; 2) at the 81-, 141-, and 228-foot (25-, 43-, and 69-m) levels on a radio tower about 6 miles (9.7 km) east of the airport location; and 3) on the shore of Lake Michigan at Belmont Harbor, about 15 miles (24 km) east of the airport (Figure 1). Specific instruments at the three reference sites are listed by brand name in Table 3, Chapter 4.

Below-canopy meteorological data were measured at the 39 sites (Figure 2) with five portable instrument packages mounted on TV antenna tripods (Figure 3) that were at a particular site for varying time periods. These measurements included air temperature and relative humidity at the 5-foot (1.5-m) height, and windspeed and direction at 7.8 feet (2.35 m).

Meteorological data were recorded on compact portable data loggers of a type that is widely used in environmental measurements. The loggers were programmed to provide instantaneous measurements every 5 seconds and, with one exception, average these over 15 minutes. For final analysis, the 15-minute averages will be combined into 1-hr averages of the meteorological data. There usually is a natural period in meteorological data near the surface of the earth such that averages over 30 minutes to 1 hour tend to represent the general trend of conditions, whereas averages over periods

much shorter than 30 minutes include considerable random scatter associated with large-scale turbulent eddies (Panofsky and Dutton 1984). Because we had to substitute a data logger with a smaller memory for one that failed at O'Hare Airport, the averages there are over 1-hr periods for about 6 of the 11 months of data collection.

To acquire accurate temperature data, it is important to place the temperature sensor in a well-shielded and ventilated location to prevent errors from the influence of solar radiation on the temperature measurement. Although commercially produced shields are available, our experience is that none provides adequate shielding for the conditions we faced — some measurements in deep shade, some in full sun. With some temperature-measurement systems, errors frequently exceed 2°F (1°C). The requirement for battery operation for the portable units made design of the shield particularly crucial; the shields we used were designed specifically for this study (Grant and Heisler 1994). Each radiation shield held a small-bead thermistor inside a 1-inch-diameter inner tube and a combination temperature and humidity sensor that was protected only by a larger outer tube. A fan pulled air over both types of sensors. Tests of shielding efficiency suggest that the maximum radiation error for the small thermistor was about 0.18°F (0.10°C), whereas the maximum radiation error for the temperature sensor in the humidity unit was about 0.90°F (0.5°C).

BELOW– CANOPY DATA POINTS
IN CHICAGO
URBAN FOREST STUDY AREA

- BELOW–CANOPY DATA POINT
· POINTS WITH ELLIPSE ANALYSIS
▲ TALL TOWER

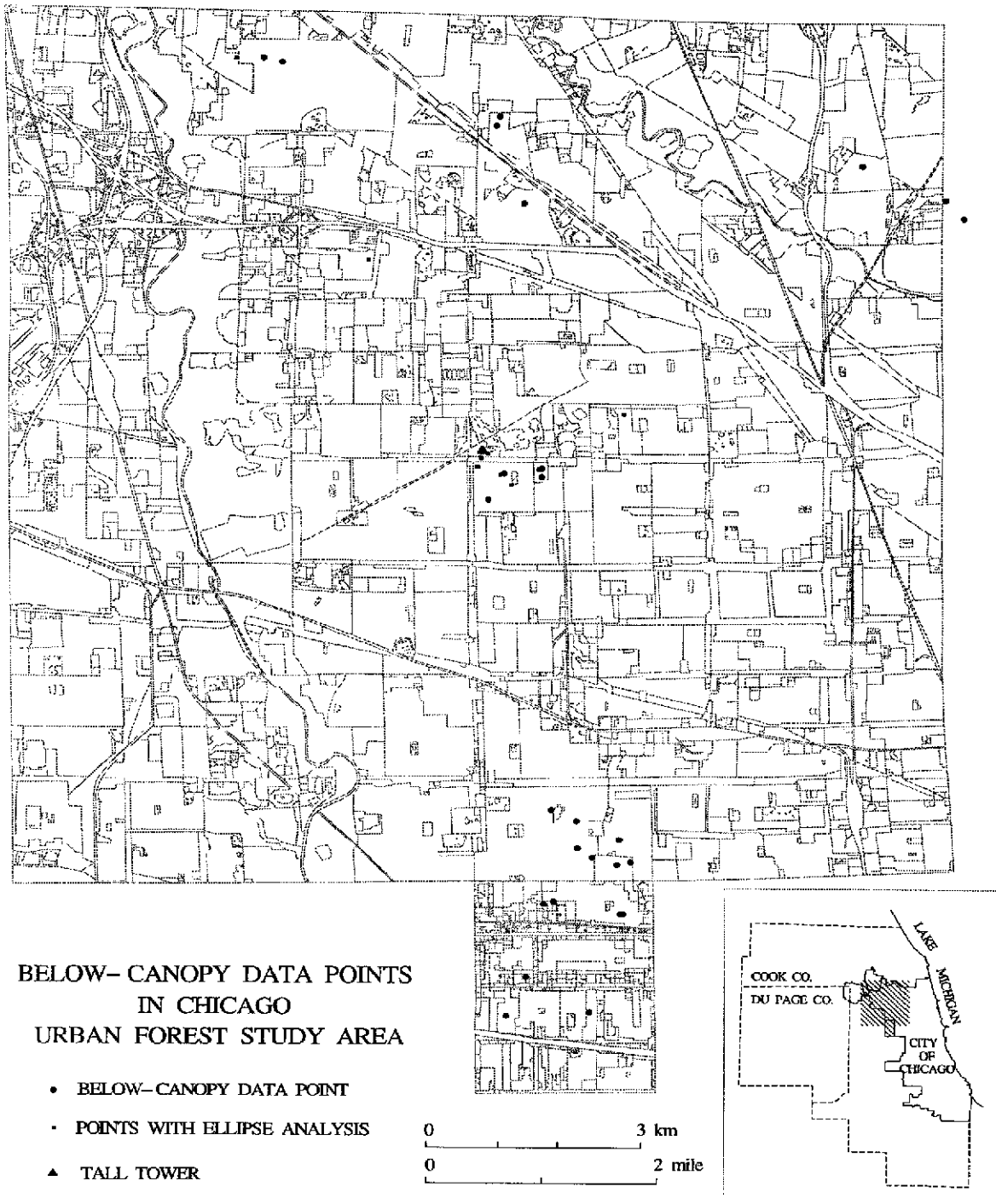Figure 2.—Location of below-canopy meteorology sampling points and the pattern of land-use polygons in the land-use data base. Square symbols mark ten points used in ellipse spatial analysis.
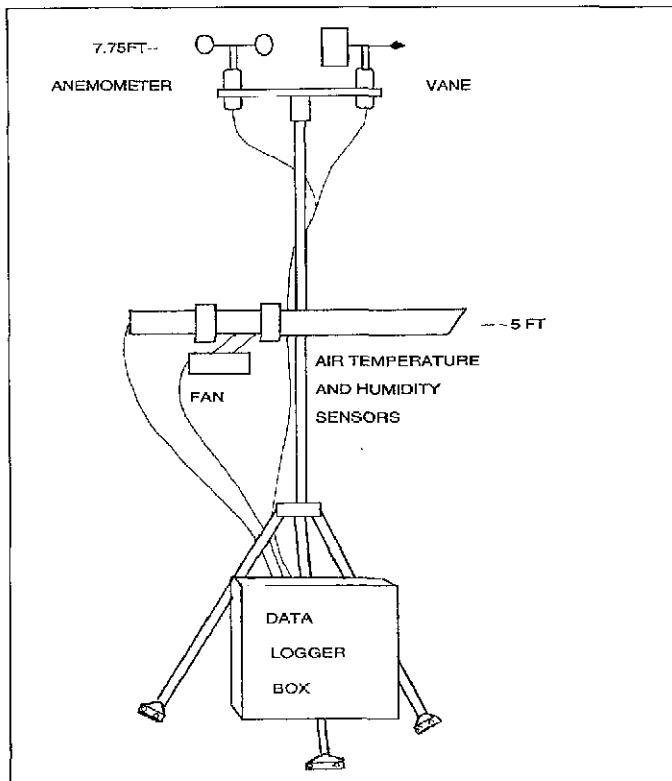
Figure 3.—Schematic of portable tripod and instruments for below-canopy measurements.

Each week, all sites in the network of meteorological instruments were visited for maintenance, to collect the data, and to move portable units scheduled for rotation. The below-canopy units generally performed well until mid-December 1992, when an ice storm apparently damaged some of the small-bead thermistors and caused some of the fans to fail. Fans on the below-canopy units and at the airport were changed, generally within several days of detected malfunctions.

## Observation Site Selection

One of the five below-canopy units was maintained for the entire time in an area of tall grass near the ISPT3 tall tower (Figure 2). The other four units were rotated between sites in back yards, in front yards, in vacant lots, in narrow spaces between houses, and in an extensive woodlot, all between 3 and 9 miles (6 and 15 km) easterly from the airport, for 1 to 11 weeks (Table I). All except for the woodlot site (which is just off the east side of the GIS map) were in areas with 5 to 50 percent of the area covered by trees (Figure 4) and at least 10-percent coverage with trees, grass, and/or shrubs (Figure 5). A large proportion of points are located in Oak Park (Figures 1 and 2) partly because that community is developing a very complete tree inventory and GIS database of building structural features that will be made available for our analyses.

The sampling pattern and schedule had to be fairly flexible to accommodate homeowners' wishes. Location of the points depended partly on finding lawn space that was not heavily used for some purpose such as playing ball and where there was some degree of security. A goal was to sample each point in both summer and winter; however because of changes in ownership or homeowners' wishes, some points were sampled in only one season (Table I). Ideally, the rotation of instruments would have been done more frequently and each point would have been sampled several times during each season; however this was precluded by the limited availability of field personnel. More frequent rotation would have resulted in smaller differences between the sites in general weather conditions sampled. At some sites where the instruments provided particularly minimal inconvenience for the homeowner and also included morphologies that were in short supply elsewhere, we sampled for longer periods than at other sites.

If building and tree effects are to be separated in statistical models, it is necessary to sample over a wide range of both building and tree morphologies (particularly for areas covered by trees and buildings). Further, there must not be a high degree of correlation between the tree and building morphology. The number of points required to sample a sufficient range of building and tree morphologies depends in part on the variability of morphologies within the neighborhoods where measurements are made. To accommodate these requirements in so far as possible, we used aerial photographs and satellite images to visually explore the study area. We had some difficulty in finding a wide range of tree and building morphologies in the study area. Almost the entire area has older homes with relatively high building density and moderate tree cover. Tree cover tends to be inversely proportional to building density, and neighborhoods with either very low or very high cover are rare. We located the sample point in the woodlot to provide a sample of conditions at the upper limit of tree density. To the west of O'Hare International Airport there are many typical suburban neighborhoods with a wide range of building density and tree cover, but travel time and the lack of a tall tower reference prevented our sampling there.

Fortunately, the method of analysis, with the airport for a reference, greatly reduced the importance of uniform general weather conditions at each climate sampling point. Also, the range of structural conditions sampled varied substantially even at individual points, as the vegetation or buildings with greatest influence changed with wind direction. The Results Section has further discussion of the degree to which we succeeded in sampling in neighborhoods with differing morphologies.

For many of the points, a special effort was made to find lawn spaces between houses that were at least as wide as most of the houses so that meteorological conditions near the middle of the lawn would be representative of a possible house location. However, other points sampled a range of distances to nearest buildings, to dense conifer trees, to tall-crowned deciduous trees, and to hedges. Some points sampled narrow spaces between houses. In the prototype study by Heisler (1989 and 1990a), anemometers were located to sample the effects of the general aggregate of vegetation throughout the neighborhoods; dense tree rows and hedgerows were avoided. In this study we included the

USDA Forest Service Gen. Tech. Rep. NE-186. 1994.

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Table 1. —Location of below-canopy meteorological instruments. Unit indicates which of the five below-canopy systems was used; and the "loc" column is the order of site placement, alphabetically, for that unit.

| Site | Unit | Loc | Address | Total Days (Julian) | Started Date | Time | Finished Date | Time | Leaves[*] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | a | Irving Park Road and Harlem, Chicago | 198-165 | 16 Jul 92 | 0900 | 14 Jun 93 | 1240 | O,S,I,F |
| 1 | 3 | l | Irving Park Road and Harlem, Chicago | 084-103 | 25 Mar 93 | 1147 | 13 Apr 93 | 1015 | O |
| 2 | 2 | a | 7915 Irving Park Rd., Chicago | 199-206 | 17 Jul 92 | 1030 | 24 Jul 92 | 1000 | I |
| 3 | 3 | a | 3915 Neva, Chicago | 199-206 | 17 Jul 92 | 1345 | 24 Jul 92 | 1025 | I |
| 3 | 3 | k | 3915 Neva, Chicago | 068-082 | 9 Mar 93 | 1000 | 23 Mar 93 | 1245 | O |
| 4 | 4 | a | 3909 Neva, Chicago | 199-206 | 17 Jul 92 | 1345 | 24 Jul 92 | 1045 | I |
| 5 | 5 | a | 3642 N. Nordica, Chicago | 200-206 | 18 Jul 92 | 1030 | 24 Jul 92 | 1400 | I |
| 5 | 5 | h | 3642 N. Nordica, Chicago | 033-047 | 2 Feb 93 | 1409 | 16 Feb 93 | 1131 | O |
| 6 | 2 | b | 3846 N. Sayre, Chicago 60634 | 206-212 | 24 Jul 92 | 1315 | 30 Jul 92 | 1600 | I |
| 6 | 3 | h | 3846 N. Sayre, Chicago 60634 | 026-040 | 26 Jan 93 | 1458 | 9 Feb 93 | 1319 | O |
| 7 | 3 | b | 3839 N. Nora, Chicago | 206-212 | 24 Jul 92 | 1130 | 30 Jul 92 | 1730 | I |
| 7 | 3 | j | 3839 N. Nora, Chicago | 054-068 | 23 Feb 93 | 1153 | 9 Mar 93 | 1639 | O |
| 8 | 4 | b | 6730 W. Byran, Chicago 60634 | 206-222 | 24 Jul 92 | 1230 | 30 Jul 92 | 900 | I |
| 8 | 3 | i | 6730 W. Byron, Chicago 60634 | 040-054 | 9 Feb 93 | 1435 | 23 Feb 93 | 1045 | O |
| 9 | 5 | b | 6727 W. Byron, Chicago 60634 | 214-217 | 27 Jul 92 | 1845 | 4 Aug 92 | 1917 | I |
| 10 | 2 | c | 7546 Bryn Mawr, Chicago | 212-287 | 30 Jul 92 | 1630 | 13 Oct 92 | 1132 | I |
| 10 | 4 | h | 7546 Bryn Mawr, Chicago | 012-033 | 12 Jan 93 | 1220 | 2 Feb 93 | 1446 | O |
| 11 | 3 | c | 6221 Knox, Chicago | 212-252 | 30 Jul 92 | 1830 | 8 Sep 92 | 0835 | I |
| 11 | 5 | f | 6221 Knox, Chicago | 330-357 | 25 Nov 92 | 1100 | 29 Dec 92 | 0930 | O |
| 12 | 4 | c | 6728 W. Byron, Chicago 60634 | 212-224 | 30 Jul 92 | 1617 | 11 Aug 92 | 1410 | I |
| 12 | 4 | i | 6728 W. Byron, Chicago 60634 | 033-047 | 2 Feb 93 | 1527 | 16 Feb 93 | 1103 | O |
| 13 | 5 | c | 4308 Moody, Chicago 60656 | 217-252 | 4 Aug 92 | 1648 | 8 Sep 92 | 1510 | I |
| 13 | 3 | g | 4308 Moody, Chicago 60656 | 364-026 | 29 Dec 92 | 1445 | 26 Jan 93 | 1407 | O |
| 14 | 4 | d | Newland and Grace, Chicago | 224-252 | 11 Aug 92 | 1515 | 15 Sep 92 | 1550 | I |
| 14 | 3 | f | Newland and Grace, Chicago | 329-364 | 24 Nov 92 | 1400 | 29 Dec 92 | 1345 | O |
| 15 | 3 | d | 5535 N. Linden Ave., Norwood Park | 252-315 | 10 Sep 92 | 0915 | 10 Nov 92 | 1405 | I,F |
| 16 | 5 | d | Pulaski Rd., Chicago | 254-288 | 10 Sep 92 | 1200 | 17 Nov 92 | 1404 | I |
| 16 | 5 | g | Pulaski Rd., Chicago | 357-033 | 22 Dec 92 | 1505 | 2 Feb 93 | 0915 | O |
| 17 | 4 | e | 506 Western Ave., Park Ridge | 259-315 | 15 Sep 92 | 1130 | 10 Nov 92 | 1239 | I,F |
| 18 | 2 | d | 505 Delphia, Park Ridge | 287-321 | 13 Oct 92 | 1312 | 16 Nov 92 | 1235 | F |
| 19 | 4 | f | 6855 W. Thorndale | 315-343 | 10 Nov 92 | 1330 | 8 Dec 92 | 0900 | O |
| 20 | 2 | e | Pulaski Rd., Chicago | 321-329 | 16 Nov 92 | 1515 | 24 Nov 92 | 0900 | O |
| 21 | 3 | e | Pulaski Rd., Chicago | 321-329 | 16 Nov 92 | 1200 | 24 Nov 92 | 0930 | O |
| 22 | 5 | e | Pulaski Rd., Chicago | 322-329 | 17 Nov 92 | 1500 | 24 Nov 92 | 0915 | O |
| 23 | 2 | f | 539 S. Chester Ave., Park Ridge | 329-357 | 24 Nov 92 | 1500 | 22 Dec 93 | 1011 | O |
| 24 | 4 | g | 6460 Nordica, Chicago | 343-012 | 8 Dec 92 | 0954 | 12 Jan 93 | 1134 | O |
| 25 | 2 | g | 7024 W. Devon Ave., Chicago, 60631 | 357-019 | 22 Dec 92 | 1104 | 19 Jan 93 | 1251 | O |
| 26 | 2 | h | 529 N. Harvey, Oak Park 60302 | 047-068 | 16 Feb 93 | 1349 | 9 Mar 93 | 1422 | O |
| 27 | 4 | j | 741 Fair Oaks Ave., Oak Park 60302 | 047-068 | 16 Feb 93 | 1300 | 9 Mar 93 | 1530 | O |
| 27 | 4 | n | 741 Fair Oaks Ave., Oak Park 60302 | 139-165 | 19 May 93 | 1134 | 14 Jun 93 | 0835 | S,I |
| 28 | 5 | i | 1133 N. Linden, Oak Park 60302 | 047-068 | 16 Feb 93 | 1230 | 9 Mar 93 | 1257 | O |
| 29 | 2 | i | 819 Mapleton, Oak Park 60302 | 068-082 | 9 Mar 93 | 1510 | 23 Mar 93 | 0925 | O |
| 29 | 2 | l | 819 Mapleton, Oak Park 60302 | 139-165 | 19 May 93 | 1245 | 14 Jun 93 | 0845 | S,I |
| 30 | 4 | k | 945 Fair Oaks Ave., Oak Park 60302 | 068-082 | 9 Mar 93 | 1621 | 23 Mar 93 | 1027 | O |
| 30 | 5 | m | 945 Fair Oaks Ave., Oak Park 60302 | 139-165 | 19 May 93 | 1210 | 14 Jun 93 | 0815 | S,I |
| 31 | 5 | j | 701 S. Elmwood, Oak Park 60302 | 068-082 | 9 Mar 93 | 1400 | 23 Mar 93 | 1145 | O |
| 32 | 2 | j | 233 N. Euclid, Oak Park 60302 | 082-084 | 23 Mar 93 | 1000 | 25 Mar 93 | 1310 | O |
| 33 | 4 | l | 213 S. Grove, Oak Park 60302 | 082-089 | 23 Mar 93 | 1130 | 30 Mar 93 | 1320 | O |
| 34 | 5 | k | 630 N. Lombard, Oak Park 60302 | 082-112 | 23 Mar 93 | 1215 | 22 Apr 93 | 1015 | O,S |
| 35 | 2 | k | 320 N. Euclid, Oak Park 60302 | 084-139 | 25 Mar 93 | 1325 | 19 May 93 | 1245 | O,S |
| 36 | 4 | m | 702 N. Elmwood, Oak Park 60302 | 089-139 | 30 Mar 93 | 1415 | 19 May 93 | 1130 | O,S |
| 37 | 3 | m | 725 S. Clinton | 103-139 | 13 Apr 93 | 1145 | 19 May 93 | 0905 | S |
| 38 | 5 | l1 | 175 N. Lombard, Oak Park 60302 | 112-117 | 22 Apr 93 | 1045 | 27 Apr 93 | 1430 | S |
| 39 | 5 | l2 | 175 N. Lombard, Oak Park 60302 | 117-138 | 27 Apr 93 | 1430 | 18 May 93 | 1200 | S |

[*] I=in leaf, F=fall transition(Oct. 13- Nov.17, Days 287-322), O=out of leaf,
S=spring transition(Apr. 13 to May 25, Days 73-115).

TREE COVERAGE OF CHICAGO
URBAN FOREST STUDY AREA

| | |
|---|---|
| ☐ | 0% |
| ☐ | 0% to 5% |
| ▨ | 5% to 10% |
| ▨ | 10% to 50% |
| ■ | > 50% |
| • | BELOW–CANOPY DATA POINT |
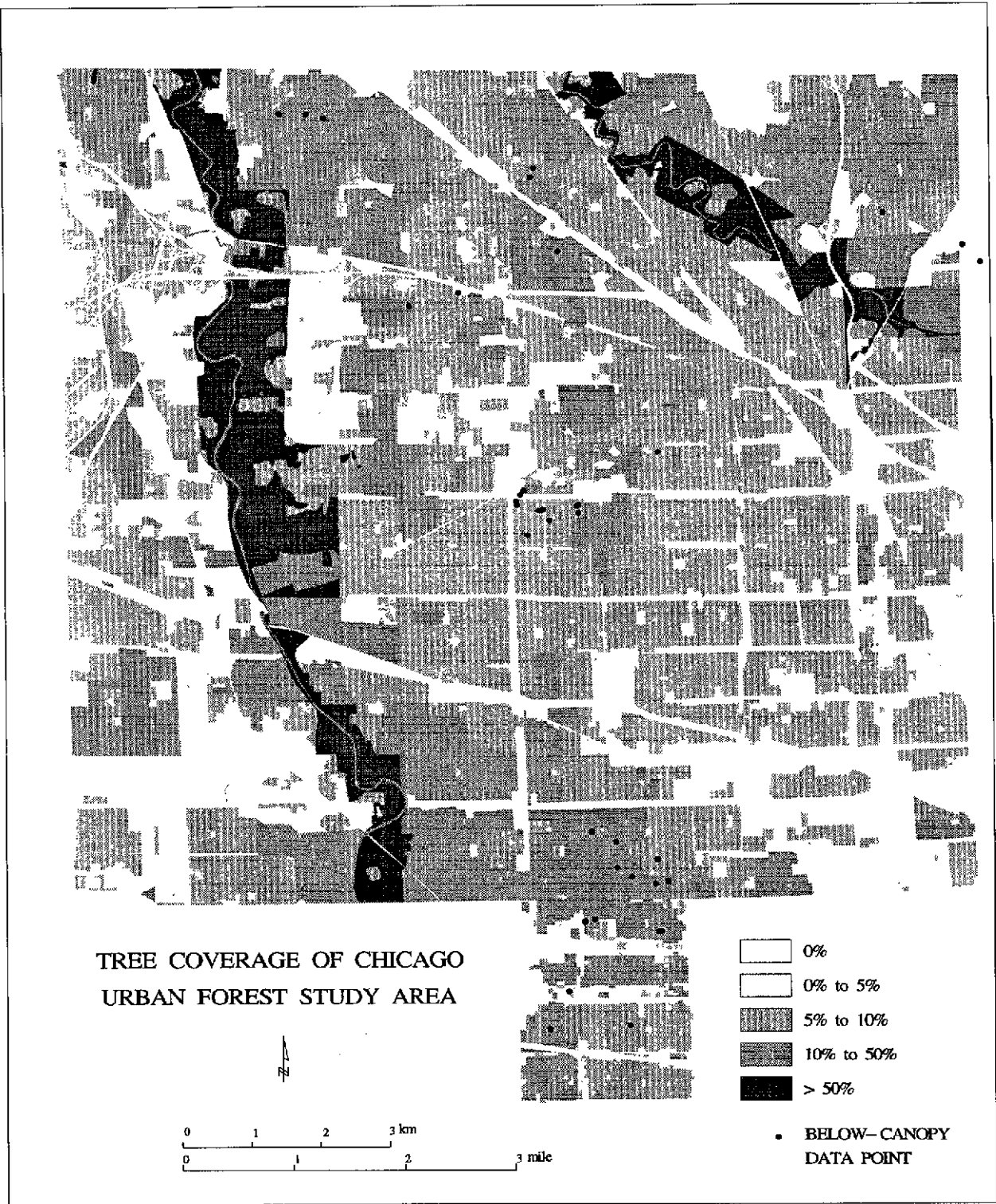
Figure 4.—Tree cover within study area and below-canopy points.

TOTAL VEGETATION COVERAGE OF
CHICAGO URBAN FOREST STUDY AREA

| | |
|---|---|
| | 0% |
| | 0 to 5% |
| | 5% to 10% |
| | 10% to 50% |
| | >50% |
| ● | BELOW–CANOPY DATA POINT |

0    1    2    3 km

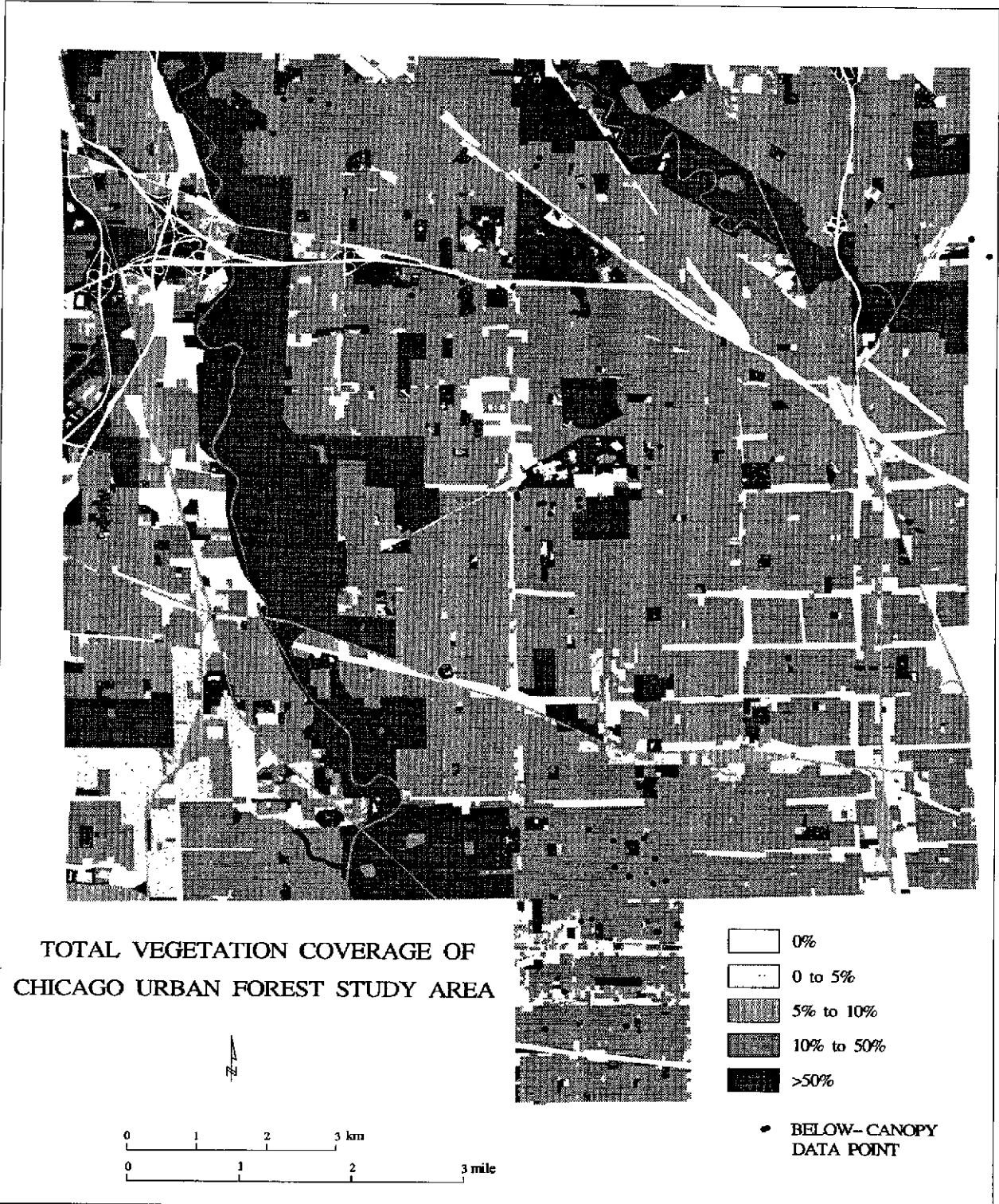0    1    2    3 mile

Figure 5.—Cover of all vegetation within study area and below-canopy points.

local effects of dense tree rows by locating some sampling points within one tree height of dense rows.

## Reference Conditions

Although we make the assumption that the airport site is relatively uninfluenced by buildings and trees, we cannot assume that the general air flow over the airport site always is identical to the flow over the neighborhood sites, which are 3 to 9 miles (6 to 15 km) closer to the lake. Airport reference conditions will have to be adjusted to account for differences in wind, air temperature, and humidity between the boundary-layer air at the airport and over the below-canopy sites. The adjustments essentially will be an extrapolation from the airport conditions by first extrapolating vertically upward from the airport site, then across horizontally to above the residential neighborhoods, and then back down to the level of the below-canopy instruments at approximately 8 feet (2 m). The extrapolation must account for mesoscale variations, primarily the lake effect which prevails during part of the year (Grant 1993). The extrapolation will be derived for five classes of general (synoptic) weather conditions, as described in Grant (1993), so that for any hour of our observations, the lake effects can be estimated by knowing the general synoptic pattern. Vertical profiles of wind and air temperature derived from the three levels of measurement on the tall tower (ISPT3) along with the Belmont Harbor observations will facilitate the extrapolation. Indices of atmospheric thermal stability, which causes variations in the vertical profiles of wind and temperature, will aid in the extrapolations. The indices will be derived from our observations of net all-wave radiation (Grimmond and Cleugh 1994), which was measured at both the airport and ISPT3, and from the standard deviation of wind direction by a method of Slade (1968).

In the complete analysis, dependent variables will be formed as the differences between the values of windspeed and air temperature at the below-canopy sites and the extrapolated reference conditions. In the results presented here for tree and building effects on windspeed, the differences between the airport and below-canopy sites form the dependent variables, without extrapolation. This is a reasonable approach because results here are for essentially the same time period, and the below-canopy points are relatively close together.

## Characterizing Urban Structure

Many characteristics of urban structure can be related to the meteorological differences that we measured. Looking from above in plan view, some possible characteristics are the areal coverage as a percentage or decimal fraction of buildings, trees, and impervious surfaces. Combined with these attributes, the average height of buildings and trees within land-use units adds the third dimension. These characteristics can be averaged over differently shaped and sized areas in the upwind direction in search of correlations with observed meteorological differences. Looking horizontally from below-canopy points, the heights of buildings and trees and the density of tree crowns in upwind directions, and to a smaller extent in downwind directions, also are related to microclimate, particularly windspeed.

In this study we are developing a set of independent variables to describe tree and building morphology, generally in the upwind direction from each below-canopy climate data point, to be entered into a data set with separate observations for each instrument-hour for each below-canopy point. The variables for describing the more distant morphology generally will be derived by GIS spatial analysis.

One source of data will be the surface database for the 8- by 8-mile (13- by 13-km) area used for hydroclimate analysis as described in Grimmond et al 1994: Chapter 4, this report. For each of the more than 2500 polygons shown in Figure 2, a set of attributes is assigned to indicate the percentage of area covered by buildings, trees, other vegetation or other surface characteristics (Table 6, Chapter 4 ). Because this database was developed for classes of land-use polygons, and some of the polygons have considerable variation in attributes within them, this database has limitations for developing descriptors of morphology for the near vicinity of particular points. The accuracy with which some of the attributes could be determined also was limited by the black-and-white aerial photos, which were available only for the leaf-off season for trees.

To provide land-use coverage for some of the sites near the edge or just off the original square area (Figure 2), we will digitize some additional areas on the northwest and northeast corners and around Oak Park. The sites included in the initial analysis reported here are near the center of the study area.

In our initial spatial-analysis to develop descriptors of morphology we used ARC/INFO GIS software, to average the attributes on an area-weighted basis across elliptically shaped areas in the upwind direction from each point. The ellipse shapes were cut from the coverage (cookie cutting) to determine the area of each land-use polygon within each ellipse as a proportion of ellipse area. The weighted average of an attribute within an ellipse was the sum over all land-uses in the ellipse of the attribute value for each polygon times proportional area. The attributes that have been used to date are: building cover; average building height; tree cover; total vegetation cover; and impervious, bare, and water-surface areas. The product of building cover times average building height forms an estimate of building volume (with dimensions feet$^3$ of building per foot$^2$ of land area), the building attribute that we expect to be most closely related to reductions in windspeed.

The spatial-analysis program averaged the attributes for ellipses centered on each 15 degrees for each of the below-canopy points. Thus, for each shape and attribute, there were 24 average values for each point. The average attributes were merged with the wind data by rounding wind direction over the residential area to the nearest 15-degree azimuth for which morphology averages were obtained in the spatial analysis. Wind direction at the ISPT3 tower is assumed to represent direction across the study area. The elliptical sample areas had lengths of 328, 984, 1640, and 3280 feet (100, 300, 500, and 1000 m), with widths equal to half the lengths, and with the downwind vertex over each below-canopy point. The spatial analysis for the ellipses has been completed for 10 of the 39 points. After the spatial

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analysis using ellipses was completed, average tree and shrub height was added as an attribute for each polygon, and this attribute will be used in any further analyses. The product of average tree and shrub height times tree and shrub cover fraction will provide an index of the volume of tree and shrub crowns.

Unlike the state of the technology related to above canopy source areas for vertical transfer of heat and vapor (Grimmond et al. 1994), there are few guidelines from previous experimentation that would aid in assigning appropriate shapes for averaging land-use structure that would relate to below-canopy microclimate. The elliptical averaging shapes were chosen for initial analysis partly because of their mathematical simplicity. Other shapes may better represent the land-use areas that influence wind and air temperature in the below-canopy space. The next step in analysis of the land-use database is to average attributes over sections of concentric circular bands at different distances from the below-canopy points. The band sections will be centered on mean wind direction and weighting will be applied according to angular distance from mean direction based on the standard deviation of wind direction on the tall tower during the sampling period. The band sections will be plus and minus 2 standard deviations, and weighting along the band, perpendicular to wind direction, will be based on area under a normal curve. Standard deviations on the tower are usually between 8 and 20 degrees. Hence, the band sections will range from about 30° to 80° wide as viewed from the below-canopy points. Five bands will be used: 0 to 100, 100 to 205, 205 to 410, 410 to 820, and 820 to 1640 feet from the point.

To provide more accurate descriptors of building morphology for areas near below-canopy points, another spatial GIS database of building footprints within 600 feet (180 m) of each below-canopy point (Figure 6) is being developed. The information sources are plat maps which are available for all Chicago locations and aerial photographs for other communities. A field survey and estimation from black-and-white stereo photos is providing approximate heights for each building. The building footprint database will provide average building density, height, and volume for differently shaped upwind areas, by a spatial analysis process similar to that applied to the larger land-use database. Ideally, color infrared aerial photographs for the trees-in-leaf season would have been available for development of a tree-cover database on the scale of the building footprint data, but no such current photos could be located.

The descriptors for building and tree morphology visible from the below-canopy points are being acquired from 180-degree hemispherical slide photos. These were taken at each point from a height of 3 feet (1 m) with the camera lens pointing directly overhead and with the top of the camera oriented toward north. The slides are projected onto polar grids from which technicians record, by 15-degree sector, average tree crown density and the maximum and minimum vertical angles from the horizon of the photo to the tops of visible buildings and trees. Tree crown density is estimated for upper and lower halves of the space between the horizon and the tallest tree within each sector. Separate photo sets were taken for the points where meteorological data were collected in both summer and winter. Changes in leaf phenology in the

fall and spring transition periods (Table 1) were tracked with photos at a subset of the sample points.

## Regression Analysis

Multiple regression models are being used to develop prediction equations to describe the influence of the vegetation and building morphology on the differences in airport to below-canopy wind and air temperature. Some of the morphological indicators are combined in physically meaningful ways prior to insertion in the model. For example, from the hemispherical photo data, distance to upwind buildings or trees relative to the building or tree height can be derived from the vertical angle from horizon to the top of the object. The product of normalized distances to upwind and downwind objects provides a descriptor that, if small, indicates that the point is between closely spaced obstacles and that wind tends not to penetrate downward into the canopy, but occurs mainly as skimming flow above the canopy (Oke 1987), resulting in large wind reductions below canopy.

The regression models are the usual general linear models with polynomial terms (Neter et al. 1985) or nonlinear models (Wilkinson 1990). The linear models are of the form

$$Y = B_0 + B_1X_1 + B_2X_2 + B_{12}X_1X_2 + B_{11}X_1X_1 + B_{22}X_2X_2 + \ldots + E$$
$$[1]$$

with E as the normally distributed error term with constant variance across all Y and X. In studying effects on windspeed, the dependent variable Y is, for example, a fractional reduction in windspeeds in the neighborhoods compared to the airport reference, and the $X_1$'s are descriptors of either morphology or atmospheric conditions. In discussing wind reductions by trees, buildings, or other obstacles it is common practice to use a nondimensional normalized form rather than absolute windspeed (e.g., Heisler and DeWalle 1988, McNaughton 1989). Indices of atmospheric thermal stability calculated from vertical wind and temperature gradients, from net radiation (Grimmond and Cleugh 1994), or from windspeed and cloud cover (Turner's index, Panofsky and Dutton 1984) can be used to form descriptors of atmospheric conditions. The $B_1$'s are regression coefficients. This is mathematically an additive effects model; each independent variable adds an effect, such as a fractional reduction in windspeed. The intercept $B_0$ will be near 0 if the X variables together account for most of the reductions in windspeed.

For studying effects of urban morphology on air temperature, the $X_1$'s can include some of the same morphological characteristics as for windspeed in addition to others that are related to radiation exchanges, heat storage, moisture availability, and deficit of moisture in the air. Radiation exchange can be indexed by percent of unobscured sky above the below-canopy meteorological measurement point. In addition to building volume, heat storage may be significantly related to percentage of impervious cover from the land-use analysis. Impervious cover may also be related to moisture availability. Another index of moisture availability may be derived from the amount of precipitation over various lengths of time preceding the observation time. Moisture deficit is calculated as the difference between actual vapor pressure and vapor pressure if the air were saturated at the same temperature.

BUILDING FOOTPRINTS

AND

LOCATION OF SITES 1–4

1:4000

0           100        200 METER

0     200     400     600 FEET
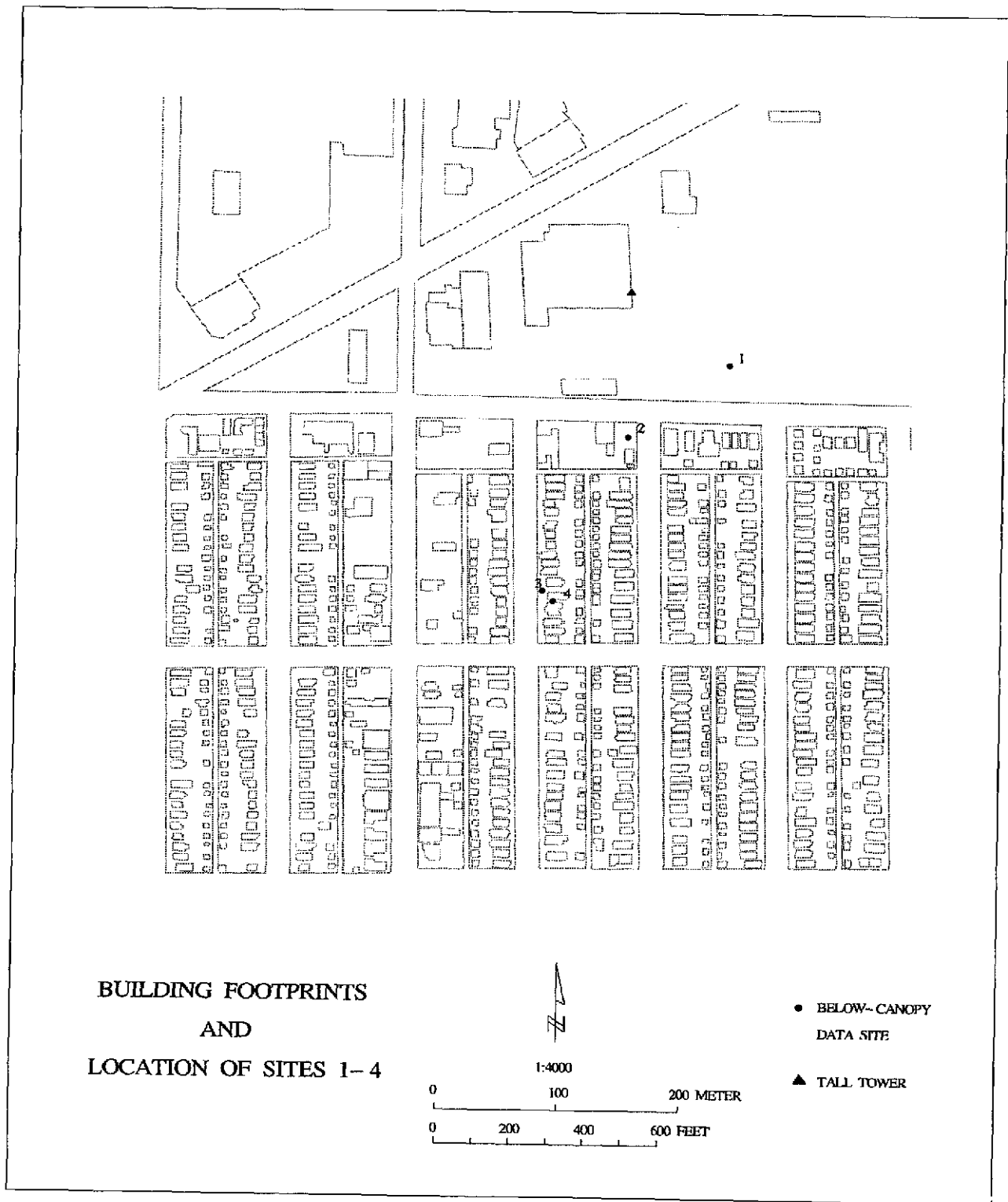
•   BELOW–CANOPY DATA SITE

▲   TALL TOWER

Figure 6.—Example of building footprints in GIS and location of four below-canopy points used in this analysis.

We might expect that the influence of morphology on micro-climatic variables would be nonlinear. Nonlinear models can take various forms, such as

$$Y = B_0 \exp(B_1X_1 + B_2X_2 + \ldots + B_nX_n) + E \qquad [2]$$

Here the Y would be, for example, a relative windspeed, that is, wind in the neighborhood divided by wind at the reference. Such models can be fit with standard nonlinear methods [e.g. SYSTAT (Wilkinson 1990)] depending on how many variables are included (interpretation of results becomes more difficult with each parameter that is added). Equation 2 is a multiplicative or exponential model, in that each independent variable has a multiplicative effect.

# Results and Discussion

## Land-Use Attributes

The study area has a complex pattern of land uses (Figure 4a, Chapter 4), including large areas in forest that are part of the Forest Preserve (areas with greater than 50 percent tree cover in Figure 4). Although overall tree cover is not high within Chicago (Nowak 1994a: Chapter 2, this report), the study area contains land-use categories with a wide range of tree cover (Figure 4). All vegetation combined typically covers 20 to 50 percent of the area in residential neighborhoods in which our below-canopy measurements were made (Figure 5).

One concern in interpreting the regression results is that some morphological descriptors that serve as independent variables are naturally correlated. Specifically, when building density is very high as in much of Chicago residential areas, tree cover generally also cannot be high. The relationship between building cover and tree cover is illustrated in the left side of Figure 7, which is derived from the land-use analysis with elliptic averaging shapes of different lengths and areas. The data for each scatter diagram are for 10 below-canopy points. Building cover ranged up to nearly 0.7 in some of the 328-foot (100-m) ellipses, and tree cover ranged up to about 0.4. The scatter of points shows a high degree of correlation between tree and building cover, particularly for the 328-foot ellipses. A small part of the reason for the close relation is an artifact of these data, because in development of the land-use database, only one type of coverage was allowed for any given sample point. Hence, where trees overhung buildings, the coverage category was trees rather than trees and buildings.

Steps can be taken to account for relationships between some independent variables in the regressions. The product of building-area coverage times height forms a building volume, which seems to be less well-correlated with tree cover (Figure 7, right column). Groups of below-canopy meteorological sites that have a wide range of morphological characteristics can be selected.

## Initial Model Building

To illustrate the analysis that is being done to evaluate the effects of urban trees on wind, preliminary regression analyses were done for four sites, using a selection of the

meteorological data collected within a 13-day period, July 21 (day 203) to August 2, 1992 (day 215). (The day of the year system is used because of ease of referring to dates in graphs.)

### The sites

The locations of the sites, numbered 1 to 4, are plotted on a section of the GIS map of land-use in Figure 8. These four sites were all within 1000 feet (300 m) of each other and within about the same distance of the tall tower. Hence, these results serve to illustrate the range of microclimate within a short distance.

The hemispherical camera views (Figure 9) show the tree and building structure visible from each point. Site 1 was in a relatively open location in a large grassy field, but a natural stand of 25-foot (7.5-m) deciduous trees edges the north side of the field, about 75 feet (25 m) from the meteorological unit. Site 2 was in a vacant lot on the north edge of a residential development just 230 feet (70 m) south of site 1. Sites 3 and 4 were farther south within the development. Site 3 was in a small front yard along a street with many large street trees with crowns almost overhead; site 4 was in a narrow space between two houses.

### General conditions

Windspeeds at O'Hare Airport ranged up to about 12 mph (5.5 m/s) between July 21 and July 24, days 203 through 206 (Figure 10). (Data for sites 2, 3, and 4 are available for these days only; site 1 also has data for days 212-215.) Windspeeds followed a diurnal pattern that is typical of locations within the atmospheric boundary layer—low speeds at night when the air becomes thermally stable because of radiational cooling near the ground. Figure 11 shows that day 203 had a smooth trace for both solar and net all-wave radiation, indicating a clear sky, resulting in high positive net radiation during the day and strong negative radiation at night compared to cloudy conditions on following nights). About 0.25 inch (3.8 mm) of rain fell on days 204 and 205 (Figure 8, Chapter 4).

### Air temperatures

Air temperatures at below-canopy sites remained within 3.6°F (2°C) of the temperature at the same height at the airport (Figure 12a). Sites 2, 3, and 4, all in the residential neighborhood, were 0.5° to 0.7°F (0.28° to 0.39°C) warmer, on average, than the airport site. The general diurnal pattern, with temperatures in neighborhoods being warmer than the airport at night and cooler during the day is probably caused largely by different rates of heating and cooling in the neighborhoods compared to the airport. This pattern is fairly typical of the so-called urban heat island phenomenon (Oke 1987, 1989). For example, on day 203, which was cloud free, net radiation at night was strongly negative and open sites such as the airport cooled more quickly than the neighborhoods. This is more clearly seen in Figure 12b which shows that periods when sites 2, 3, and 4 were decidedly warmer than the airport (by up to 3.3°F or 1.8°C) are associated with negative net radiation. Neighborhood sites also tend to be warmer under periods of high positive net radiation resulting from high solar radiation. The fact that site 3 was close to trees and site 4 on the adjacent property was in a narrow space between two houses (Figure 9) appears to have resulted
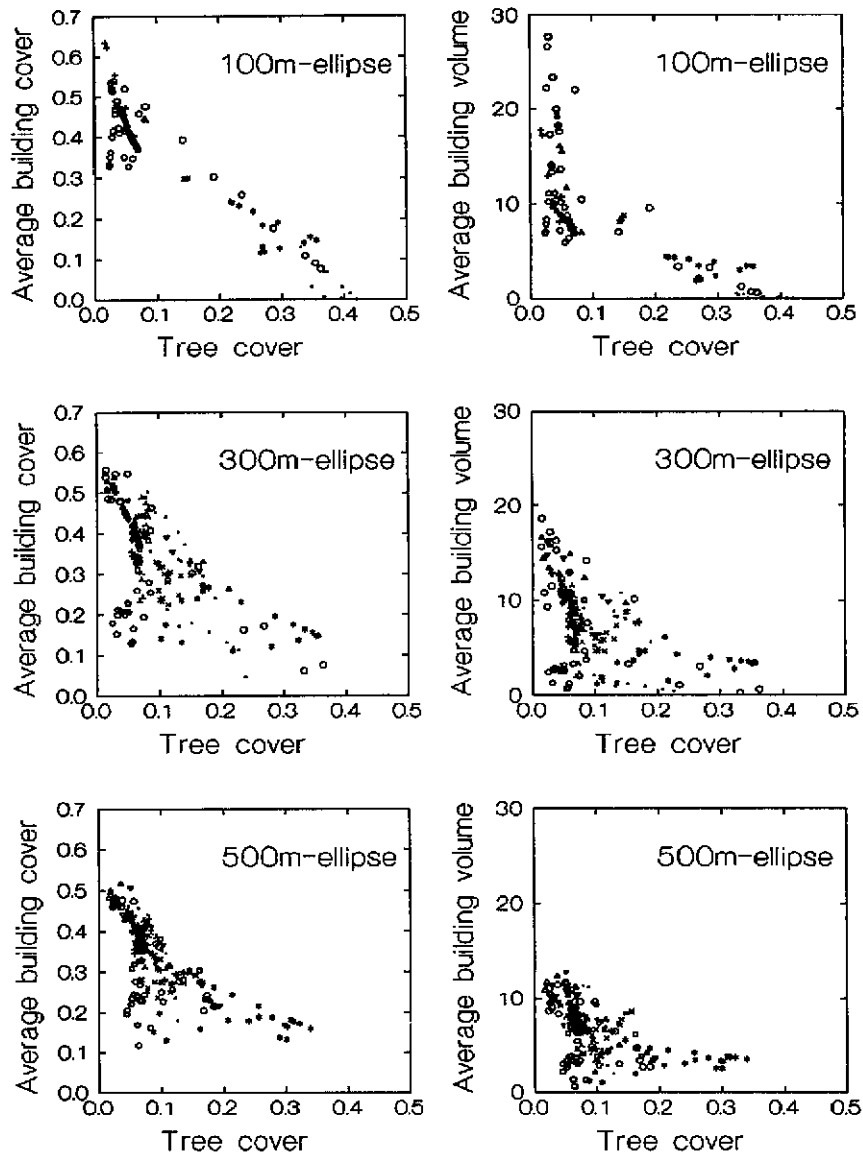
Figure 7.—Average building cover (fraction of area covered) and average building volume (cubic units of volume per squared units of area) versus tree cover (fraction of area covered) in elliptic sampling areas cut from the GIS database around ten of the below-canopy points. Different symbols show values for different points.

in site 3 being about 0.5°F (0.3°C) cooler at high values of net radiation (Figure 12b), even though the difference in overall average temperatures at the two sites was within the limits of instrumental error (0.18°F). Site 1 was cooler on average than the other below-canopy sites and had nearly the same mean temperature as the airport. The pattern of actual temperatures during days 203 through 206 (Figure 13) generally reflects the influence of the radiation balance,

with a large diurnal swing accompanying the period of clear skies.

*Effects of morphology on windspeed*

Figure 10 shows that except for a few 15-minute observation periods with low windspeed at the airport, windspeeds at the below-canopy sites were lower than at the airport. However, there is considerable scatter in the 15-minute averages. A
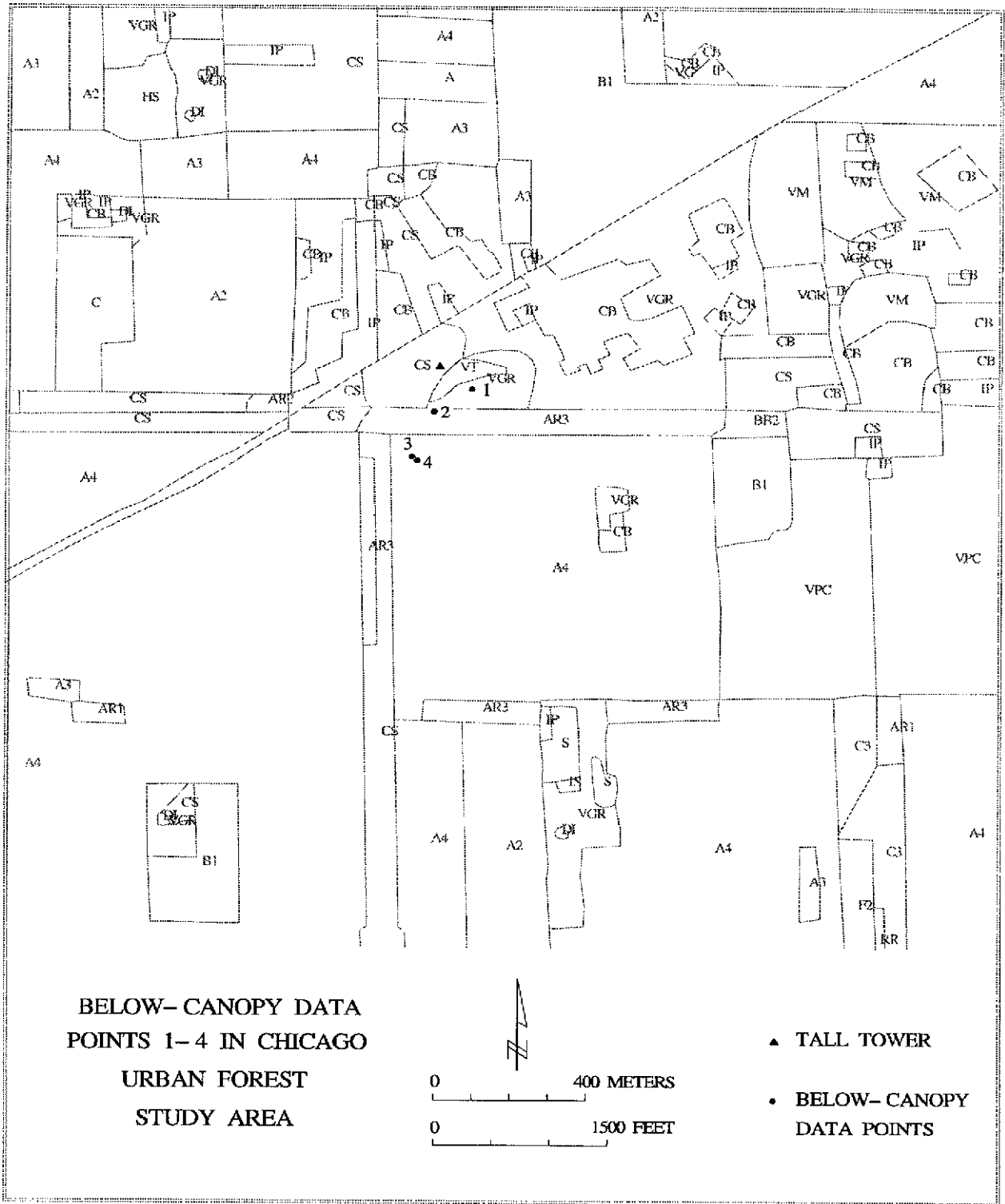
Figure 8.—Land-uses around the four below-canopy meteorology sampling points. See Table 5 in Chapter 4 for land- use categories. Near the points the classes are: VT, trees and shrubs; VGR, grass; A4, high density housing, yards small, mainly grass, few trees; CB, large commercial buildings, fewer than 6 stories; CS, small commercial buildings; AR3, apartments, highly mixed. (The tall tower is ISPT3 in Grimmond et al., Chapter 4, this report.).
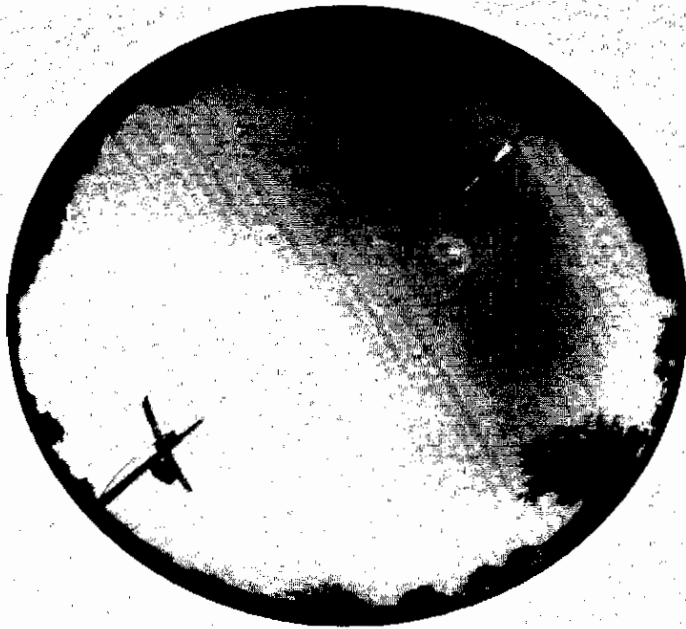
Site 1

Site 2

Site 3

Site 4

N
↑
E —┼— W
↓
S
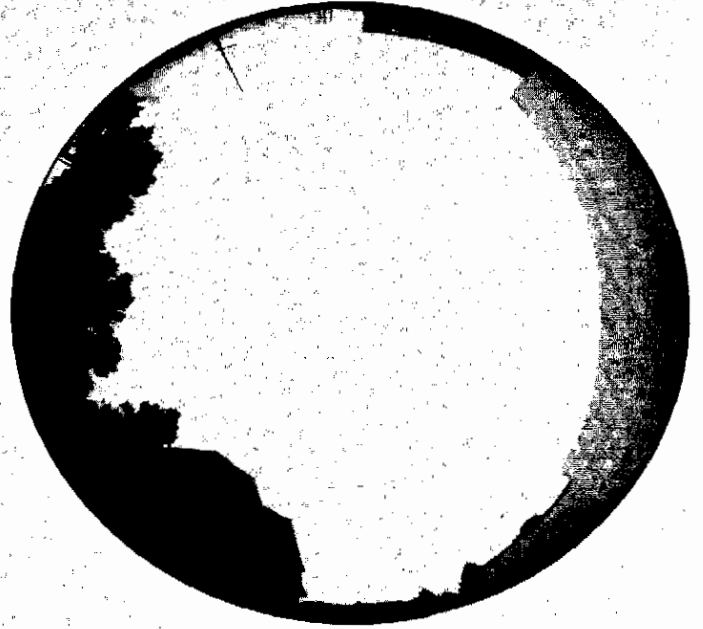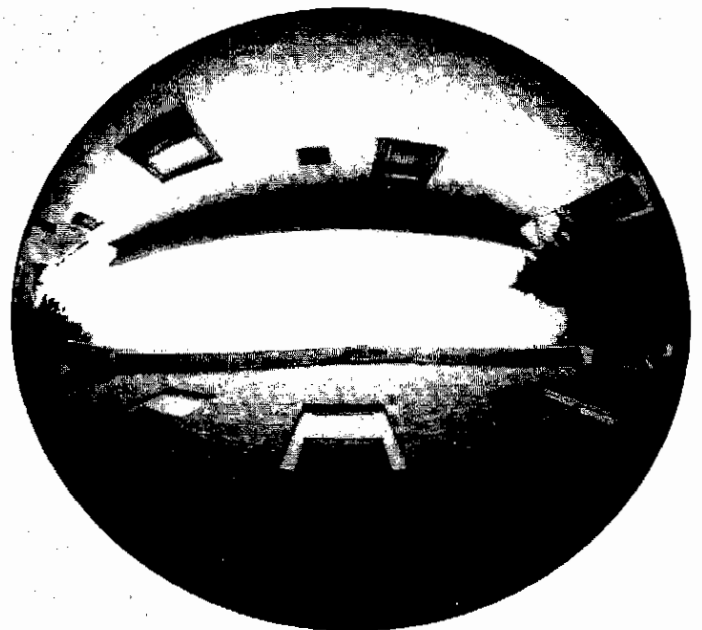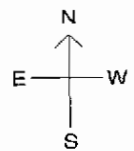
Figure 9.—Hemispherical photo views from horizon to zenith, from height of 3 feet at four sites.
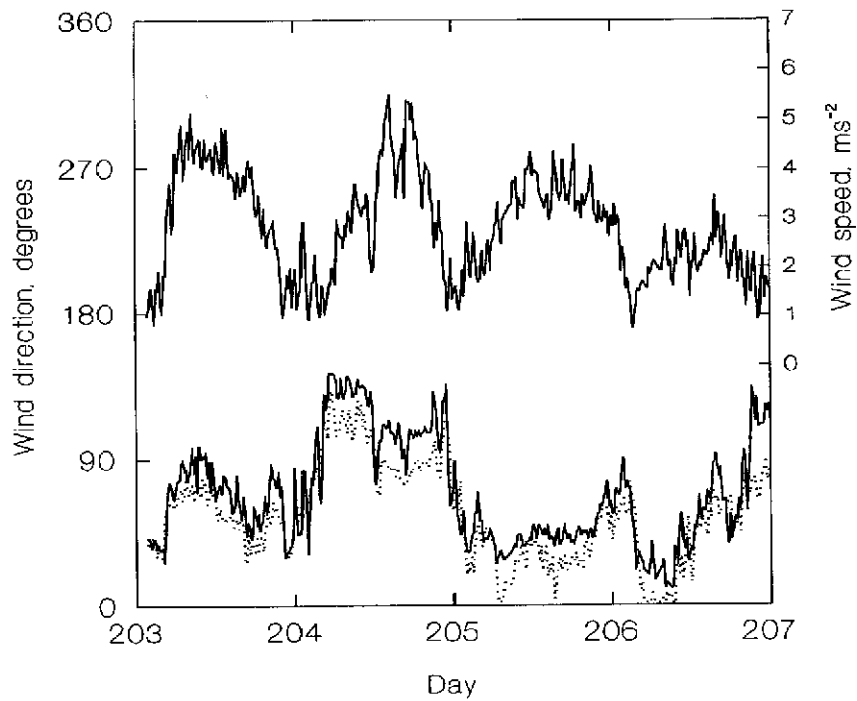
Figure 10.—Windspeed at O'Hare airport (upper curve) and wind direction at the airport (lower solid line) and on the lower level of the tall tower (dotted) on July 21 to July 24, 1992. The dates are shown at midnight starting the day.
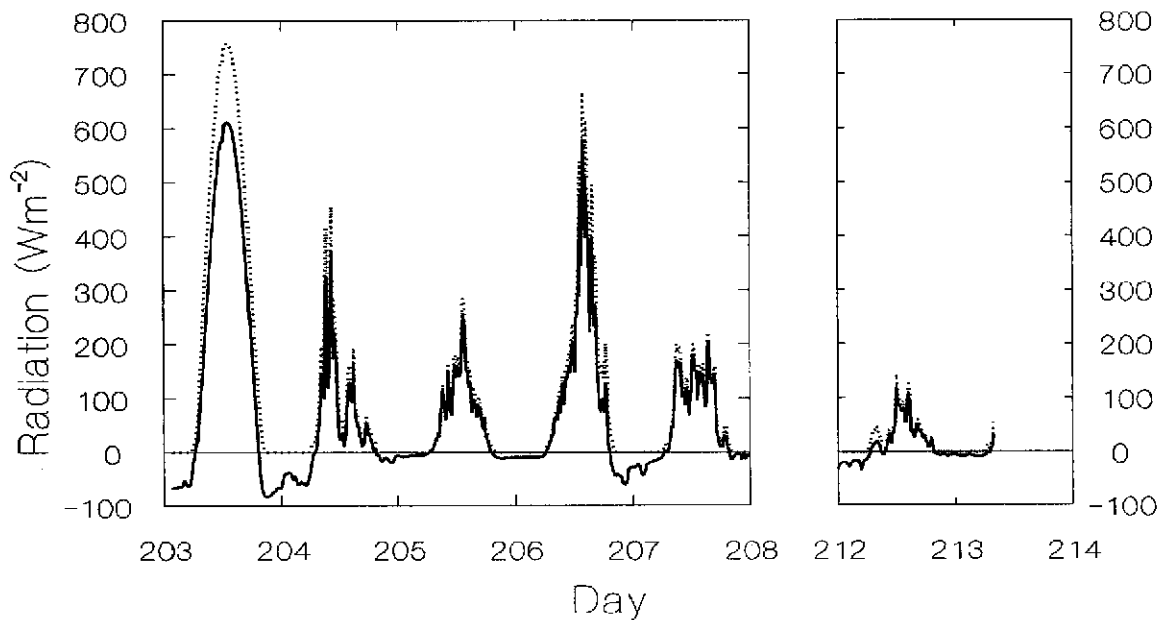


Figure 11.—Shortwave solar (dashed) and net all-wave radiation (solid) at the fixed tower.
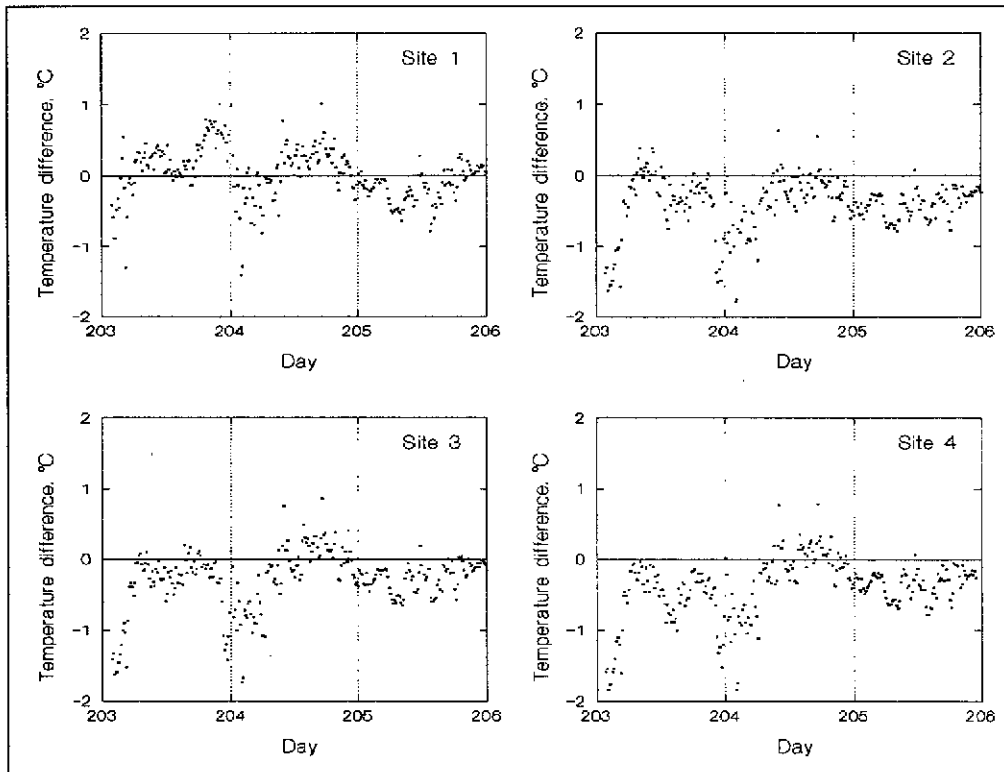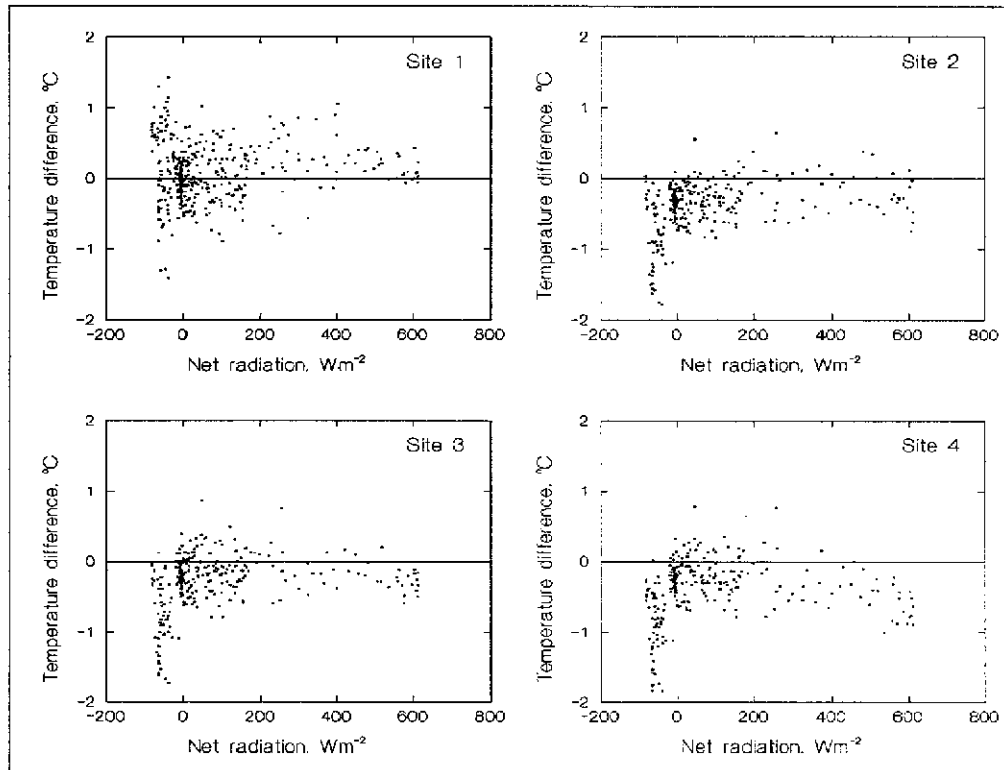
Figure 12.—Pattern of air-temperature differences (airport minus below-canopy) between O'Hare Airport and four below-canopy sites; a) time series, b) versus net radiation.

better sense of the pattern of windspeed differences is shown by plots of a normalized reduction in windspeed:

$$U_r = (U_{airport} - U_{site}) / U_{airport}. \quad [3]$$

In Figure 14a, normalized reductions in windspeed are plotted for each site in a time series. The anemometers that we used had a threshold windspeed of 0.45 mph (0.2 m/s). Though the cups did not rotate until windspeed reached the threshold, the data loggers were programmed to indicate 0.45 mph (0.2 m/s) as a minimum speed, so that as wind reached the threshold speed and the cups began to rotate, the speed indicated was correct. However, the minimum recorded speed places a significant bias on the apparent reductions when wind is slow and anemometers at the below-canopy sites are stopped while the control at the airport is measuring a speed that is just slightly higher than the threshold. For airport speeds of 6.7 mph (3 m/s) or greater, the below-canopy anemometers generally indicated speeds above the threshold, and bias was negligible. Hence, data for airport speeds less than 6.7 mph were omitted from Figure 14a. From this point the discussion will pertain to the higher speed wind conditions.

With the higher reference windspeeds, the apparent effects of trees and buildings on windspeed vary less than at low relative windspeeds, and derivation of models to predict the effects of these obstacles is thus relatively more precise for the higher speeds. Also, influences of trees at higher windspeeds generally are of greatest importance for concerns such as energy use.

In Figure 14a we see a pattern of differences in windspeed reductions from site to site that is to some extent related to the amount of sky blockage in the hemispherical views (Figure 9). However, there is considerable within-site scatter, particularly at sites 1 and 2. Much of this scatter is explained by looking at wind reduction versus above-canopy wind direction (Figure 14b). For example, site 1 has large
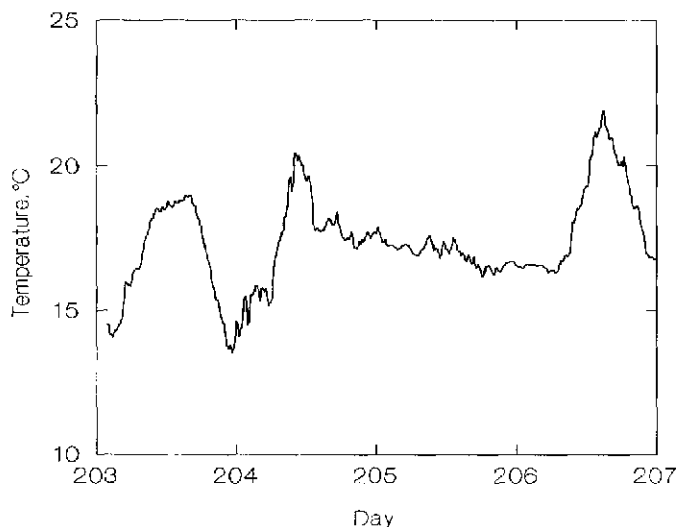


Figure 13.—Air temperatures at 5-foot height at O'Hare International Airport.

wind reductions when wind is from the north, apparently because wind is blocked by the tree row in that direction (Figure 9). The east is relatively free of obstacles and wind reductions are low in that direction (90 degree azimuth). At site 2, reductions are small at 45 degrees, evidently because wind comes relatively unabated through the opening between north and northeast. The very close buildings and street tree crowns account for large reductions at sites 3 and 4.

The descriptors obtained from the hemispherical photos and a nonlinear regression model provided an initial means of quantifying the relationship between morphology and reductions in windspeed. The photos were first analyzed in 15° sectors (see Methods). In the results reported here, we combined three sectors to describe average morphology in 45° sectors in the upwind and downwind directions (based on airport wind direction) for each 15-minute windspeed average for each below-canopy site. The most successful model included four independent variables. For buildings, we averaged the highest and lowest angles to the tops of buildings in the upwind direction (UBA) and in the downwind direction (DBA). For trees, similar descriptors were formed (UTA and DTA), but average angles were multiplied by fractional tree-crown density (0 to 1.00) estimated from the hemispherical photos. Thus a solid tree stand, with a visual density of nearly 1.00 as seen to the north of site 1 (Figure 9) would yield UTA and DTA values nearly equal to angular height. The street trees near site 3 have an overall visual density of less than 1.00, primarily because of the open space at the bottom and would yield UTA or DTA values of less than their angular height. Hence, trees often were weighted less than buildings of the same angular height.

The relationship between wind reductions and the morphology descriptors was explored by plots of wind reduction versus the descriptors or various combinations of descriptors. A combination of building and tree descriptors in the upwind and downwind directions that showed one of the closest relationships with wind reduction was BTUD; where

$$BTUD = max(UBA,UTA) + (max(DBA,DTA))/3, \quad [4]$$

"max" yields the larger of the two values in the following parentheses, and the divisor 3 is based on the trial assumption that downwind trees and buildings reduce windspeeds one-third as much as upwind buildings and trees. The scatter diagram of observations (Figure 15) suggested an exponential relationship with the general form of equation 3. The regression model

$$U_r = 1 - a*BTUD + exp(b*BTUD), \quad [5]$$

where a and b are parameters to be estimated, produced a good fit to the data (Figure 15) with a corrected correlation coefficient, $R^2$, of 0.78, indicating that about 78 percent of the wind reduction is explained by model [5]. Adding net radiation as an additional variable helped to explain additional variation and reduced residuals by about 0.1 at high positive values of net radiation.

With the four components of BTUD in the model separately, as

$$U_r = a + exp(b*UBA + c*UTA + d*DBA + e*DTA), \quad [6]$$

where a, b, c, and d were coefficients to be estimated, $R^2$ increased to 0.80. The estimated coefficients were all

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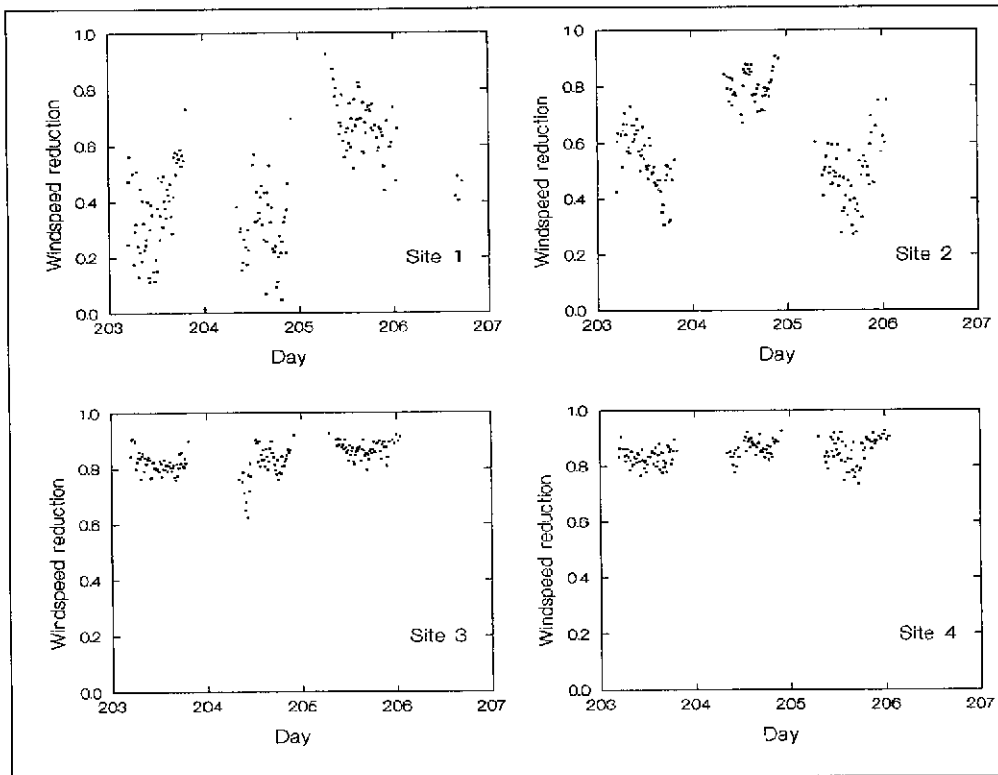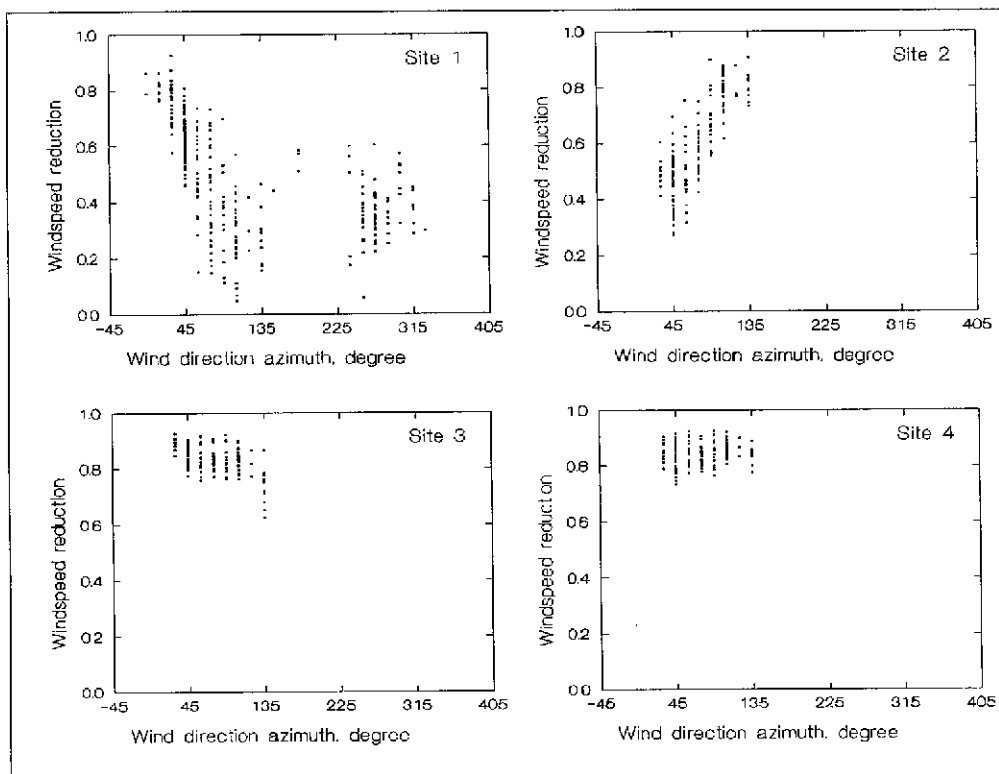
Figure 14.—Normalized reductions in windspeed at four below-canopy sites compared to the airport, with airport windspeeds greater than 6.7 mph (3 ms-1); a) as time series, b) versus wind direction.

significantly different from 0. (Because all variables were correlated over time, and because of the nature of nonlinear estimation, the test based on R² values is approximate.)

With the estimated coefficients, equation 6 becomes

$$U_r = 0.89 + \exp(-0.090\text{*UBA} - 0.073\text{*UTA} + 0.012\text{*DBA} - 0.019\text{*DTA}).\quad [7]$$

Equations of this type can be used to predict tree and building effects on windspeed, though care must be taken in interpretation. In the case of equation 7, the estimated coefficient d for downwind buildings DBA is positive, indicating smaller reductions with downwind buildings nearby. However, in this particular data, upwind and downwind building angles are positively correlated, and it is likely that one building-angle term tends to overestimate the building effect, while the other compensates for the overestimation. Inclusion of data from other sites combined with analysis of residuals (observed values minus estimates from the regression) will help in interpreting regression results.

Some of the residuals from the regressions are inflated partly by trees and structures obscured from view in Figure 9, partly by random turbulent eddies, partly perhaps because the assumption of no obstacle effect on wind at the airport is not completely met, and possibly in part by differences in thermal stratification in the atmosphere. The probability of this last effect being significant was reduced by our selection of higher speed winds for analysis. Future regressions will

be based on hourly averaged data, which will reduce the effect of the random fluctuations. Descriptors of building and tree morphology from the GIS analysis will be included as independent variables to account for buildings and trees not visible in the hemispherical photos.

## Conclusions and Application

Preliminary analysis of tree and building effects on windspeed and air temperature at points in one Chicago residential neighborhood over approximately one July week showed that windspeed was reduced by 83 to 85 percent on average compared to a location in the middle of O'Hare Airport, 6 miles to the west. Buildings occupied about 40 percent and tree crowns covered about 10 percent of the area within the neighborhood. In a long narrow open field adjacent to the residential area, windspeed was reduced an average of 46 percent, but reductions varied with distance to obstructions. When wind came to the field site from the direction of a 25- to 30-foot deciduous forest stand about 75 feet to the north, windspeeds were similar to those in the residential area.

Average air temperatures in the open field were essentially the same as the airport, but at times open field temperatures were from 2.5°F (1.4°C) greater to 2.3°F (1.3°C) less than at the airport in a pattern that reflected differences between the sites in rates of cooling and heating responses to the net radiation balance. Within the residential neighborhood, a
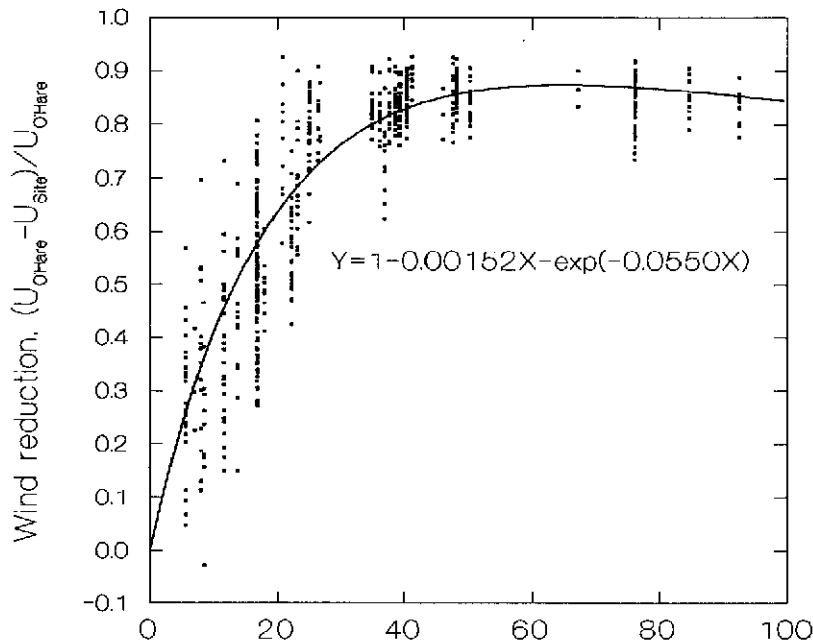


Upwind & Downwind maximum obstacle function

Figure 15.—Normalized wind reductions for all four sites versus a descriptor of upwind and downwind trees and buildings (BTUD) defined in the text. The curve is fit to the points by a nonlinear regression technique.

similar range and pattern of temperature differences from the airport were observed, but average temperatures were 0.5° to 0.7°F (0.28° to 0.39°C) higher in the neighborhood than in the open field.

One approach to developing information for planning tree management to save energy for heating and cooling is to simulate the effects of particular tree arrangements on energy use (Heisler 1991, McPherson 1994). This can be done by comprehensive, commercially available energy-analysis programs that include an hour-by-hour analysis of energy use in a building for an entire year. Input for these programs includes averaged or representative hourly weather data prepared specifically for energy analysis. However, the energy analysis programs do not include built-in procedures to estimate tree effects.

One method for including tree effects on wind, air temperature, and humidity in energy-use predictions, is to preprocess the representative weather data by algorithms that predict tree effects on these microclimatic variables. A primary goal of this study is to provide the algorithms to preprocess weather data. Although considerable analysis remains, the initial results reported here show considerable promise of success in predicting wind climate in residential neighborhoods. Most important, there is a strong likelihood that tree and building effects on windspeed can be reasonably well separated. The data from our airport reference site adjacent to a standard weather observing system, from which long-term weather data is archived, will enhance development of equations for preprocessing weather data for energy calculations. In further analysis, emphasis will be given to developing and using predictor variables that could be gathered without undue difficulty in extrapolating the methodology to other locations.

Different approaches to analysis of tree effects on temperature are possible using the 11 months of data. There are periods of 1 to 3 weeks in which the below-canopy sampling pattern remained stationary and when the sites were about the same distance from the lake. With data from such periods, temperature differences can be related to differences in tree and building cover directly, without extrapolation to the airport, thus reducing extrapolation errors. One reason for not using this method exclusively is that the range of morphological conditions sampled within each period generally will be smaller than when longer time periods and more sites are included. This method is similar to that used in an ongoing study in two neighborhoods in the Los Angeles area in which Simpson et al. (1994) used the below-canopy average temperature as a reference for comparing the neighborhoods.

The analysis has not yet proceeded to prediction equations for air temperature, and here the probability of success is less certain, at least in terms of separating tree and building effects. The differences in temperature will be relatively subtle and the physical causes of temperature difference between sites are far more complex than for wind. The comparisons of temperatures between neighborhoods as presented in the results indicate many of the considerations that must be included in model development.

## Acknowledgments

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# Chapter 4

# Local Scale Energy and Water Exchanges in a Chicago Neighborhood

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## Abstract

Outlines the methods of measurement and analysis of "above-canopy" meteorological measurements undertaken to investigate the nature of surface controls on energy and water exchanges at the local scale. Observations were made over two periods: "intensive" (July 1992), and "extensive" (July 1992 through June 1993). During the intensive measurements, the vertical fluxes of sensible and latent heat were measured by eddy correlation methods at one above-canopy site. By combining these with measurements of net radiation and storage heat flux and detailed characterization of urban surface materials and morphology, a general understanding of energy exchanges of the urban surface at the local scale (100 to 1000 m) was obtained. Means of energy-balance values over the study period and their variability are presented and compared with results from other cities. Additional analyses to be conducted are described.

## Introduction

Urban areas represent locations where a large and ever increasing proportion of the world's population lives, and where a disproportionate share of natural resources is used. Urbanization brings about significant changes in land-cover. The replacement of natural surface materials (the substitution of concrete, asphalt, trees, etc. for the natural vegetation) significantly alters the aerodynamic, radiative, thermal, and moisture properties of the surface. In turn the pre-urban balances of energy, mass, and momentum are altered. This leads to the modification of the atmosphere and the generation of an "urban climate" commonly characterized by enhanced temperatures, the "urban heat island" (Ackerman 1985, 1987), poorer air quality (Hanna 1971; Wadden et al. 1979; Sexton and Westberg 1980; Swinford 1980; Scheff et al. 1984), and other effects.

Increasing attention is being directed toward strategies that mitigate negative, inadvertent environmental effects of urbanization. For example, strategically planting trees or lightening building and pavement surfaces have been suggested as alternate ways to reduce the summertime urban heat island and thus reduce energy demand for cooling (Heisler 1974; Akbari et al. 1992). These strategies entail some alteration of the morphology or material properties of the urban surface, that have an effect through the alteration of surface energy and water exchanges. Relatively little research has been conducted to quantify these effects. Hence, we cannot make informed decisions about planning or directing urban morphological changes, as we do not know how such changes would affect the local environment and its inhabitants.

More fundamentally, our understanding of the biophysical processes involved in the generation of urban climates is limited. Direct observations of energy and mass exchanges in urban areas have been collected only in a restricted number of cities, with a small range of surface morphologies and climates (Oke 1988; Grimmond and Oke 1994). Thus, results of model simulations and predictions on the effects of changing the urban surface must be used with caution. To understand how urban morphology influences local climate (energy and water exchanges) it is necessary to undertake detailed investigations of local meteorology in conjunction with an understanding of urban surfaces. This paper reports on research conducted to study energy and water exchange processes in a neighborhood of Chicago. In addition to enhancing our understanding of biophysical processes, these data are to be used to evaluate physically based meteorological models, which, in turn, will be used to investigate the effects of proposed changes in urban morphology on the urban climate.

The surface-energy balance provides a framework with which to study energy and water exchanges at a range of spatial scales. It can be expressed:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \;[W\;m^{-2}]$$

where $Q^*$ is the net all wave radiation (net available energy from solar and terrestrial radiation); $Q_F$ is the anthropogenic heat flux (heat generated from fuel combustion); $Q_H$ is the sensible heat flux (energy for heating the air); $Q_E$ is the latent heat flux (energy for evapotranspiration); $\Delta Q_S$ is the net storage heat flux (energy for heating the urban fabric); and $\Delta Q_A$ is the net horizontal heat advection. $Q_E$, the term that links the energy and water balances, is the energy equivalent of evapotranspiration, a mass (water) term. If temperature is known, it is possible to convert between energy and mass (water) equivalents using the latent heat of vaporization. Thus, $Q_E$ provides information about both energy and mass (water) exchanges. The surface energy balance concept, and the history of its application for an urbanized surface, was reviewed by Oke (1988).

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Urban effects on climate are forced at a range of scales: from the urban canopy layer (UCL) where microclimates are determined by building/tree size and spacing, to the land-use scale, to the whole city. Table 1 (adapted from Oke 1984) illustrates this range of scales and associated atmospheric processes in urban areas. The Chicago study was conducted at three scales: micro (length scale $10^{-1}$—$10^1$ m), local ($10^2$—$10^3$ m) and meso ($10^4$ m) (Figure 1; Table 2).

We report on the local scale above-canopy studies (i.e., those representative of areas the size of city blocks to land-use zones) and outline the methodology used to select the study sites and collect meteorological data and information about the urban surface. The surface-energy balance provides the methodological framework (for measurement and modeling) for the local scale research. Using this framework, the partitioning of energy in Chicago is studied and compared with that in other cities, and research directions are described. The methodology and preliminary results from microscale "below-canopy" studies are presented in Heisler et al. 1994: Chapter 3, this report.

# Methodology: Meteorology

To understand the nature of surface controls on energy and water exchanges, detailed measurements of local scale meteorology and surface conditions were conducted for one area within the City of Chicago.

## Measurement Program

The meteorological measurements were conducted over two periods, referred to here as intensive (July 1992) and extensive (July 1992 through June 1993) (Table 2). The short-term intensive measurements were taken to collect direct observations of the energy and water fluxes from a representative neighborhood within Chicago. The extensive measurements were taken to provide data input for numerical modeling for all seasons; to aid in the development of relationships between routinely measured data at the National Weather Service (NWS) airport site and "urban" values representative of specific neighborhoods to allow NWS data to be extrapolated to urban sites; and to study relations between local scale and microscale conditions.

Table 1. —Framework for urban climate classification adapted from Oke (1984)

Turbulent Boundary Layers

|  | Layer | Flow characteristics | Dimensions[a] | Scale |
|---|---|---|---|---|
| I | Urban canopy layer (UCL) | Highly turbulent, controlled by roughness elements | Same as $H^b$ typically 10 m | Micro |
|  | Roughness sub layer | Highly turbulent, wakes and plumes, transition zone | $2D - 3D^b$ | Micro |
| II | Urban boundary layer (UBL) | Turbulent, includes surface and mixed layers | Depends on surface fluxes of heat and momentum (typically 1 km day; 0.2 km night) | Local |

Urban Morphology

| Urban unit | Urban features | Urban climate phenomena | Dimensions[b] H | D | L | Scale |
|---|---|---|---|---|---|---|
| Building | Single building, tree or garden | Wake, plume, shadow | 10 m | 10 m | 10 m | Micro |
| Canyon | Urban street and bordering buildings or trees | Canyon shelter, shade bioclimate | 10 m | 10 m | 10 m | Micro |
| Block | City block, park, factory complex | Climates of parks, building clusters cumulus, mini-breezes |  | 0.5 km | 0.5 km | Micro |
| Land-use zones | Residential, commercial industrial | Local climates, winds, cloud modification |  | 5 km | 5 km | Local |
| City | Urban area | Heat island, urban circulation, urban effects in general |  | 25 km | 25 km | Meso |

[a] Dimensions of boundary layers are depths of affected atmosphere; dimensions of urban units are those of urban structures or plan area
[b] H is building height; D is building spacing; L is building length.
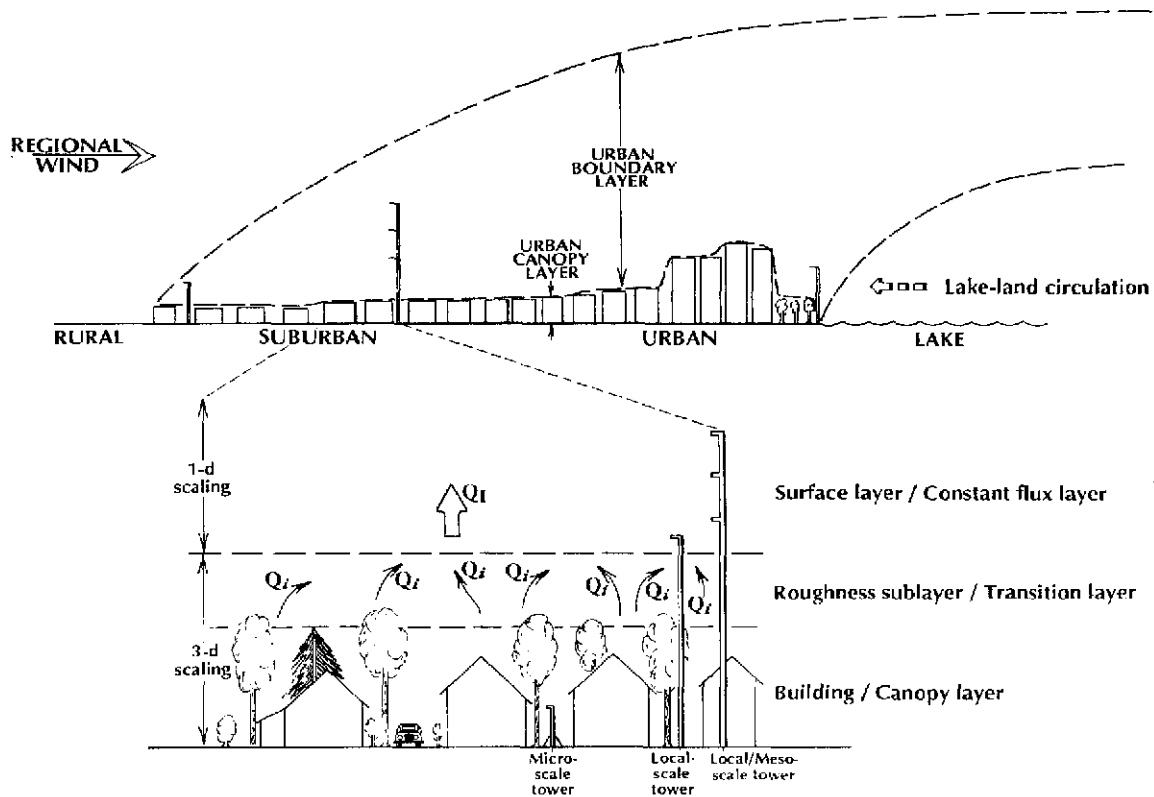
Figure 1.—Schematic representation of spatial scales and atmospheric processes in urban areas (adapted from Oke 1984; Oke et al.1989).

Table 2. —Scales of meteorological measurements in the Chicago Urban Forest Climate Project

| Scale | Urban features | Urban climate phenomena | Tower sites | Measurement period |
|---|---|---|---|---|
| Regional $10^3$ to $10^5$ m | Cook and DuPage counties, Chicago Metropolitian area, Lake Michigan | Lake-land breeze | Belmont Harbor ISPT3 O'Hare airport | July 92 to June 93 |
| Local $10^2$ to $10^3$m | City-blocks, land-use zones, neighborhoods, community areas[a] | Above canopy local scale climates, constant flux layer, urban boundary layer | ISPT3 Pneumatic flux tower | July 92 to June 93 July 92 |
| Micro $10^{-1}$ to $10^1$m | Individual properties buildings, gardens | Below canopy, shading, shelter | Below canopy 1 Below canopy 2-5 | July 92 to June 93 < 1 month at a site rotated between sites |

[a] Community area numbers referred to correspond to Figure 18 in McPherson et al. (1993): 9, 10-12[T], 13, 14, 15[T], 16, 17-19[T], 20-23, 25, 76[T], 87-91, 115[T]
[T] Community areas completely within 13 x 13 km study area (see Figure 3), remainder are partially in area.

## Selection of Study Sites

Chicago is located along the southwest shore of Lake Michigan and occupies a plain which for the most part is only meters above the lake (Figure 2). The lake does not thermally modify the predominant synoptic-scale flow from the west, but it does generate a mesoscale breeze (lake-land breeze) as a result of differential heating between land and water. This effect decreases with distance due to the modification of airflow by the underlying urban surface. In this study it was essential to identify the effect of the lake on micro- and local scale climates from other controls. This required careful selection of study sites. Additional constraints on measurement locations were imposed by logistics, primarily by the location of pre-existing towers on which equipment could be mounted and where access was permitted.

The extensive meteorological measurements were conducted from three towers: City Parks Board tower at Belmont Harbor; Illinois State Police District 3 tower (ISPT3) near the intersection of Forest Preserve, Harlem, and Irving Park; and next to the NWS climate station at O'Hare International Airport (Figure 2). The intensive flux measurements were conducted on the grounds of the Read Mental Health Center, directly adjacent to ISPT3 (Figure 2). The sites are aligned along a transect east-west across the city, from the lake, past the intensive-flux site to the O'Hare station (Figure 2).

The area surrounding the ISPT3 and intensive-flux towers includes the neighborhoods of Harwood Heights and Norridge, Chicago. It has predominately two-storied densely packed houses and a large number of mature deciduous trees with many greenspaces (parks, cemeteries, etc.). In the immediate vicinity of the towers are large greenspaces (cemetery and grounds of the mental health facility) to the east, northeast, and west; a shopping mall and garages to the north and northwest; and houses to the south.

## Meteorological Measurements

### Intensive observations
The intensive observations consisted of direct measurements of sensible and latent heat flux, and net all-wave radiation (Table 3). The convective fluxes ($Q_H$ and $Q_E$) were measured using eddy correlation techniques (Lenschow 1986; Oke 1987). All of the equipment was installed on a pneumatic tower that could be lowered when rainfall, high winds, and/or thunderstorms were anticipated. A Campbell Scientific Inc. (CSI) one-dimensional sonic anemometer and fine-wire thermocouple system (SAT: CA27) was used to measure vertical wind velocity and temperature; a CSI krypton hygrometer (KH20) was used to measure the absolute humidity. Fluctuations in the vertical wind velocity, air temperature and humidity were sampled at 5 Hz and the covariances determined over 15-minute periods. Flux corrections were made for oxygen absorption by the sensor and air density (Webb et al. 1980; Tanner and Greene 1989). Corrections were not made for frequency response and spatial resolution of the eddy correlation sensors, which probably would increase $Q_E$ by 1 percent (M. Roth 1992 pers. commun.; Grimmond et al. 1993). All times have been corrected to Local Apparent Time.

Net all-wave radiation was measured at two levels (Table 3). It is not practical to measure $\Delta Q_S$ directly at urban/suburban sites due to the complexity of the materials and morphology of the urban surface (Oke and Cleugh 1987; Grimmond et al. 1991). Hence $\Delta Q_S$ is determined as a residual in the energy balance ($Q^*-(Q_H+Q_E)$) if $Q_F$ and $\Delta Q_A$ are neglected. This approach has the inherent problem that all measurement errors of other energy balance fluxes are accumulated in the $\Delta Q_S$ term.

$Q_F$ has not been determined for this site. Grimmond (1992) calculated the size of this flux for a suburban area of Vancouver, British Columbia, based on combustion from stationary and mobile sources and metabolic rates. The magnitude of this flux is dependent on the spatial pattern of the sources (Schmid et al. 1991). In residential areas, the most notable influences on $Q_F$ are major roadway systems and significant non-residential stationary anthropogenic heat sources, for example, strip malls with energy-intensive users. Given the location of the local anthropogenic heat sources relative to the measurement sites, summertime air-conditioning, and the magnitude of $Q_F$ calculated by various authors (Oke 1988), the peak diurnal values of $Q_F$ at the study site probably were about 20 Wm-2 (4.5 percent of mean $Q^*$ values).

Spatial differences in surface cover across the city result in differential heating and the lateral movement of energy (advection). The horizontal advection term ($\Delta Q_A$) is difficult to determine. The observation site was located in an area that was extensively suburbanized, but, as discussed earlier, there are known regional scale circulations that are generated due to differential heating patterns between land and Lake Michigan (e.g. Hall 1954; Lyons 1972). The intensive flux-tower and ISPT3 site are less than 15 km from the lake (Figure 2), without intervening topographic barriers. Following an analysis in the Sunset neighborhood in Vancouver, where there is also a large water body which generates a sea-breeze circulation, Steyn (1985) concluded that advection could be neglected at the local scale when working under similar land-use conditions. For this report, $\Delta Q_A$ has been ignored, so the energy balance residual ($\Delta Q_S$) should be interpreted accordingly. The influence of advection is the subject of further investigation.

### Extensive observations
The instrumentation used in the extensive measurements, and the heights at which it was mounted, are listed in Table 3. A full description of ventilated temperature systems developed for the Chicago Urban Forest Climate Project is presented by Grant and Heisler (1994). All instruments used in the local scale study and the below-canopy study were inter-compared before and after the measurement campaigns (May 1992, July 1993). Appropriate corrections were made for inter-instrument differences.

# Methodology: Surface Controls

## Rationale
The active surface of any system is one of the most important determinants of climate because it is the primary site of
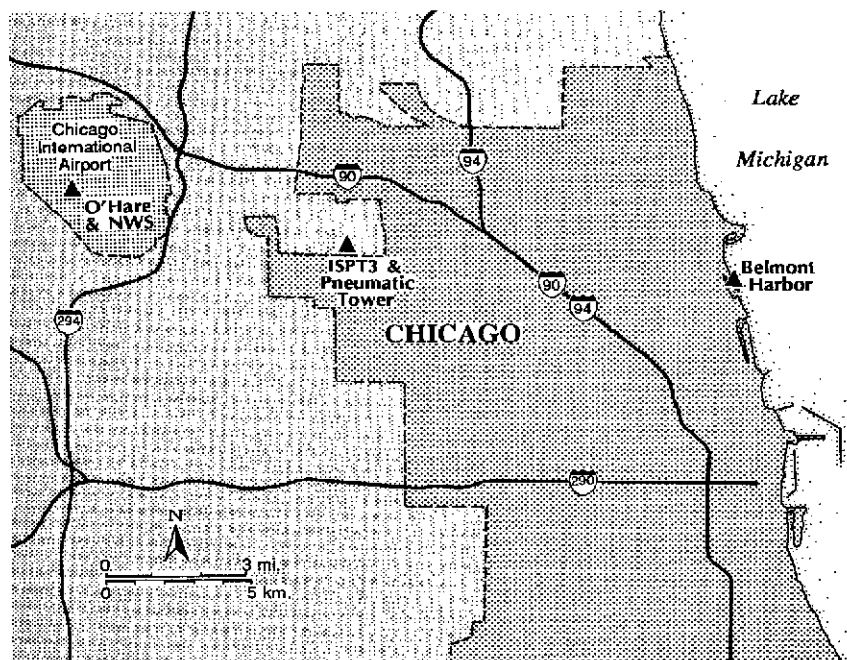
Figure 2.—Location of the local scale measurement sites across the city of Chicago (Chicago is identified with the darker shading).

Table 3. —Instrumentation used on pneumatic tower during intensive measurements and on fixed towers for extensive measurement period (July 1992 to June 1993)

Intensive Measurements

| Variable | Instrumentation | Level installed (m) |
|---|---|---|
| Sensible heat flux ($Q_H$) | CSI sonic anemometer and fine wire thermocouple | 18 |
| Latent heat flux ($Q_E$) | CSI krypton hygrometer | 18 |
| Net all wave radiation ($Q^*$) | Swissteco miniature net radiometer | 18 |
| Soil heat flux ($Q_G$) | REBS Soil heat flux plates | -0.08 |

Extensive Measurements

| Variable | Instrumentation | Illinois StatePolice Tower ISPT3 | Belmont Harbor | O'Hare |
|---|---|---|---|---|
| Air temperature | Vaisala HMP35C | 24.6, 43.1, 69.5 | 17.1 | 1.5 |
|  | YSI thermistor 44020 | 24.6, 43.1, 69.5 | 17.1 | 1.5, 4.0 |
| Relative humidity | Vaisala HMP35C | 24.6, 43.1, 69.5 | 17.1 | 1.5 |
| Wind speed | R.M. Young Wind Sentry | 24.6, 43.1, 69.5 | 17.1 | 2.5 |
| Wind direction | R.M. Young Wind sentry | 24.6, 69.5 | 17.1 | 2.5 |
| Net all-wave radiation | REBS Net radiometer | 24.6 |  | 2.5 |
| Solar radiation | Li-cor pyranometer | 24.6 |  | 4.0 |
| Precipitation | Texas Instruments rain gauge | 3 |  |  |
| Surface moisture status | Weiss type wetness sensor | 0 |  |  |

transfer and transformation of energy, mass and momentum. Climatological and meteorological measurement and modeling studies require the surface datum to be defined and described to characterize the site where measurements have been conducted; provide input for numerical models; or ensure spatial consistency between measured and modeled data. In model evaluations, it is essential that surface parameters (the model domain) represent the same surface area for which the measurements were conducted (the measurements' source area) (Grimmond and Souch 1994). In this study the nature of surface controls on energy and water exchanges is of primary interest.

The source area for meteorological measurements is dependent on the physical process involved, the instrumentation used, and the meteorological conditions under which the measurements occurred. For radiant fluxes, the source area is fixed in time by the field of view of the instruments (i.e., by geometry). This source area can be determined using procedures outlined by Reifsnyder (1967) and Schmid et al. (1991). For turbulent fluxes, the source area is not fixed but varies through time as a sensitive function of sensor height, atmospheric stability, and surface roughness (in that order of importance). Numerical models, based on boundary-layer diffusion theory have been developed to determine the dimensions, weighting, and areal extent of the source area

of turbulent measurements (e.g., Gash 1986; Schuepp et al., 1990; Leclerc and Thurtell 1990; Schmid and Oke 1990; Horst and Weil 1992).

In this study, a methodology to link a source area model for turbulent fluxes (based on Schmid and Oke 1990) to a surface database within a geographic information system (GIS) was developed (Grimmond and Souch 1994). This surface database in conjunction with the flux data will provide a basis for assessing the relationship between energy and water fluxes and vegetation (Demanes 1994).

## Surface Database

Preliminary calculations based on the Schmid and Oke (1990) source area model for turbulent fluxes were used to identify the approximate dimensions of the source areas for the convective flux ($Q_H$ and $Q_E$) measurements during the intensive study period. Based on these calculations a square approximately 13 km by 13 km, centered on the ISPT3 tower site, was delineated (Figure 3). A three-tier surface database was developed for this area, bounded by Touhy Avenue to the north, Chicago Avenue to the south, Mannheim Road to the west, and Pulaski Road to the east (Table 4). At the regional scale the spatial distribution of land use (Table 5) was mapped from aerial photographs. Given the focus of the
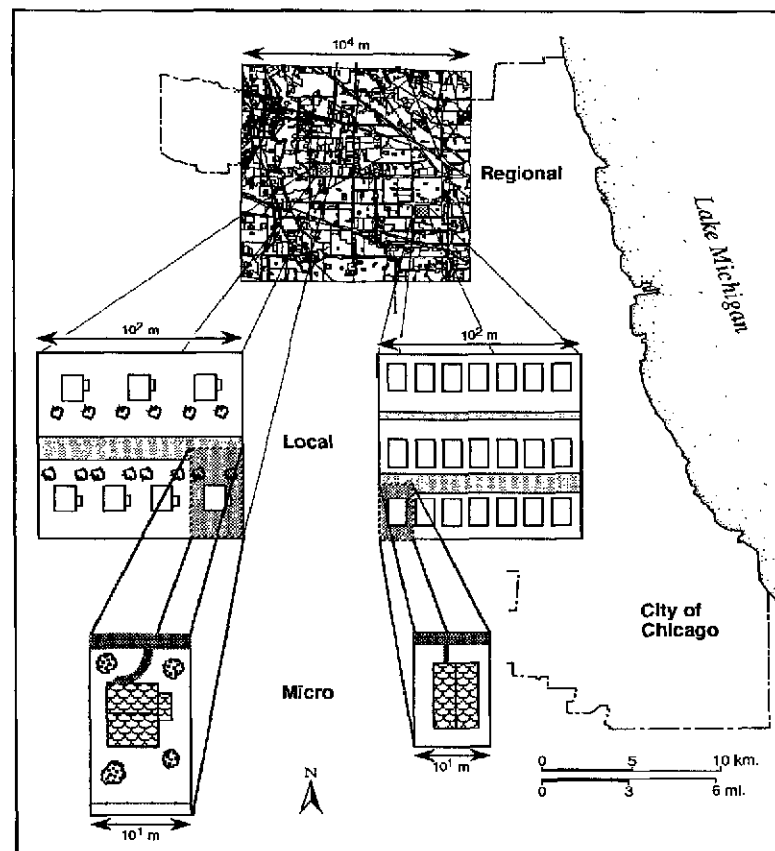


Figure 3.—Schematic representation of the structure of the surface database (adapted from Grimmond and Souch 1994).

study on the effects of vegetation on urban climate, the two primary criteria for identifying the land-use categories were building dimensions and density, and vegetation dimensions and density. The digitized, geo-corrected map contains more than 2500 polygons (Figure 4).

At the local scale (Figure 3), 200 m x 200 m grid squares were located randomly on a second set of more detailed (1:4800) aerial photos (Table 4). For each square the percent cover of building, grass, trees, pavement, and other variables (Table 6) was estimated. Based on replicates within each land-use category, means and standard deviations were calculated for building and vegetation densities and percent plan-area surface type (Table 6). These data were linked to the regional digital land-use map to allow the areal distribution of attributes to be illustrated.

At the microscale (Figure 3), field surveys were conducted to provide detailed information on surface cover at the scale of the individual lot in residential neighborhoods or 1/10 acre plot (0.04 ha) in non-residential areas. Weighted stratified random sampling was used to select sample plots within each land-use category to obtain detailed information on specific surface characteristics (Table 7). Data from 147 plots (87 residential, 60 nonresidential) were collected within the study region, 47 surveys conducted as part of the survey on urban forest structure (see Nowak 1994: Chapter 2, this report) and 100 supplementary sites. The additional surveys were conducted to ensure there were replicate surveys for each general land-use class. Field data stored in database files are linked to the regional scale land-use database to provide information on the attributes within land-use categories. These include building heights (of interest in the calculation of roughness length); surface materials (important for albedo, emissivity, drainage properties, storage heat flux modeling, etc.); and tree species and tree density (which aid in calculating leaf area index, important in evaporation modeling) (Grimmond and Souch 1994).

Figure 5 illustrates the spatial variability of vegetative cover and built impervious surfaces across the study region. Impervious surfaces are important in defining retention and detention storage capacities which are used in both runoff and evaporation modeling. Vegetative cover is important for defining surface resistances for evaporation and air quality modeling. When these figures are compared with the land-use map (Figure 4), differences in surface properties among the classes, which influence the energy and water exchanges become clear. For example, note the differences in surface cover within the residential A classes (A to A4) and how the city generally becomes more impervious toward the east.

## Results

### Representativeness of the Measurement Periods

Analysis of synoptic classifications during the study period show that the weather the Chicago area experienced was similar to that of the prior 10 years (Grant 1993). Cold fronts and warm sectors passed through the Chicago area 25 and 12 percent of the study period respectively; within 2 percent of the occurrence during the prior 3 years, and within the range of percent occurrence over the past 10 years. Chicago experienced fewer warm fronts during the study period than in the recent past, but experienced as many as have occurred in two of the last ten years. Polar high pressure was the dominant synoptic feature during the study period (35 percent of the time north, west or east of Chicago, and 11 percent of the time south of Chicago). The frequency of occurrence of the polar high located north, west, or east of Chicago equaled the occurrences in 3 of the past 10 years. The frequency of occurrence of the polar high south of Chicago exceeded the highest frequency of occurrence in the prior ten years. The presence of more frequent polar high pressure systems to the south of Chicago helps explain the relatively cold temperatures experienced during the study period (Table 8).

At O'Hare Airport a total of 95.8 mm of rain fell on 23 days during July 1992 (normal: 92.2 mm); longest period without rainfall was 2 days. Consequently, the surface was almost continuously wet throughout the study period (Figures 6 and 8). The range of general climatic conditions measured from the ISPT3 site in July 1992 (the intensive period) are presented in Figure 6.

Table 4. —Information source for surface database at each scale (See Figure 3 for scale dimensions)

| Scale | Method | Area covered | Output |
|---|---|---|---|
| Regional | Land-use mapping on air photos Geonex Chicago Aerial Survey(CAS), Des Plaines Flown: March 2, 1992 scale: 1: 24000 | 13 km x 13 km square centered on ISPT3 Area bounded by Touhy Ave, Chicago Ave., Mannheim Rd. & Pulaski Rd. | Land-use categories (see Table 5) |
| Local | Detailed photo analysis Sidwell Company, West Chicago: Flown: Spring 1987 scale: 1: 4800 Geonex CAS: March 24, 1990,1:4800 | Randomly located replicates within each land-use category | Attributes for each land-use (see Table 6) |
| Micro | Field surveys | 147 randomly located points and immediate surrounding area within region | Surface details (see Table 7) |

Table 5. —General land-use categories for Chicago

| General Land-use | Categories and description |
| --- | --- |
| **Residential (Single)** | |
| A | High density housing, A1-A4 differentiated by shape of buildings and whether attached or not. Yards small, mainly grass, few trees. |
| B | Moderate density housing, small houses with trees |
| C | Moderate density housing, small houses, large yards. C1-C3 differentiated by size of houses. All have many trees/extensive landscaping |
| D | Large houses, small grass yards with some trees and shrubs |
| E | Large houses, large yards, yards landscaped with shrubs and trees |
| EA | Mixture of "A" and "E" type housing |
| F | Houses equally spaced, large grass yards, few trees, F1 and F2 differentiated on housing density |
| MH | Mobile homes |
| **Apartments** | |
| AA | 5-6 stories, U-shaped, distinguished from AA2 based on arrangement of parking |
| AB | Square shaped buildings |
| AL | L-shaped buildings, 7 stories tall, no trees |
| AL1 | Rectangular shape |
| AR1 | Duplexes |
| AR2 | Mixture of AR1 and A type houses |
| AR3 | Highly mixed |
| BB | Low-level apartments (2 stories), rectangular shape. BB1, BB2 and BB3 distinguished on height and size |
| **Commercial-Industrial** | |
| CB | Large commercial buildings - < 6 stories |
| CC | Very tall commercial buildings - > 15 stories |
| CS | Small commercial buildings |
| I | Industrial - large low level buildings or many small buildings |
| **Institutional** | |
| HS | High school - large building, few trees, medium size parking lot |
| S | Elementary/ Junior High school - much smaller buildings than HS |
| U | University - large buildings, parking lot, vegetated grounds |
| **Transportation** | |
| MRI | Major roads e.g. interstates |
| RR | Railroad tracks or side/yards: |
| **Vacant/Wild** | |
| DI | Dirt |
| **Vegetated** | |
| VG | Golf course |
| VGR | 100% grass |
| VM | 50% grass/50% tree and shrub |
| VPC | Cemetery |
| VT | Trees and shrubs |
| **Impervious Surfaces** | |
| CN | Concrete |
| IP | Parking lot (impervious) |
| IS | Tennis court |
| **Water** | |
| WL/R | Lake/river |

4a
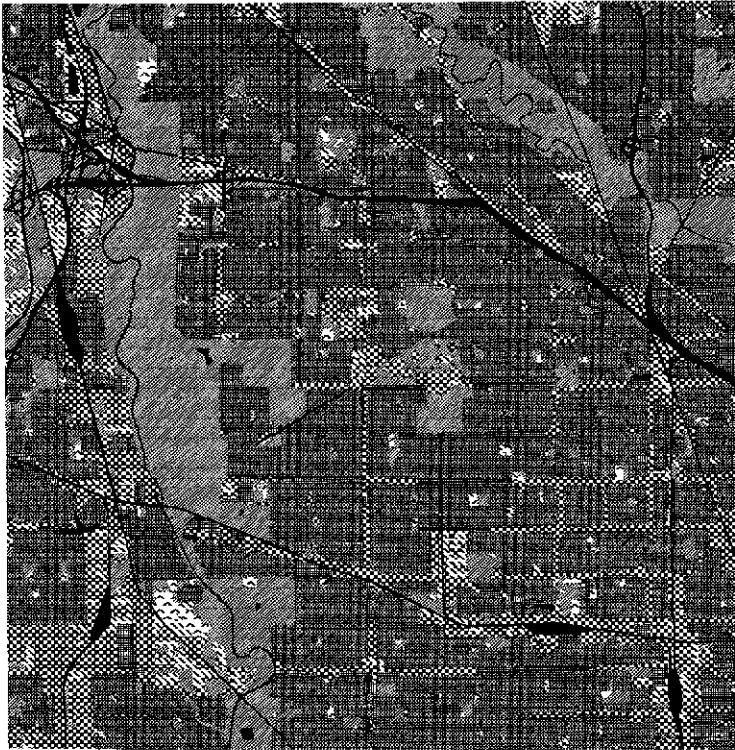


**General land use classes**

- Residential
- Apartments
- Commercial and industrial
- Institutional
- Impervious
- Transportation
- Vegetation
- Water

km

0    2    4

4b



**Residential classes**

- A
- A1
- A2
- A3
- A4
- B1
- C
- C1
- C2
- C3
- D
- E
- E1
- EA
- F
- F1
- F2
- MH
- Transportation & water
- Apartments
- Remainder

km

0    2    4

Figure 4.— a) General land-use classes across the study area b) Residential land-use classes (see Table 5 for descriptions)

Table 6.— Attributes determined for each land-use category

| Densities (number per area) | |
|---|---|
| Buildings | |
| Trees | |
| Roads | |

| Percent areal cover | |
|---|---|
| Buildings | |
| Garages | |
| Grass | |
| Trees/shrubs | |
| Parking lot | |
| Main road | |
| Water | |
| Dirt | |
| Sand | |
| Pavement (non parking lot) | |
| Scruff | |

Table 7. —Information collected in the field survey

| Non residential (0.1 acre, 0.04 ha plots) | |
|---|---|
| Landscape: | Managed/ unmanaged and condition |
| Land-use: | Residential, commercial etc. and % of plot covered |
| Ground cover: | % cover by: building, structures, cement, tar, wood, other impervious, soil, rock, duff/mulch, herbaceous/ivy, grass, wild grass, water, shrubs |
| Building attributes: | Type, length, width, material, azimuth from front door outward, age, height, number of floors, roof color, wall color, % wall glass, average distance to nearest building, height of nearest building |
| Structure shrub and trees: | Full listing of species and size of each tree and shrub, condition of tree, % beneath canopy of artificial surfaces, d.b.h, height, height to lower crown, crown width, crown shape,  percent of crown volume occupied by leaves, tree condition. |

| Residential (variable size based on lot size; from mid-street to mid-alley or back of lot) | |
|---|---|
| Road: | Width of road, length of road in front of property, type, width of curb to sidewalk, % of strip covered by cement |
| Alley: | Width, length, surface type |
| Length: | Length of front part of lot, width of front part of lot, presence, type and height of any overhead obstructions |
| Irrigation: | % vegetation irrigated |
| Structure: | Length, width, height of structure, % plot occupied by structure, type of  structure, material, structure of roof |
| Shrubs: | Species, length and height of shrub mass, % shrub volume occupied by leaves, density of leaf mass, number of stems in mass, average diameter of stems in mass |
| Trees: | Species, number of stems, d.b.h., tree height, bole height, crown width, crown shape, percent of crown volume occupied by leaves, crown density |
| Positions: | Sketch and photo of building and tree locations referenced to tree information |

**Greenspace (%)**

0
0.01 - 5
5.01 - 10
10.01 - 15
15.01 - 20
20.01 - 25
25.01 - 30
30.01 - 40
40.01 - 50
50.01 - 60
60.01 - 70
70.01 - 80
80.01 - 90
90.01 - 95
95.01 - 100

km
0    1    2

5a

**Built impervious (%)**

0
0.01 - 5
5.01 - 10
10.01 - 15
15.01 - 20
20.01 - 25
25.01 - 30
30.01 - 40
40.01 - 50
50.01 - 60
60.01 - 70
70.01 - 80
80.01 - 90
90.01 - 95
95.01 -100

km
0    1    2
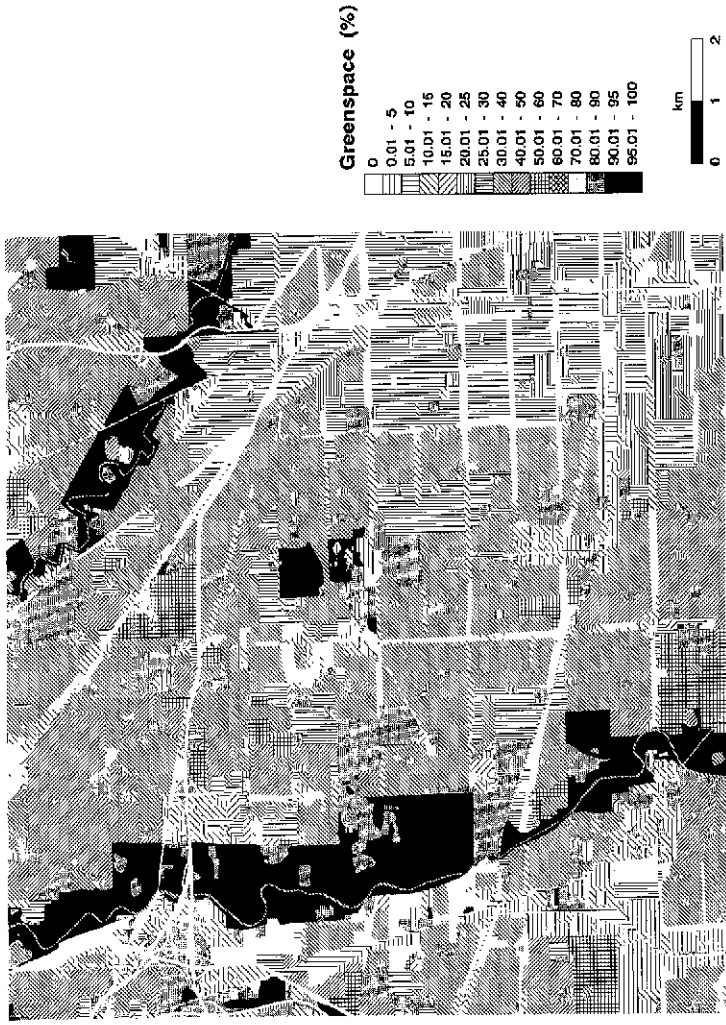
5b
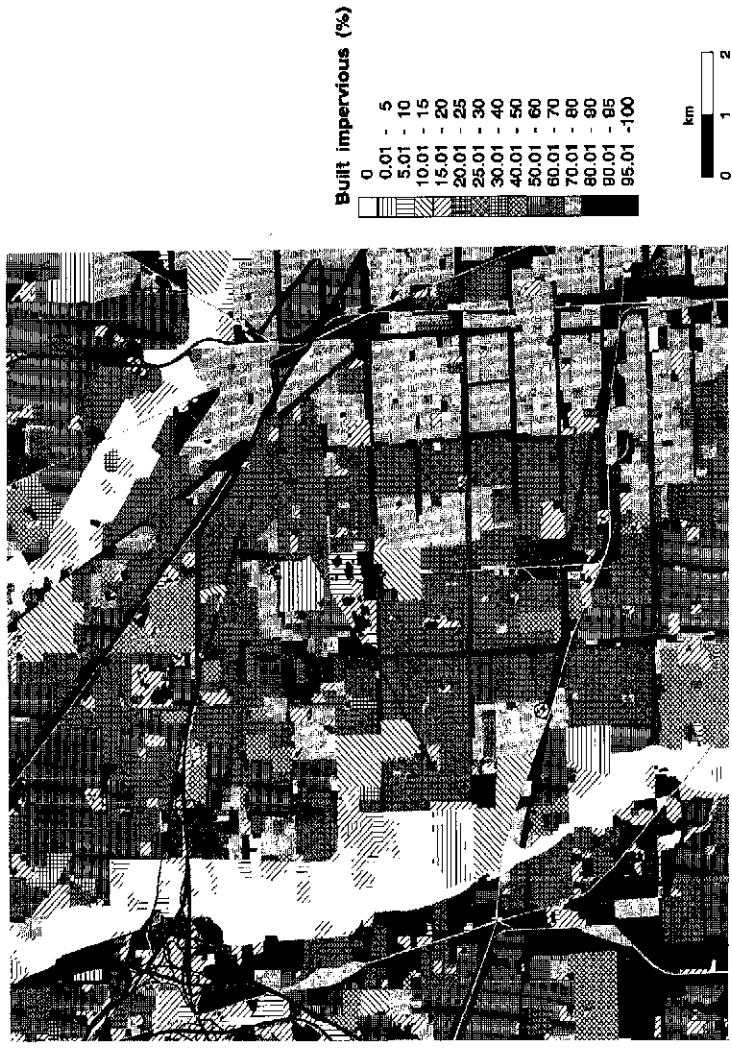
Figure 5.—Surface cover in the vicinity of the measurement site: a) Percent plan-area vegetation; b) Percent plan-area built impervious

Table 8.—Meteorological conditions during extensive study period (July 1992 to June 1993) and departures from Normal (1951-80). Source of data NOAA (National Climate Data Center, Local Climatological Data, Chicago O'Hare station). (SP study period; D departure from Normal).

| Month | Temp (°C) | | Precip (mm) | |
|---|---|---|---|---|
| | SP | D | SP | D |
| July | 20.7 | -2.1 | 95.8 | 3.6 |
| August | 19.4 | -2.7 | 90.4 | 0.8 |
| September | 17.1 | -1.1 | 109.5 | 24.4 |
| October | 10.2 | -1.7 | 45.5 | -12.4 |
| November | 3.5 | -0.8 | 137.4 | 85.1 |
| December | -1.9 | 0.5 | 63.3 | 9.9 |
| January | -3.2 | 2.9 | 97.3 | 58.4 |
| February | -4.2 | -0.6 | 20.8 | -13.7 |
| March | 1.2 | -1.7 | 114.8 | 46.5 |
| April | 7.2 | -2.0 | 116.1 | 23.6 |
| May | 8.8 | 0.4 | 46.5 | -37.8 |
| June | 24.8 | -1.2 | 253.0 | 157.0 |

The climatological conditions experienced during the extensive study period are summarized in Table 8 and Figure 7. Overall, the period was slightly cooler and wetter than normal.

## Energy Balance Fluxes

During the intensive measurement period 127 hours of eddy correlation flux measurements were collected. Because the measurements were conducted during a period with a high frequency of rainfall, there are many breaks in the data (Figure 8). The mean value for each of the fluxes for each hour and their variability is shown in Figure 9. From Figures 8 and 9 it can be noted that clouds occurred throughout the day during the measurement period. The maximum output flux (i.e., removal of energy from the surface) was $Q_E$ followed very closely by $Q_H$ and $\Delta Q_S$. The convective fluxes ($Q_E$ and $Q_H$) peak at solar noon whereas $\Delta Q_S$ peaks about 1100 Local Apparent Time, with a marked hysteresis pattern (values higher in the morning and lower in the afternoon).

To allow direct comparisons of flux partitioning from day to day (i.e., to remove the effect of the available energy varying from day to day), each of the fluxes are normalized by net radiation to calculate ratios: $\chi(Q_H/Q^*)$, $\Upsilon (Q_E/Q^*)$ and $\Lambda (\Delta Q_S/Q^*)$ (Figures 10 and 11). The ratio of the two convective fluxes, the Bowen ratio: $\beta = Q_H/Q_E$ (i.e., the amount of energy warming the air relative to that evaporating water), also is calculated. The mean daytime Bowen ratio for the observations, determined from the mean daytime fluxes, is 0.87. Thus, more energy is being removed from the surface by the latent heat flux than sensible heat flux (i.e., more energy during this period was going into drying the surface than into warming the air). The mean ratios of $\chi$, $\Upsilon$, and $\Lambda$ are 0.32, 0.38, and 0.30 respectively for the daytime ($Q^*>0$) (32 percent of the energy going into heating the air, 38 percent into the evaporation of water, and 30 percent into

heating the urban fabric), and 0.35, 0.49 and 0.16 for the day (24 hours) (35 percent heating the air, 49 percent evaporating water, and 16 percent heating the urban fabric). These results are biased to slightly higher Bowen ratios than the true average for the period as measurements were restricted to times when rainfall was neither occurring nor imminent (i.e., evaporation may have been more significant at the other times).

The variability of the fluxes from day to day can be seen by the ranges on Figure 10. It is notable that the data are remarkably consistent except for one day (Year/day; 92/210) when Bowen ratios were 3 to 5 (i.e., much greater $Q_H$ than $Q_E$). This day was at the end of one of the slightly longer intervals between rainfall events (Figure 8). The high Bowen ratios were associated with a suppressed $Q_E$, while $Q_H$ remained similar to that of previous days (Figure 8). Instead the energy went into storage heat flux ($\Delta Q_S$) (heating the urban fabric). On the previous day (92/209), the largest $Q_E$ fluxes in the measurement period were observed. By 92/210 there had been a significant reduction in availability of surface moisture (Figure 8: surface moisture sensors), so the surface was starting to exert a more significant control on energy partitioning. Throughout July 1992 in Chicago, it is probable that the influence of surface morphology on flux partitioning is not as evident as it may be at other times because of the frequency of rainfall events.

The Bowen ratio determined in this study, 0.87, is lower than the "typical" value of 1.0 suggested by Oke (1982) for suburban areas. It also is considerably lower than values observed in the summertime in Tucson, Sacramento, and Los Angeles (1.80, 1.40, and 1.38 respectively for daytime values) (Grimmond and Oke 1994). However, the value is not physically unrealistic given the conditions in Chicago in 1992. As was noted, flux measurements were restricted as to the time period for which they were conducted and the range of conditions experienced.

The $\chi$ ratio expresses how much energy is going into warming the air rather than drying the surface or warming the urban fabric. The $\chi$ ratio in Chicago behaves in a similar manner to that in other urban areas, showing an increase through the day ($Q^*>0$ time period) (Grimmond and Cleugh 1994). The mean daytime ratio (0.32) (daily value 0.35) is lower than the typical (0.39) values suggested by Oke (1982), and lower than those reported for Tucson, Sacramento and Los Angeles (0.46, 0.40 and 0.36) (Grimmond and Oke 1994). Given the prevailing meteorological conditions in Chicago during the study period, it is likely that more energy than usual was used to dry surfaces rather than warm the air or the urban fabric, i.e., the $\beta$ and $\chi$ ratios are lower than would have been obtained under drier periods, and $\Upsilon$ is higher.

To obtain an idea of the variability of energy partitioning between seasons and years, it is useful to consider the data from Vancouver (Table 9). The Sunset neighborhood in Vancouver is one of the few urban sites where energy balance studies have been conducted over a number of years and thus under a range of synoptic conditions. There is considerable variability among seasons both within and across years (Table 9). However, it is important to note that
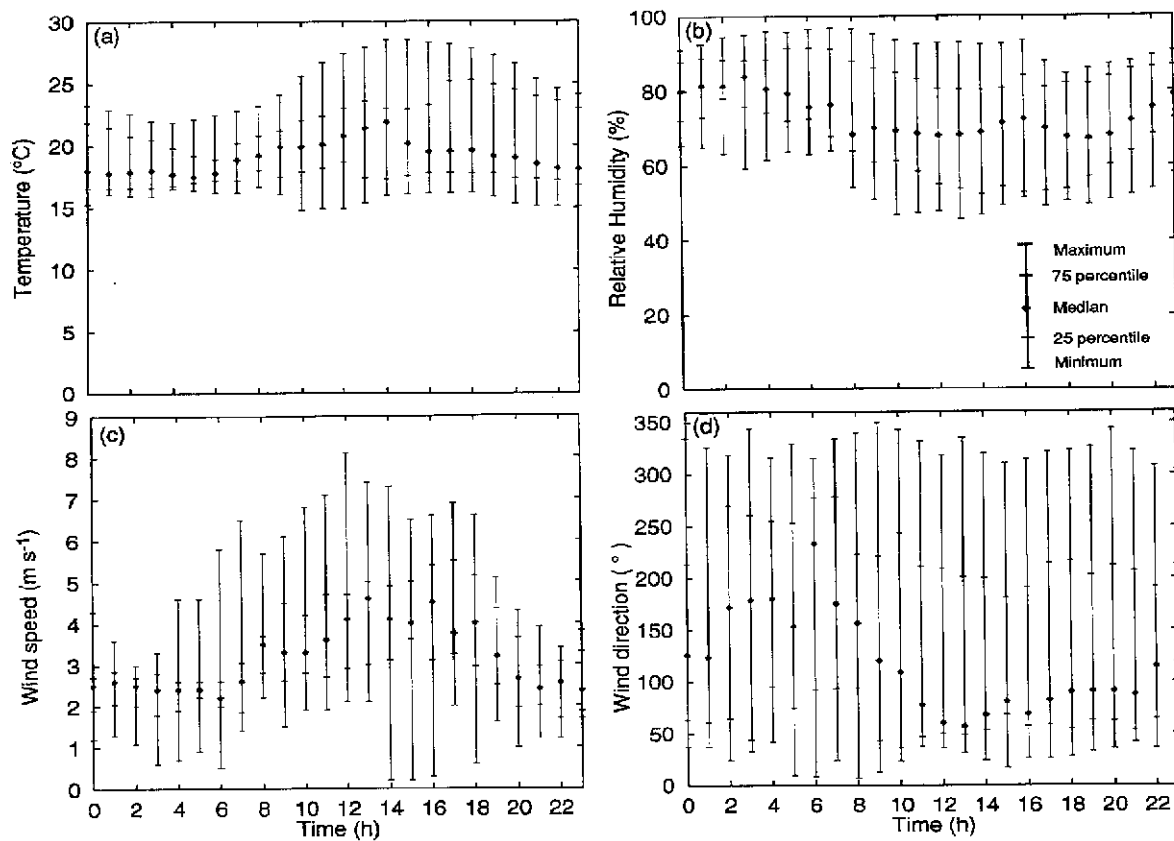
Figure 6.—Range of meteorological conditions during the intensive study period: Diurnal ranges of temperature, relative humidity, windspeed and wind direction. Minimum (0), 25, 50 (median), 75 and 100 (maximum) percentiles plotted. Median plotted as a diamond, and minimum, 25 and 75 percentile values, and maximum plotted as horizontal lines).
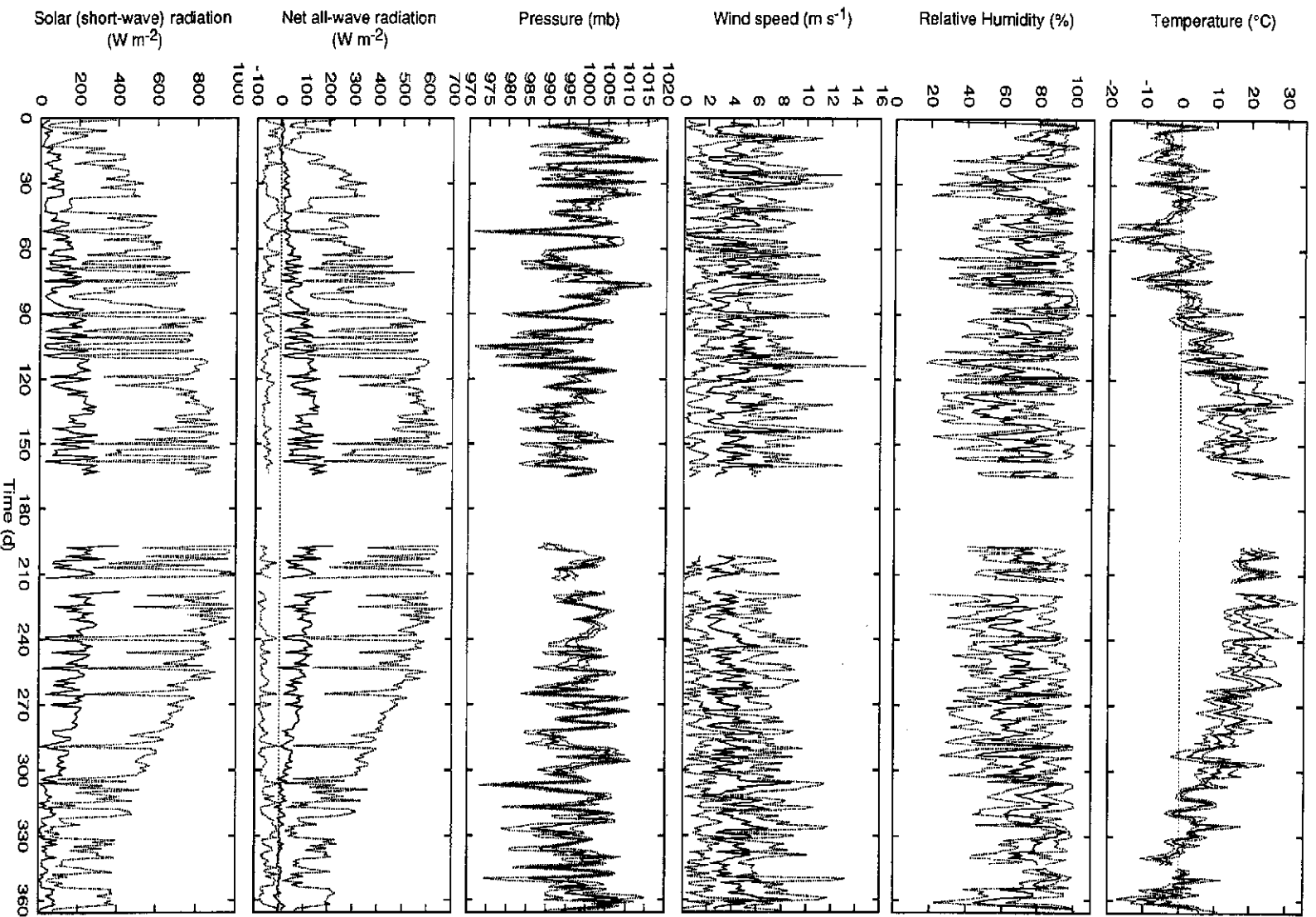
Figure 7.—Meteorological conditions during the extensive study period measured at the lowest level on the ISPT3 fixed tower: Mean, maximum and minimum daily temperature, relative humidity, windspeed, pressure, net radiation and solar radiation.
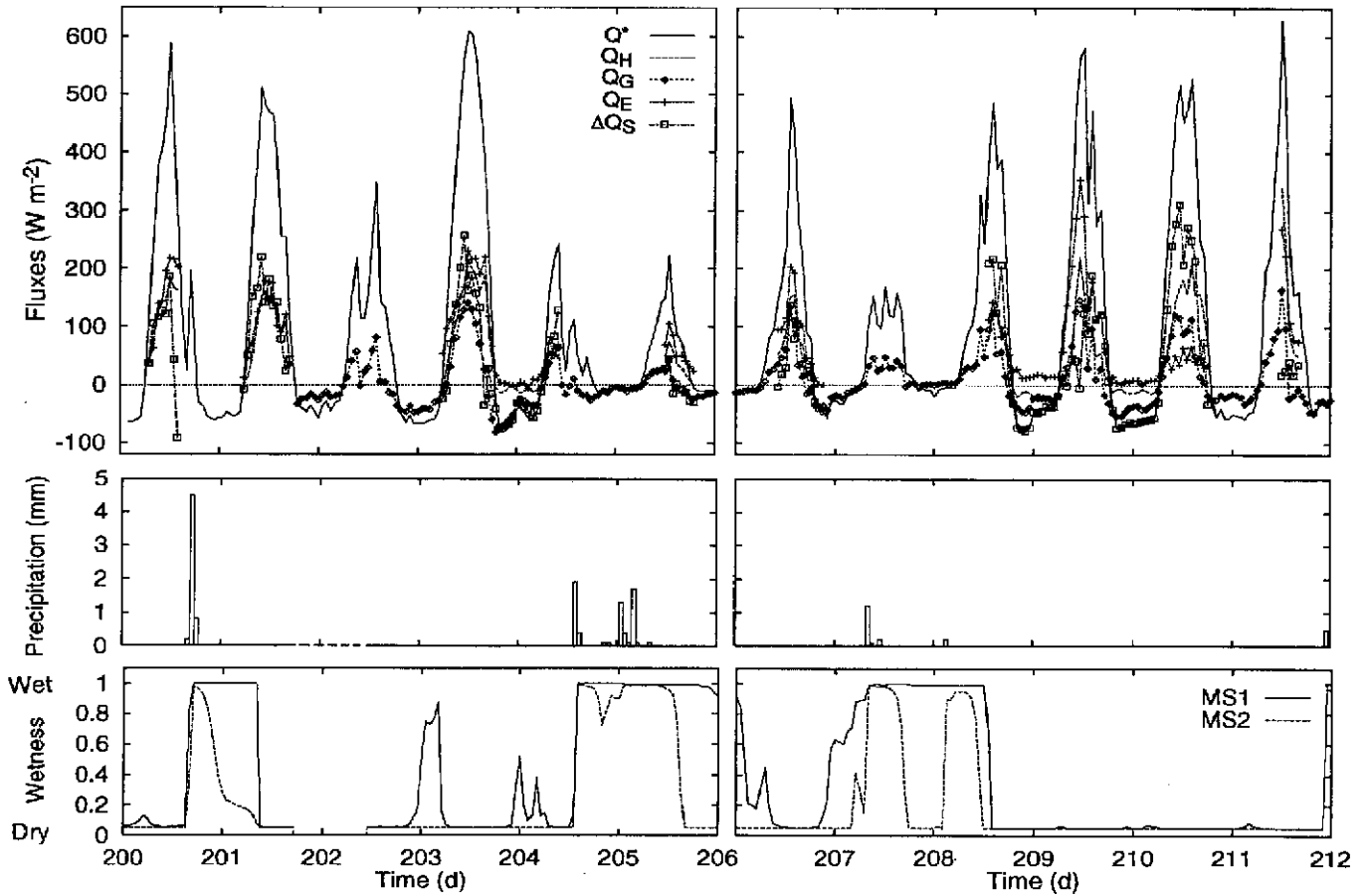
Figure 8.—Time series of energy balance fluxes, precipitation and surface moisture status. (Note the surface moisture status is a relative index, wet 1.0, dry 0.0, MS1 and MS2 are moisture sensors on vegetation and impervious surfaces respectively. These respond to both precipitation events and dew). (From July 20th (day 200) to July 31st (212), 1992). Note break in data 201-202.
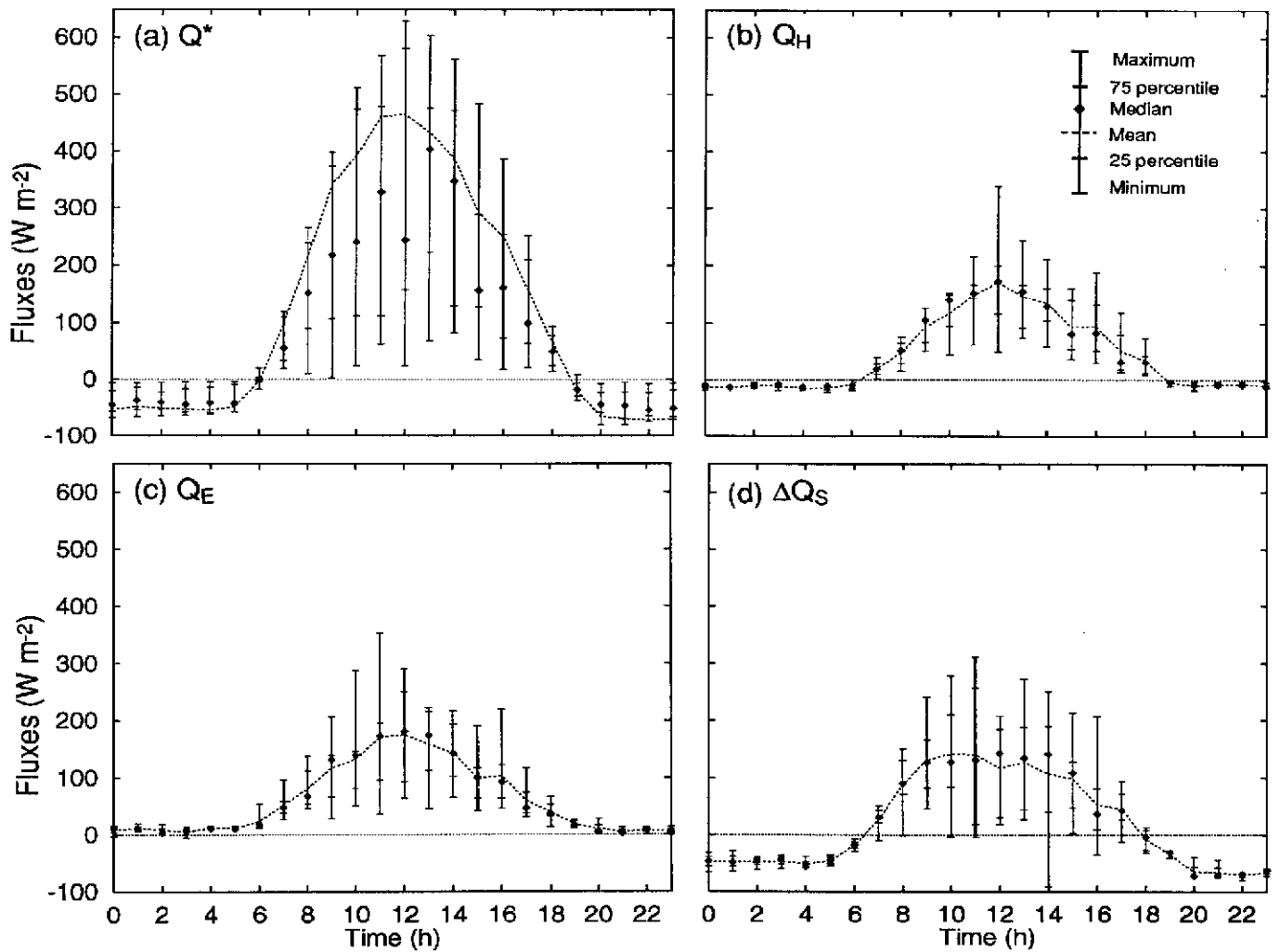
Figure 9.—Ensemble diurnal energy balance fluxes for Chicago, July 1992. Mean, 0 (minimum), 25, 50 (median), 75 and 100 (maximum) percentiles plotted. Mean values joined with a dashed line, median plotted as a diamond, and minimum, 25 and 75 percentile values, and maximum plotted as horizontal lines. The number of hours used in the analysis is indicated on Figure 11.
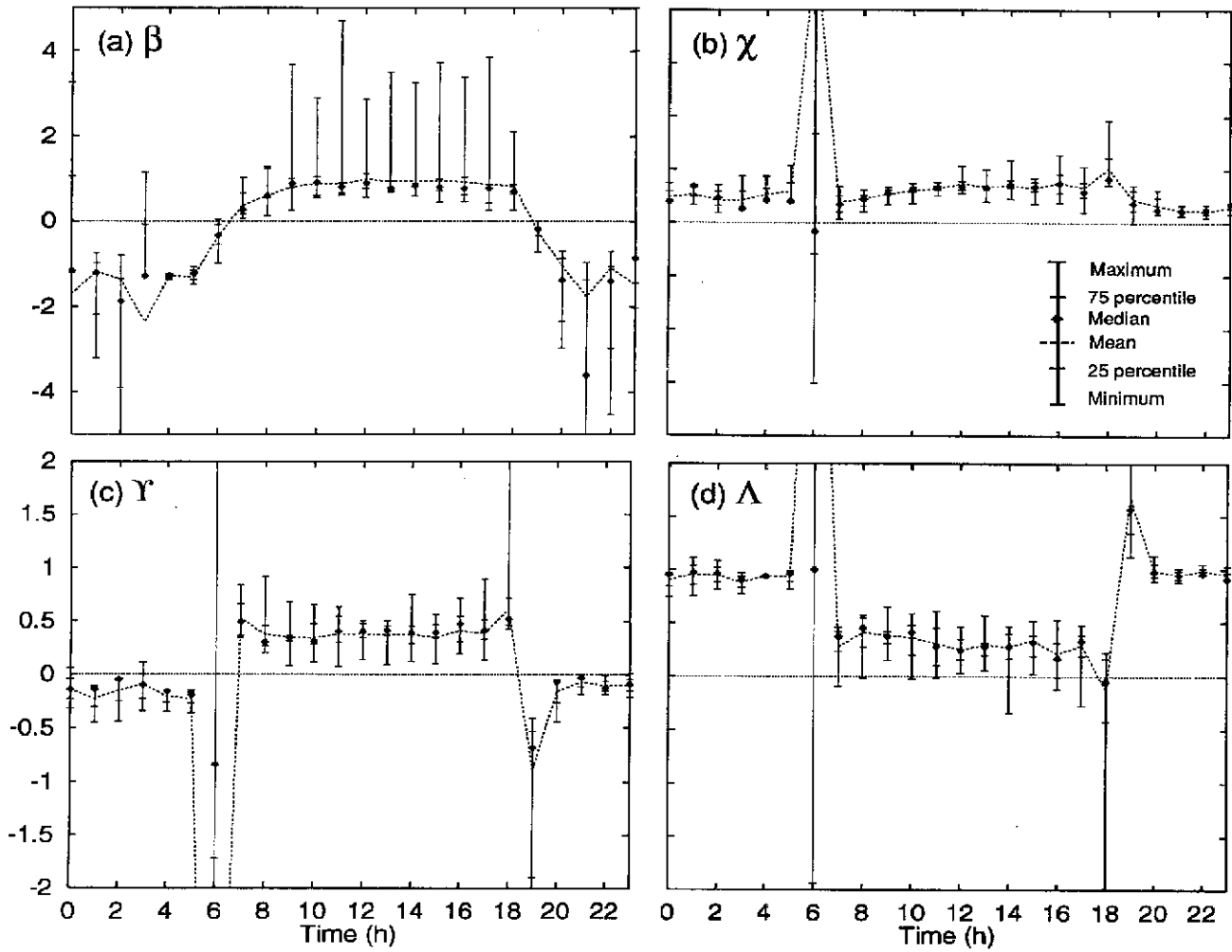
Figure 10.—Diurnal patterns and variability of ß, $\chi$, $\Upsilon$ and $\Lambda$ ratios (see text for explanation)
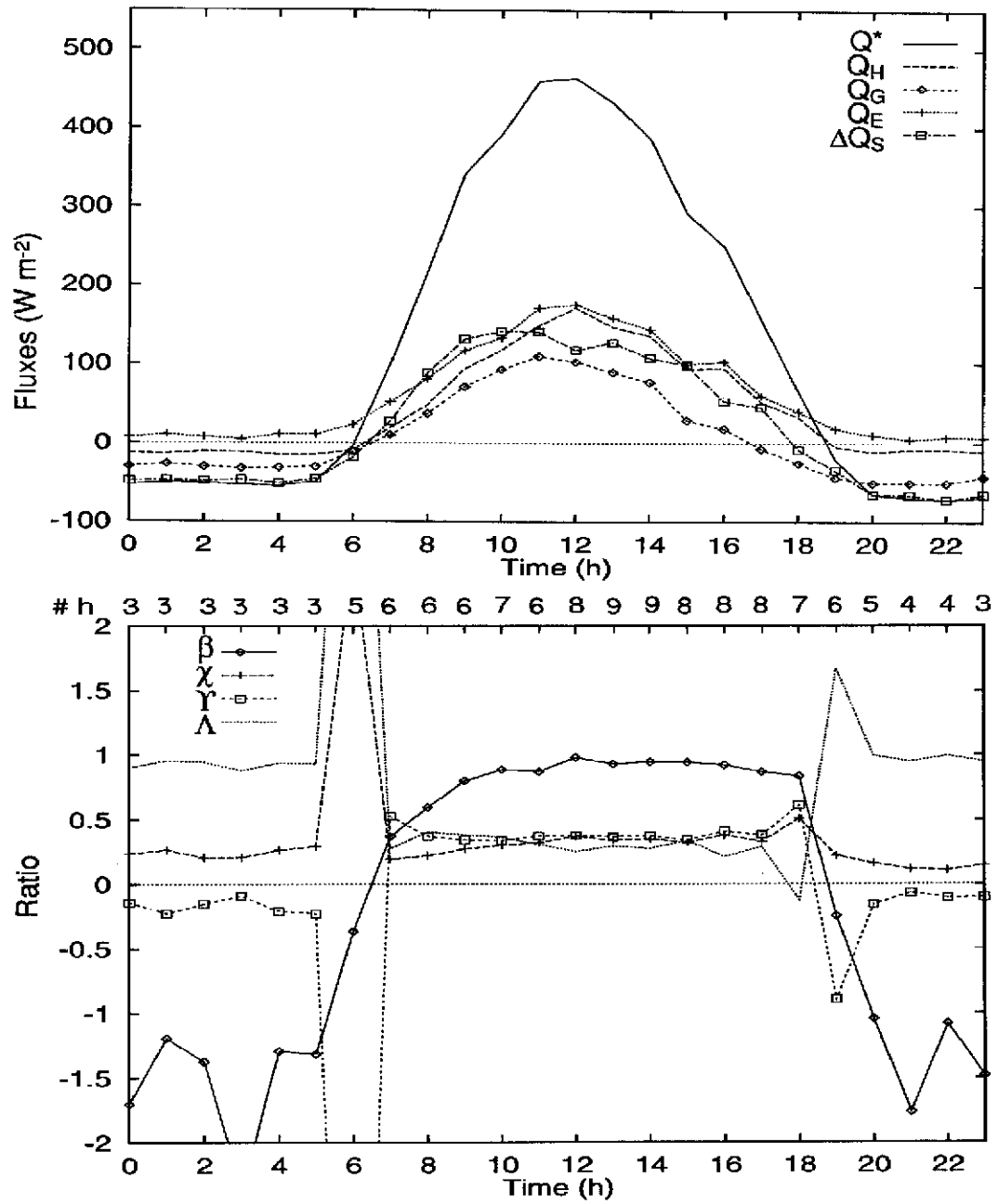
Figure 11.—Ensemble energy balance fluxes and ratios of flux partitioning for Chicago, July 1992. The numbers on the Figure #h indicate the number of hours used in analyses.

not all the results of the studies are directly comparable because of differences in instrumentation and methods between years (Table 9). As in this study, only Roth and Oke (in press) used eddy correlation techniques to measure directly both convective fluxes ($Q_E$ and $Q_H$). Roth (1991) intercompared Bowen ratios determined from a Bowen ratio system $\beta_B$ (a reversing-temperature difference system) and from eddy correlation techniques ($\beta_{EC}$). He concluded that the $\beta_{EC}$ generally were lower in the daytime than the $\beta_B$. The data from Chicago fall within the range of observations for Vancouver.

## Future Directions

An issue that needs further study is the representativeness of the observations reported here. This requires consideration of both the climatological and morphological conditions of the study period and site. There are obvious advantages to supplementing these data with further direct observations and data analysis to document the spatial and temporal variability of fluxes for this metropolitan area and to investigate further the role of advection.

Work is in progress to correlate fluxes ($Q_E$ and $Q_H$) with tree-cover density (Demanes 1994), with the intention of investigating the influence of trees on flux partitioning, for example, the ratio $\Upsilon$. The hypothesis is that greater $\Upsilon$ and smaller $\beta$ ratios are associated with more heavily treed source

areas; this would imply that energy is going into evaporation so that air below might be expected to be cooler. The GIS system will provide a basis for interpreting flux measurements in terms of the surface features influencing them and their spatial representativeness, and for objectively determining model input for surface parameters which are spatially consistent with the measured data used to evaluate numerical boundary layer models. These numerical models will be used to predict the effects of different tree-planting scenarios on local scale energy and water exchanges.

## Acknowledgments

Table 9.—Variability of ratios determined in the Sunset Neighborhood of Vancouver, British Columbia

| Reference | Period | Daytime | | | | Daily | | | | Methods | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | | $\beta$ | $\chi$ | $\Upsilon$ | $\Lambda$ | $\beta$ | $\chi$ | $\Upsilon$ | $\Lambda$ | $\Delta Q_S$[1] | Conv[2] |
| Kalanda (1979)[3] | 77/Aug 19 to Oct 3 | 1.03 | | | | | | | | A | a |
| Oke and McCaughey (1983)[4] | 80/Jul to mid Aug | 0.16 | 0.11 | 0.67 | 0.23 | 0.14 | 0.1 | 0.73 | 0.20 | A | a |
| Cleugh & Oke (1986) | 83/Jul 18 to Sep 22 | 1.28 | 0.44 | 0.34 | 0.22 | | | | | A | b |
| Cleugh (1990) | 86/Apr 5 to Oct 2 | 2.15 | 0.50 | 0.26 | 0.24 | | | | | B | c |
| Grimmond (1992)[5] | 87/Jan 21 to Feb 28 | 0.80 | 0.36 | 0.45 | 0.19 | 0.69 | 0.59 | 0.85 | -0.44 | B | c |
| | 87/ Mar 1 to 31 | 1.29 | 0.42 | 0.32 | 0.26 | 1.19 | 0.53 | 0.45 | 0.02 | B | c |
| | 87/ Apr 1 to 30 | 0.87 | 0.35 | 0.40 | 0.25 | 0.85 | 0.42 | 0.49 | 0.09 | B | c |
| | 87/ May 1 to 31 | 1.26 | 0.40 | 0.33 | 0.29 | 1.36 | 0.48 | 0.36 | 0.16 | B | c |
| | 87/ Jun 1 to 28 | 1.40 | 0.42 | 0.30 | 0.29 | 1.47 | 0.50 | 0.34 | 0.17 | B | c |
| Roth and Oke (1994)[6] | 89/July | 1.97 | | | | | | | | B | d |

[1]$\Delta Q_S$: A= Oke et al. 1981; B= Grimmond et al. 1991.

[2]Conv: Method of convective flux determination: a= Bowen ratio/energy balance—reversing temperature difference system; b= $Q_H$ SAT and $Q_E$ residual; c= Bowen ratio and SAT; d= KH20 and SAT eddy correlation systems.

[3]Mean of daytime $\beta$ values (rather than determined from the mean of the fluxes for the period); median 0.77, range of daytime values 0.3 to 2.39.

[4]Very wet spring.

[5]Ratios are over $Q^*+Q_F$ rather than $Q^*$ only.

[6]Mean of daytime hourly mean $\beta$, median 1.85, range of mean hourly values during the daytime 1.25 to 3.0. Also determined using Bowen ratio methods; $\beta$ was smaller using eddy correlation techniques.

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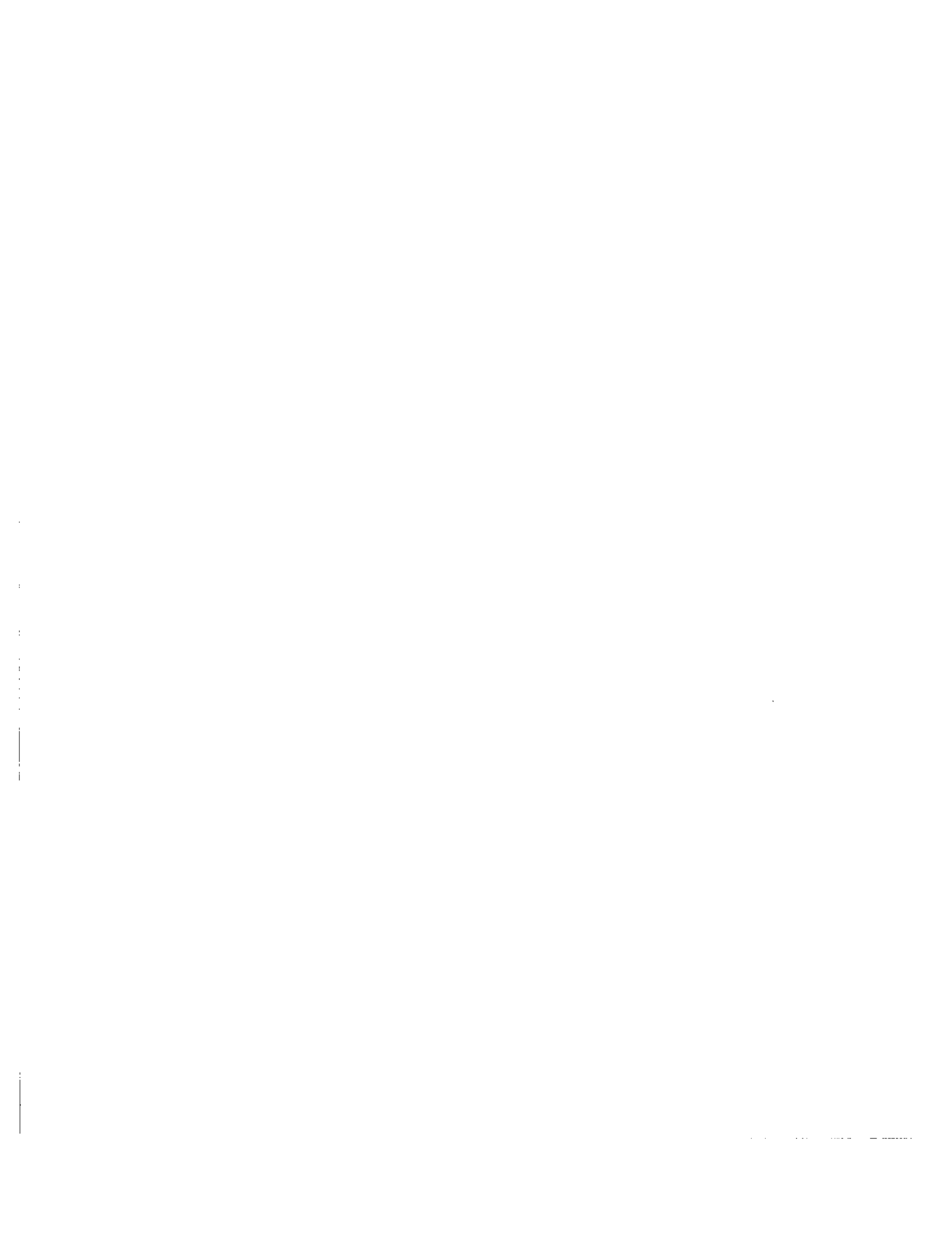
## Chapter 5

# Air Pollution Removal by Chicago's Urban Forest

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## Abstract

In 1991, trees in the City of Chicago (11 percent tree cover) removed an estimated 15 metric tons (t) (17 tons) of carbon monoxide (CO), 84 t (93 tons) of sulfur dioxide ($SO_2$), 89 t (98 tons) of nitrogen dioxide ($NO_2$), 191 t (210 tons) of ozone ($O_3$), and 212 t (234 tons) of particulate matter less than 10 microns (PM10). Across the study region of Cook and DuPage Counties, trees (in-leaf season) removed an average of 1.2 t/day (1.3 tons/day) of CO, 3.7 t/day (4.0 tons/day) of $SO_2$, 4.2 t/day (4.6 tons/day) of $NO_2$, 8.9 t/day (9.8 tons/day) of PM10 and 10.8 t/day (11.9 tons/day) of $O_3$. The value of pollution removal in 1991 was estimated at $1 million for trees in Chicago and $9.2 million for trees across the study area. Average hourly improvement (in-leaf season) in air quality due to all trees in the study area ranged from 0.002 percent for CO to 0.4 percent for PM10. Maximum hourly improvement was estimated at 1.3 percent for $SO_2$, though localized improvements in air quality can reach 5 to 10 percent or greater in areas of relatively high tree cover, particularly under stable atmospheric conditions during the daytime (in-leaf season). Large, healthy trees remove an estimated 60 to 70 times more pollution than small trees. This paper discusses the ways in which urban trees affect air quality, limitations to estimates of pollution removal by trees in the Chicago area, and management considerations for improving air quality with urban trees.

## Introduction

Air pollution is a multibillion dollar problem that affects most major U.S. cities. Air pollution is a significant human health concern as it can cause coughing, headaches, lung, throat, and eye irritation, respiratory and heart disease, and cancer. It is estimated that about 60,000 people die annually in the United States from the effects of particulate pollution (Franchine 1991). In addition, air pollution damages vegetation and various anthropogenic materials. In some of the more heavily polluted areas of the world, observed material deterioration rates are 10 to 100 times faster than those in the preindustrial age (NAPAP 1991). Air pollution also reduces visibility. In the rural mountain/desert areas of the Southwest, the standard visual range is about 130 to 190 km. In rural areas south of the Great Lakes and east of the Mississippi River, the standard visual range is about 20 to 35 km. Aerosol data indicate that this difference is due to greater sulfate concentrations in the East (and the interaction of sulfates with the higher humidity of the East) (Trijonis et al. 1990). Air pollution also contributes to acidic deposition (Smith 1990).

Major air pollutants in urban areas are carbon monoxide (CO), predominantly from automobiles in urban areas; nitrogen oxides ($NO_x$), mainly from automobiles and stationary combustion sources; ozone ($O_3$), formed through chemical reactions involving the principal precursors of $NO_x$ and volatile organic compounds; sulfur dioxide ($SO_2$), emissions mostly from stationary combustion sources and smelting of ores; and particulate matter.

Small particulate matter (PM10: particulate matter less than 10 $\mu$m) results from local soils, industrial processes, combustion products, and chemical reactions involving gaseous pollutants. Small particles can have significant health effects because particles less than 5 $\mu$m may escape the defense mechanisms of the upper respiratory tract and enter the lungs. Particles 0.5 to 5 $\mu$m may be deposited as deep as the bronchioles in the lung but usually are removed by cilia within a few hours. Particles less than 0.5 $\mu$m may reach and settle in the lung alveoli, remaining for weeks, months or years (Stoker and Seager 1976).

Air pollution is removed from the air primarily by three mechanisms: wet deposition, chemical reactions, and dry deposition. (Rasmussen et al. 1975; Fowler 1980). Wet deposition involves precipitation scavenging that includes "rainout" (transfer of pollutants to cloud droplets before they begin to fall) and "washout" (transfer of pollutants to falling rain/snowdrops) mechanisms. Gas phase reactions in the atmosphere can create aerosols that are removed by wet or dry deposition or produce oxidized products such as carbon dioxide ($CO_2$) and water vapor. Dry deposition is the mechanism by which gaseous and particulate pollutants are transported to and dry deposited on various surfaces, including trees.

### Gaseous Pollutants

Dry deposition of gases to trees occurs predominantly through the leaf stomates, though some deposition occurs on the plant surface (Fowler 1985; Murphy and Sigmon 1990; Smith 1990). During daylight hours when plant leaves are transpiring water and taking up $CO_2$, other gases including pollutants are taken up into the leaf. Once inside the leaf, these gases diffuse into intercellular spaces and can be absorbed by water films on inner-leaf surfaces. Pollutant uptake by plants is highly variable as it is regulated by numerous plant, pollutant, and environmental forces (e.g., plant water deficit, light intensity, windspeed, gas solubility in water, leaf size and geometry) (Smith 1990). Once the gas reacts with the tree and is absorbed, it is removed from the atmosphere. However, plants also emit various compounds that can contribute to air pollution. The following sections outline plant-pollutant interactions for significant gaseous air pollutants in urban areas.

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### Carbon Monoxide

Carbon monoxide is harmful principally to animals due to its affinity for hemoglobin. When CO reacts with hemoglobin it reduces the ability of blood to transport oxygen (Ziegler 1973; Stoker and Seager 1976). It has been hypothesized that CO inhibits $N_2$-fixation in plants (Ziegler 1973). Most CO absorbed by plants is reduced and incorporated into serine, which is subsequently converted to sucrose (Bidwell and Fraser 1972).

Trees emit volatile organic compounds such as isoprene and monoterpenes into the atmosphere. These compounds are natural chemicals that make up essential oils, resins, and other plant products, and may be useful in attracting pollinators or repelling predators (Kramer and Kozlowski 1979). Complete oxidation of volatile organic compounds ultimately produces $CO_2$, but CO is an intermediate compound in this process. Oxidation of volatile organic compounds is an important component of the global CO budget (Tingey et al. 1991); CO also can be released from chlorophyll degradation (Smith 1990).

### Nitrogen Dioxide

After nitrogen dioxide is absorbed through leaf stomates, it can react with water on the moist surfaces of the inner leaf to form nitrous ($HNO_2$) and nitric ($HNO_3$) acids. Pollutant interactions and altering of pH in the leaf can lead to altered plant metabolism (e.g., inhibition of $CO_2$ fixation, suppressed growth) (Ziegler 1973; Smith 1990). Visible leaf injury would be expected at concentrations around 1.6 to 2.6 ppm for 48 hours, 20 ppm for 1 hour, or a concentration of 1 ppm for as many as 100 hours (Natl. Acad. of Sci. 1977a). Concentrations that would induce foliage symptoms would be expected only in the vicinity of an excessive industrial source (Smith 1990). Trees generally are not considered as a source of atmospheric nitrogen oxides, though plants, particularly agricultural crops, are known to emit ammonia ($NH_4$). Emissions occur primarily under conditions of excess nitrogen (e.g., after fertilization) and during the reproductive growth phase (Schjoerring 1991); $NH_4$ in the atmosphere can be converted to $NO_x$.

### Ozone

Ozone has low solubility in water but readily diffuses into stomatal cavities. The reactive nature of $O_3$ causes it to react rapidly on inner-leaf surfaces (Smith 1984). Eastern deciduous species are injured by exposures to $O_3$ at 0.20 to 0.30 ppm for 2 to 4 hours (Natl. Acad. of Sci. 1977b). The threshold for visible injury of eastern white pine is approximately 0.15 ppm for 5 hours (Costonis 1976). Sorption of $O_3$ by white birch seedlings shows a linear increase up to 0.8 ppm; for red maple seedlings the increase is up to 0.5 ppm (Townsend 1974). Severe $O_3$ levels in urban areas can exceed 0.3 ppm (Off. Technol. Assess. 1989). Injury effects can include altered photosynthesis, respiration, growth, and stomatal function (Shafer and Heagle 1989; Smith 1990).

Trees can contribute to $O_3$ formation by emitting volatile organic compounds (Brasseur and Chatfield 1991). Because these emissions are temperature dependent and trees generally lower air temperatures, it is believed that increased tree cover lowers overall volatile organic emissions and $O_3$ levels in urban areas, but additional research is needed (Cardelino and Chameides 1990). Volatile organic emissions of urban trees generally are less than 10 percent of total emissions in urban areas (Nowak 1991).

### Sulfur Dioxide

Following absorption through leaf stomates, $SO_2$ is presumed to be dissolved in moisture films on inner-leaf cell walls. Eventually, sulfurous acid ($H_2SO_3$) and, following oxidation, sulfuric acid ($H_2SO_4$) are formed. Toxic effects of $SO_2$ may be due to its acidifying influence and/or the sulfite ($SO_3^{2-}$) and sulfate ($SO_4^{2-}$) ions that are toxic to a variety of biochemical processes (Smith 1990). Stomata may exhibit increases in either stomatal opening or stomatal closure when exposed to $SO_2$ (Smith 1984; Black 1985). Acute $SO_2$ injury to native vegetation does not occur below 0.70 ppm for 1 hour or 0.18 ppm for 8 hours (Linzon 1978). A concentration of 0.25 ppm for several hours may injure some species (Smith 1990).

Trees can make minor contributions to $SO_2$ concentration by emitting sulfur compounds such as hydrogen sulfide ($H_2S$) and $SO_2$ (Garsed 1985; Rennenberg 1991). $H_2S$, the predominant sulfur compound emitted, is oxidized in the atmosphere to $SO_2$. Higher rates of sulfur emissions from plants are observed in the presence of excess atmospheric or soil sulfur. However, sulfur compounds also can be emitted with a moderate sulfur supply (Rennenberg 1991).

## Particulate Pollution

Particles can be dry deposited on plant surfaces through sedimentation under the influence of gravity or through impaction under the influence of wind. Particles hitting the tree may be retained on the surface, rebound off it, or be retained temporarily and subsequently removed (resuspended into air or transported to soil or other surface) (Smith 1990). The interception and retention of particles by plants is highly variable —smaller leaves and/or leaves with a rough surface are more efficient in collecting particles than larger and/or smoother leaves. Also, larger particles are deposited on leaves more rapidly than smaller particles (Smith 1984; Davidson and Wu 1990). Particle resuspension after 1 hour of initial retention varies from 91 percent for oak leaves to 10 percent for pines (Witherspoon and Taylor 1969).

Thus, vegetation generally is only a temporary retention site for atmospheric particles as particles can be resuspended to the atmosphere, be washed off by rain, or drop to the ground through leaf and twig fall. Trees can store various trace metals in their tissue, but the mechanisms and pathways of incorporation into trees needs to be clarified (Rolfe 1974; Baes and Ragsdale 1981; Baes and McLaughlin 1984). However, it is known that heavy metals can be absorbed directly through the cuticle (Ziegler 1973).

Trace metals can be toxic to plant leaves (Darley 1971; Smith 1990). The accumulation of particles on leaves also can reduce photosynthesis by reducing the amount of light reaching the leaf (Darley 1971; Ziegler 1973). Damage to plant leaves can occur from the deposition of acidic droplets (pH < 3.0) (Smith 1990). Acidic rain can be a source of the essential plant nutrients of sulfur and nitrogen, but also can

reduce soil nutrient availability through leaching or toxic soil reactions (Shriner et al. 1990). Particles can also affect tree pest/disease populations (Darley 1971; Smith 1990). Trees can contribute to particle concentrations in urban areas by releasing pollen and emitting volatile organic and sulfur compounds that serve as precursors to particle formation (Smith 1990; Sharkey et al. 1991).

## Effect of Urban Trees on Air Quality

Urban trees influence local air quality in various ways. First, trees can reduce or increase building energy use by shading buildings, altering air flows and lowering air temperatures through transpiration (e.g., Heisler 1986). In turn, this change in building energy use affects pollution emissions from power plants. By lowering air temperatures, trees also can affect $O_3$ photochemistry and $O_3$ precursor emission rates, thus influencing $O_3$ formation (Cardelino and Chameides 1990). Various tree configurations can alter wind profiles or create local inversions to trap pollutants such that the removal of local pollutants is enhanced (McCurdy 1978). As mentioned previously, trees emit volatile organic and other compounds that can contribute to pollution formation (Sharkey et al. 1991). Finally, trees can intercept atmospheric particles and absorb various gaseous pollutants.

There has been little research on the removal of atmospheric pollution by urban trees. Street trees in the St. Louis area have been estimated to remove approximately 3.1 kg/day (2.75 lb/acre/day) of particles for each hectare of land covered by street trees (DeSanto et al. 1976b). Other particle-removal estimates for individual trees are 1.5 to 4.4 kg/day for each hectare of land covered by trees (1.3 to 3.9 lb/acre/day); 1.5 to 4.7 kg/ha/day (1.3 to 4.2 lb/acre/day) for CO; 1.3 to 4.1 kg/ha/day (1.2 to 3.6 lb/acre/day) for nitrogen oxides; 22.7 to 74.4 kg/ha/day (20.2 to 66.3 lb/acre/day) for $SO_2$; and 34.7

to 111.5 kg/ha/day (30.9 to 99.5 lb/acre/day) for $O_3$ (DeSanto et al. 1976a).

Some of these estimates are higher than expected under typical urban conditions because average removal rates in $\mu g/m^2$ of leaf area/hr for vegetation were used. These rates are dependent on the pollutant concentrations used in the studies from which the average removal rate was derived. Often such concentrations in the literature are high so that plant responses to a pollutant can be studied under laboratory conditions. Thus, the removal rates are higher than would be expected under typical urban conditions. Other removal rates for $SO_2$ and $NO_2$ are given in Table 1.

The objective of this study was to estimate air pollution removal (dry deposition) of CO, $NO_2$, $O_3$, $SO_2$, and $PM10$ by trees in the Chicago region during 1991. The computations used to estimate pollution removal by urban trees should be considered a first-order approximation of a highly complex deposition system. Many factors influence dry-deposition removal rates, including aerodynamic roughness, atmospheric stability, pollutant concentration, solar radiation, temperature, turbulence, wind velocity, particle size, gaseous chemical activity and solubility, and vegetative surface characteristics (e.g., stomatal activity and resistances, leaf surface area) (Sehmel 1980).

# Methods

## Study Area

The study area (Figure 1 in Chapter 2) was fragmented into 117 community areas for detailed analyses of tree canopy cover (McPherson et al. 1993), pollution concentrations and total pollutant flux (Figure 1). Tree cover averages 11 percent in Chicago, 23 percent in suburban Cook County (i.e.,

Table 1. —Pollution-removal values (kg/ha/day) from the literature (divide removal rate by 1.12 to calculate lb/acre/day)

| Pollutant | Removal rate | Site | Pollutant concentration (ppm) | Reference |
|---|---|---|---|---|
| $SO_2$ | 0.59 | 1,723 km² forest dominated area on Long Island, NY | 0.015 | Murphy et al. 1977 |
| $SO_2$ | 0.20 | Argonne National Laboratory, IL[a] | * | Wesely and Lesht 1988 |
| $SO_2$ | 0.15 | 778 km² forest dominated area at Savannah River Plant, SC | 0.008 | Murphy et al. 1977 |
| $SO_2$ | 0.04 | Loblolly pine plantation at Savannah River Plant, SC | 0.003 | Lorenz and Murphy 1985 |
| $SO_2$ | 0.03 | Loblolly pine plantation in Alamance County, NC | ** | Hicks et al. 1982 |
| $SO_2$ | 0.03 | Argonne National Laboratory, IL[a] | *** | Wesely and Lesht 1988 |
| $NO_2$ | 0.18 | Salt Lake Valley, UT estimate[b] | 0.02 | Heggestad 1972 |
| $NO_2$ | 0.04 | Salt Lake Valley, UT estimate[b] | 0.005 | Heggestad 1972 |

[a]50 percent white oak, 50 percent grass.
[b]85 percent covered by vegetation.

* Peak modeled deposition in 1986 in-leaf season;
** Daytime peak removal extrapolated to entire day, therefore removal rate listed is an overestimate of the actual daily removal rate;
***Minimum modeled deposition in 1986 in-leaf season.

Cook County exclusive of Chicago), 19 percent in DuPage County, and 19 percent for the entire study area (McPherson et al. 1993).

Pollutant concentrations in Illinois in 1991 were typical of concentrations found in the mid-1980s through 1990; the exceptions were PM10 and nitrogen oxides, which were slightly below average (IEPA 1992). The average concentration of CO in the study area was 0.88 ppm. Peak hourly averages occurred in May (1.03 ppm) and minimum hourly concentrations occurred in June (0.65 ppm). The National Ambient Air Quality Standard (NAAQS) of 9 ppm (8-hr average) was not exceeded in the study area in 1991. Concentration levels cycled throughout the day (Figure 2).

Average hourly levels of $NO_2$ were highest in August (0.025 ppm) and lowest in November (0.019 ppm); the annual average in the study area was 0.021 ppm. Average levels of $NO_2$ varied through the day (Figure 3). During the in-leaf season, $O_3$ levels averaged 0.027 ppm; levels were highest in June (0.038 ppm) and lowest in October (0.013 ppm). Average hourly $O_3$ levels peaked at 2 p.m. (Figure 4). Levels of $O_3$ exceeded the NAAQS level of 0.12 ppm (1-hr average) on June 1, 18, 20, and 21 at four stations in Chicago and suburban Cook County (IEPA 1992).

The average concentration of $SO_2$ in the study area was 0.0084 ppm. Hourly averages were highest in January (0.011 ppm) and lowest in December (0.0062 ppm). Average hourly concentration peaked at 9 a.m. and 10 a.m. (Figure 5). The

24-hr average NAAQS level of 0.14 ppm was exceeded in the study area on October 16-17, November 14-15, and November 17-19 at one monitoring station in suburban Cook County (IEPA 1992).

The average level of PM10 in the study area was 34 $\mu g/m^3$. Levels were highest in July (45 $\mu g/m^3$) and lowest in December (27 $\mu g/m^3$). The 24-hr average NAAQS level of 150 $\mu g/m^3$ was exceeded on August 2 for one monitoring station in suburban Cook County (IEPA 1992). Regional air quality concentrations in 1991 probably were not high enough to induce visible damage to vegetation in the Chicago area.

### Algorithms for Estimating Pollution Removal

To estimate pollutant flux to trees it is necessary to know the deposition velocity of each pollutant to trees and the local pollutant concentration (e.g., Hicks et al. 1987; Baldocchi 1988; Smith 1990). The deposition velocity may be thought of as the rate at which the surface "cleans" a pollutant from the air. If the deposition velocity of a pollutant is 1.0 cm/sec, then the surface is completely removing the pollutant from a layer of air 1.0 cm thick each second (Smith 1990). The pollutant flux (F) is calculated as the product of the deposition velocity ($V_d$) and the pollutant concentration (C) :

$$F \text{ (g/cm}^2\text{/sec)} = V_d \text{ (cm/sec)} \times C \text{ (g/cm}^3\text{)} \qquad (1)$$

The pollutant flux is multiplied by the area of the surface ($cm^2$) over time periods for which the pollutant concentration is known around that surface (e.g., 1 hour: 3600 sec) to
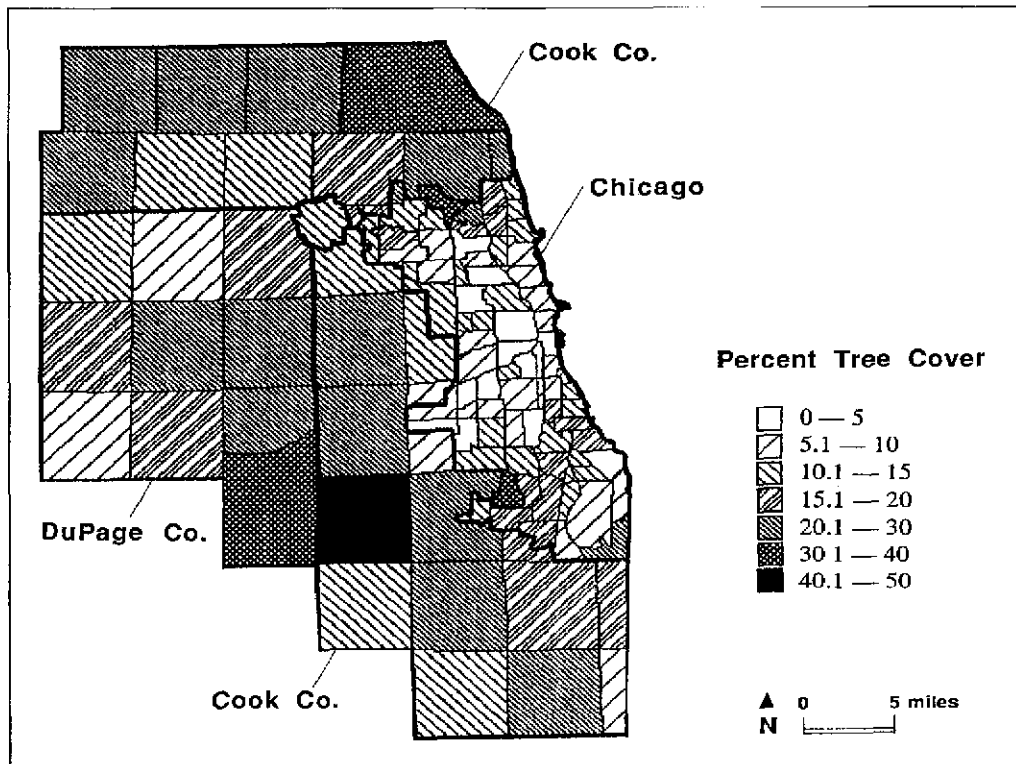


Figure 1. —Percent tree cover by community area.
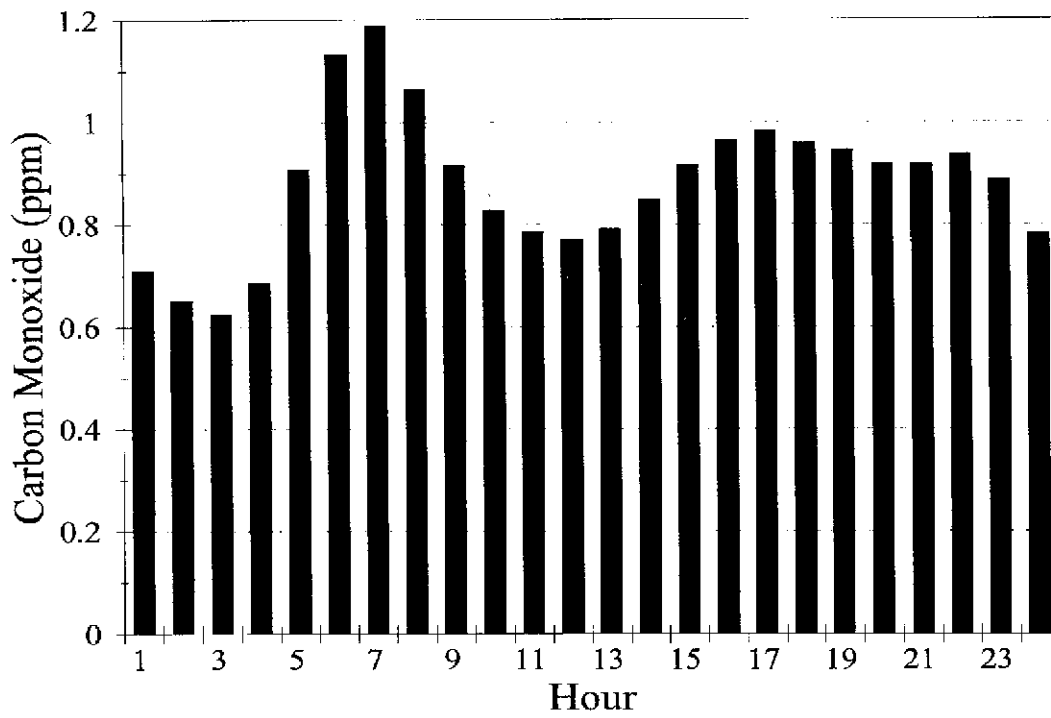
Figure 2. —Average hourly concentrations of CO calculated from seven IEPA monitoring sites in study area in 1991.
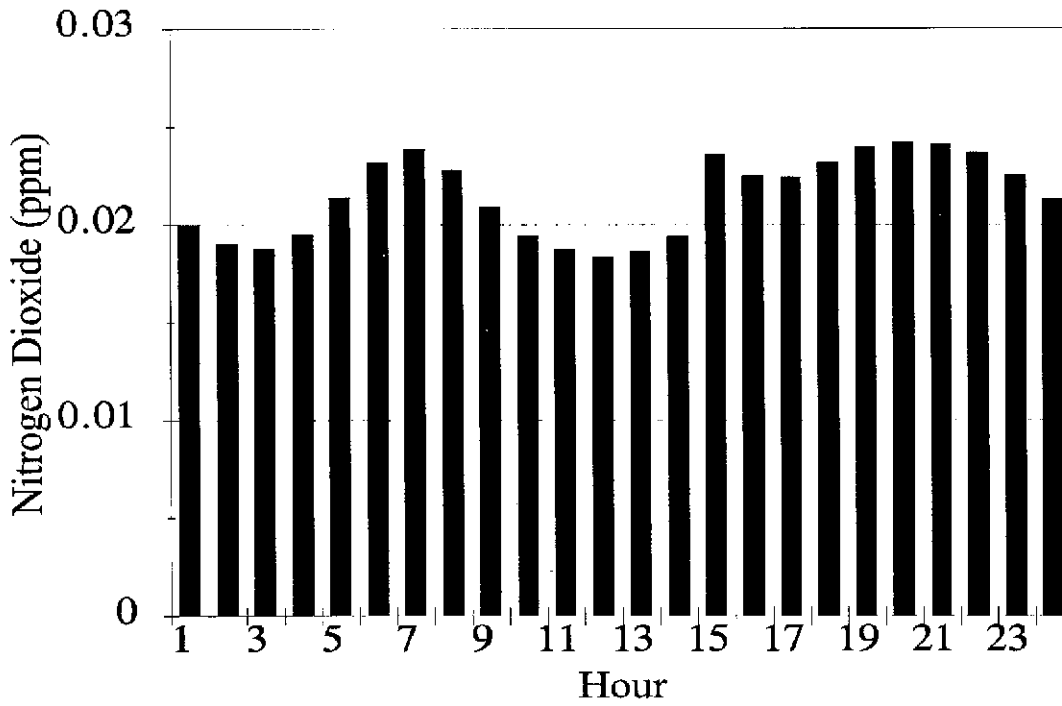


Figure 3. —Average hourly concentrations of NO₂ calculated from eight IEPA monitoring sites in study area in 1991.
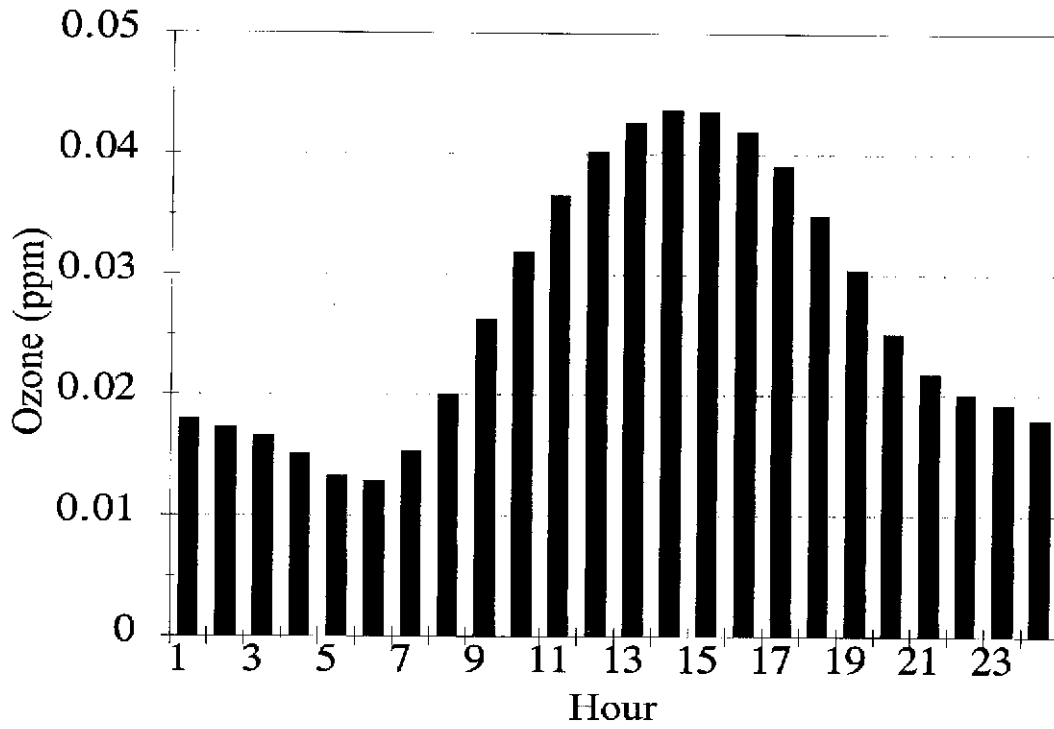
Figure 4. —Average hourly concentrations of $O_3$ calculated from 13 IEPA monitoring sites in study area during in-leaf season (May-October) of 1991.
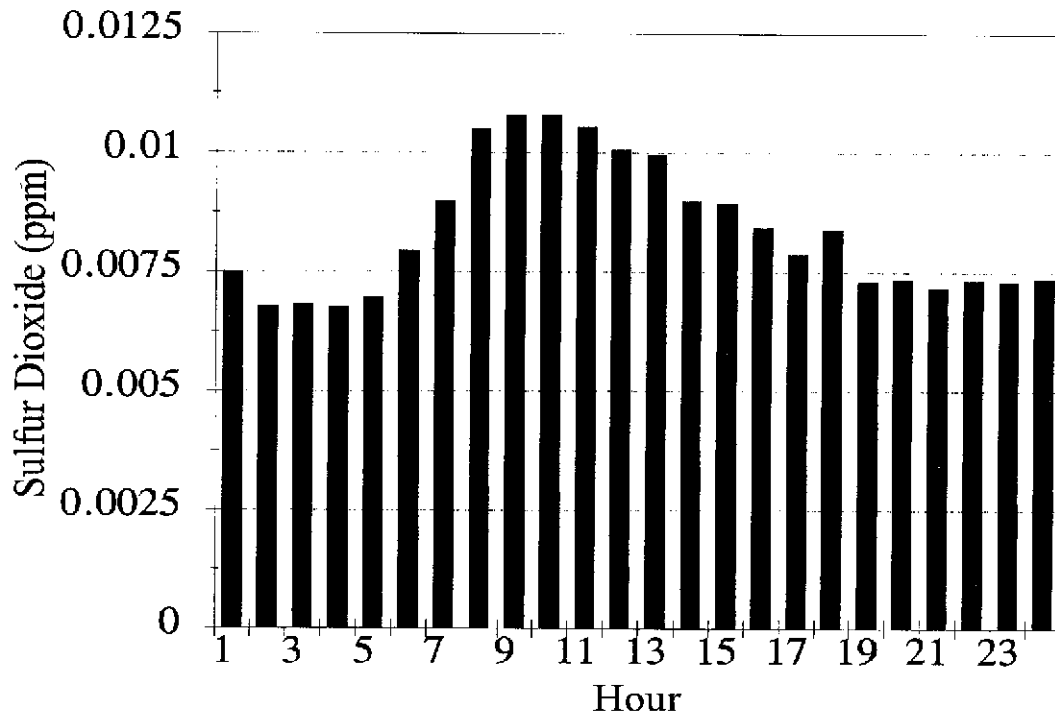


Figure 5. —Average hourly concentrations of $SO_2$ calculated from 10 IEPA monitoring sites in study area in 1991.

estimate total pollutant flux to the surface (e.g., g/hr). These hourly fluxes can be summed to estimate total daily, monthly, or yearly fluxes.

## Deposition Velocities

The rate at which pollutants are transferred onto or into various surfaces is influenced by a series of resistances to pollutant transfer. Deposition velocity is calculated as the inverse of the sum of the aerodynamic ($R_a$), quasi-laminar boundary layer ($R_b$) and canopy ($R_c$) resistances ($V_d = 1/(R_a + R_b + R_c)$). The aerodynamic resistance is associated with atmospheric turbulence, the quasi-laminar boundary-layer resistance is influenced by the diffusivity of the material being transferred, and the net canopy resistance is dominated by surface factors (Baldocchi et al. 1987). As the rate of turbulent mixing becomes high, pollutant transport to the surface is rapid as the resistance to transport through the boundary layer approaches zero and the resistance to deposition is limited by the surface resistance (Killus et al. 1984).

### Aerodynamic and Quasi-laminar Boundary-Layer Resistances

Meteorological data from Chicago's O'Hare airport (3-hr averages) were used in estimating $R_a$ and $R_b$. The aerodynamic and quasi-laminar boundary-layer resistances were estimated for the Chicago area with a method similar to that used in the Urban Airshed Model (Killus et al. 1984).

$$R_a = u(z)/u_*^2$$

where $u(z)$ is the wind speed at height $z$ (m/sec) and $u_*$ is the frictional velocity (m/sec).

$$u_* = (k \, u(z-d))/[\ln((z-d)/z_0) - \psi_m((z-d)/L) + \psi_m(z_0/L)]$$

where $k$ = von Karman's constant (0.40), $d$ = displacement length (m), $z_0$ = roughness length (m), $\psi_m$ = stability function for momentum, and $L$ = Monin-Obuhkov stability length (van Ulden and Holtslag 1985). $L$ was estimated by classifying hourly local meteorological data into stability classes using Pasquill's (1961) stability classification scheme and then estimating $1/L$ as a function of Pasquill classes and $z_0$ (Golder 1970). When $L<0$ (unstable):

$$\psi_m = 2 \ln [(1+ X)/2] + \ln [(1+ X^2)/2] - 2 \tan^{-1}(X) + \pi/2$$
(van Ulden and Holtslag 1985)

where $X = (1 - 28 \, z/L)^{0.25}$ (Dyer and Bradley 1982). When $L>0$ (stable conditions):

$$\psi_m = -17 \, (1 - \exp(-0.29(z-d)/L)$$
(van Ulden and Holtslag 1985).

The quasi-laminar boundary-layer resistance was estimated as:

$$R_b = B^{-1} u_*^{-1}$$

where $B^{-1} = 2.2 u_*^{-1/3}$ (Killus et al. 1984).

$R_a$ and $R_b$ were calculated for every three hours throughout 1991 based on Chicago meteorological data. Each estimate of $R_a$ and $R_b$ was used to represent the corresponding 3-hr period of the day. These hourly values were combined to yield the average daily conditions for each month in 1991.

### Canopy Resistance

The tree canopy resistances for each of the pollutants was estimated by averaging the $R_c$ values derived from literature on individual trees and forests. $R_c$ estimates were categorized by in-leaf season daytime, in-leaf season nighttime, and out-of-leaf season using a distribution of 90 percent deciduous and 10 percent coniferous leaf surface area (Nowak 1994: Chapter 2, this report) (Table 2). $R_c$ estimates for particles and CO could not be found in the literature, so average deposition velocity minus average $R_a$ and $R_b$ for Chicago was substituted as the $R_c$ for these pollutants. Fifty percent of the particles being deposited to trees were assumed to be resuspended from the trees to the atmosphere. Particle collection by deciduous trees in winter assumed a surface-area index for bark of 1.7 (m² of bark/m² of ground surface covered by tree crown) (Whittaker and Woodwell 1967). In-leaf daylight ranged from 11 hr/day in October to 15 hr/day in June. The in-leaf season for deciduous trees in the Chicago area was modeled as May 1 to October 31 based on local observation of foliation periods.

Hourly canopy resistances of trees were calculated for each hour in 1991 based on in-leaf vs. out-of-leaf season and day

Table 2.—Average canopy-resistance values (sec/cm) for trees in the Chicago area (90 percent deciduous; 10 percent coniferous leaf-surface area); values are estimates derived from the literature

| Pollutant | In-leaf daytime | In-leaf nighttime | Out-of-leaf season |
|-----------|-----------------|-------------------|--------------------|
| Carbon monoxide | 500 | 500 | 10,000 |
| Nitrogen dioxide | 3.01 | 7.54 | 88.3 |
| Ozone | 1.74 | 17.2 | ---a |
| Particulate matter | 0.78 | 0.78 | 2.39 |
| Sulfur dioxide | 1.87 | 9.54 | 58.2 |

a no pollutant concentrations collected during out-of-leaf season (November-April).

Sources: Bidwell and Fraser 1972; Roberts 1974; Fritschen and Edmonds 1976; Garland 1977; Garland and Branson 1977; Little 1977; McMahon and Denison 1979; Rogers et al. 1979; Sheih et al. 1979; Wesely and Hicks 1979; Galbally and Roy 1980; Sehmel 1980; Lindberg and Harriss 1981; Hicks et al. 1982; Hofken and Gravenhorst 1982; Granat and Johansson 1983; Gravenhorst et al. 1983; Greenhut 1983; Hofken et al. 1983; Lindberg and Lovett 1983; Wesely 1983; Wesely et al. 1983; Lindberg et al. 1984; Lovett and Lindberg 1984; Fowler 1985; Lorenz and Murphy 1985; Wesely et al. 1985; Voldner et al. 1986; Walcek et al. 1986; Dasch 1987; Dasch 1989; Shanley 1989; Wesely 1989; Davidson and Wu 1990; Murphy and Sigmon 1990.

vs. night. Tree-canopy resistance was combined with $R_a$ and $R_b$ to produce hourly estimates of deposition velocities to trees in the Chicago area. To limit deposition estimates to periods predominated by dry deposition, deposition velocities were set to zero during and immediately following periods of precipitation (1 hr).

*Pollution Concentration*

Hourly pollution concentrations (ppm) were obtained from the Illinois Environmental Protection Agency (IEPA) for CO (7 monitoring sites in study area), $NO_2$ (8 sites), $O_3$ (13 sites) and $SO_2$ (10 sites). Average daily concentrations of PM10 ($\mu g/m^3$) also were obtained from the IEPA (14 sites). No concentration data for $O_3$ were obtained for the out-of-leaf season (November-April).

Each of the 117 community areas were assigned the average hourly concentrations for each month from the closest monitoring station for each pollutant. The average hourly pollutant flux for each month of 1991 was calculated for each pollutant in each community area using equation (1). Hourly pollutant flux ($g/m^2$ of tree canopy coverage) for each community area was multiplied by the amount of tree canopy cover ($m^2$) in the community area to estimate total pollutant flux per hour for the average day in each month. These values were combined to yield estimates of daily, monthly, and yearly pollution flux to trees (for each pollutant) for Chicago, suburban Cook County, DuPage County, and the entire study area.[1]

Total pollutant flux also was calculated for the individual days that had the highest hourly reading of the year: CO (August 2), $NO_2$ (June 21), $O_3$ (June 18-21), $SO_2$ (October 16-17) and PM10 (July 17). Because of a lack of variance information on some of the averages used in the calculations, no error bounds could be computed for the removal estimates.

## Boundary-Layer Height

The boundary layer is the atmospheric layer characterized by well-developed mixing (turbulence). The height of the boundary layer is not constant over time. By day, thermal mixing enables the boundary-layer height to extend to about 1 to 2 km. At night, mixing tends to be suppressed and the boundary-layer height can shrink to less than 100 m (Oke 1987). The height of the boundary layer is important because the deeper the boundary layer, the less the relative effect of trees on reducing overall concentrations of air pollutants given a well-mixed boundary layer.

To approximate boundary-layer heights in the study area, average mixing heights from the closest station to the study

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[1]
$$F = \sum_{p=1}^{5} \sum_{m=1}^{12} \sum_{h=1}^{24} \sum_{ca=1}^{117} ((1/R_a+R_b+R_c) \times C)$$

where F = total annual pollution removal for five pollutants; p = pollutant species; m = month; h = hour; ca = community area (i.e., specific tree-cover data); $R_a$ and $R_b$ = aerodynamic and quasi-laminar boundary-layer resistances, respectively (calculated from local meteorological data for 3-hr periods); $R_c$ = canopy resistance (varies by day, night, precipitation, and season); and C = average hourly pollutant concentration for each month (PM10 concentrations based on daily average).

area (Peoria, IL) were used. Readings of average daily morning and afternoon mixing heights were extrapolated throughout the day to estimate the diurnal cycle of the boundary-layer height for each month (e.g., Holzworth 1972). The mixing heights used ranged from a low of 300 m in early morning (6 a.m.) to a high of 1,600 m for midafternoon (4 p.m.) in June. Average hourly mixing heights for each month were used in conjunction with data on pollution concentrations for each community area to calculate the amount of pollution within the mixing layer. This extrapolation from ground-layer concentration to total pollution within the boundary layer assumes a well-mixed boundary layer. The amount of pollution in the air was contrasted with the amount of pollution removed by trees to calculate the relative effect of trees in reducing local pollution concentrations:

$$E = R / R+A$$

where E = relative reduction effect (%); R = amount removed by trees (kg); A = amount of pollution in the atmosphere (kg).

## Effect of Individual Trees

The ability of individual trees to remove pollutants was estimated for each diameter class using the formula:

$$I_x = R_t \times (LA_x/LA_t) / N_x$$

where $I_x$ = pollution removal by individual trees in diameter class $x$ (kg/tree); $R_t$ = total pollution removed for all diameter classes (kg); $LA_x$ = total leaf area in diameter class $x$ ($m^2$); $LA_t$ = total leaf area of all diameter classes ($m^2$); and $N_x$ = number of trees in diameter class $x$. This formula yields an estimate of pollution removal by individual trees based on leaf-surface area (the major surface for pollutant removal) and a distribution of approximately 90 percent deciduous and 10 percent coniferous leaf-surface area (Nowak 1994: Chapter 2, this report).

## Estimated Monetary Value of Pollution Removal

To estimate the monetary value of pollution removal by trees, current costs for emission control were used. The cost (dollars/metric ton) of preventing the emission of a similar amount of pollutant using these control strategies was multiplied by the metric tons of pollutant removed by trees to yield an indication of the pollution removal value of trees.[2] Dollar values (1990) per metric ton of pollutant removed were \$540/t (\$490/ton) for $O_3$, \$1,014/t (\$920/ton) for CO, \$1,441/t (\$1,307/ton) for PM10, \$1,801/t (\$1,634/ton) for $SO_2$ and \$4,863/t (\$4,412/ton) for $NO_2$ (California Energy Commission 1992).

## Potential Future Effects of Tree Planting

To analyze the potential effects of future tree planting, available growing space (i.e., grass and soil area) was analyzed by land-use type throughout the study area. The future scenario assumed that none of the available space in agricultural or transportation (predominantly airport) would be planted with trees due to land-use limitations. Five percent of available

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[2] The estimation of value is approximate as emission control strategies prevent the emission of pollution while trees remove pollution that already is in the atmosphere.

space was assumed to be planted and covered with trees on large commercial-industrial areas and institutional land dominated by vegetation (e.g., parks, forest preserves, cemeteries, golf courses). Ten percent of available space was assumed to be planted and covered with trees on institutional lands dominated by building (e.g., schools); 15 percent in residential areas, 20 percent in landscaped commercial complexes, and 25 percent on vacant lands and freeways.

Removal of pollutants by the additional trees was calculated based on average removal per acre of existing tree cover times the number of new acres of tree cover that result from the new plantings. This removal was subtracted from the amount of pollution in the atmosphere to calculate a new atmospheric concentration. Because the atmospheric concentration would be lower due to the additional trees, overall uptake per acre of trees also drops due to the lower concentrations. The new pollutant flux for all trees (original plus new trees) with a lower pollutant concentration was contrasted with the original flux rate to calculate the effect of the new tree plantings.

# Results

In 1991, total estimated pollutant removal by trees in the study area was 5,575 t (6,145 tons) with PM10 and $O_3$ removed the most by trees (Table 3). Monthly removal rates varied, peaking in May for CO (41 t, 45 tons), in June for $O_3$ (498 t, 549 tons), in July for PM10 (348 t, 383 tons) and in August for $NO_2$ (152 t, 168 tons) and $SO_2$ (132 t, 145 tons). Minimum removal in the study area occurred in March for PM10 (30 t, 33 tons), in April for CO (1.6 t, 1.8 tons), in October for $O_3$ (117 t, 129 tons) (in-leaf season data only), in November for $NO_2$ (4.9 t, 5.4 tons) and in December for $SO_2$ (4.0 t, 4.4 tons) (Figure 6, Table 4). Monthly patterns of removal were similar in Chicago, suburban Cook, and DuPage Counties (Figures 7-9, Table 4).

Removal occurred mostly during the in-leaf season with daily in-leaf removal rates ranging from 1,155 kg/day (2,545 lb/day) for CO to 10,819 kg/day (23,850 lb/day) for $O_3$ (Table 5). Total removal per hectare of tree cover ranged from 3.4 kg/yr (3.1 lb/acre/yr) for CO to 30.7 kg/yr (27.4 lb/acre/yr) for $O_3$ (Table 5). Total removal per hectare of trees was 85.7 kg/yr (76.5 lb/acre/yr) for all five pollutants.

Maximum daily effects of pollution removal by trees in the study area was approximately 1.4 t (1.5 tons; 0.02 kg/ha of tree cover/day) for CO; 4.9 t (5.4 tons; 0.08 kg/ha of trees/day) for $NO_2$; 10.7 t (11.8 tons; 0.16 kg/ha of trees/day) for $SO_2$; 21.6 t (23.8 tons; 0.33 kg/ha of trees/day) for PM10; and 24.4 t (26.9 tons; 0.38 kg/ha of trees/day) for $O_3$. Peak-day effects (based on the day with highest hourly concentration) were lower than average-day effects for CO and $NO_2$ due to relatively low concentrations during nonpeak hours. Peak daily effects for these pollutants were based on peak average-day effects for a month (CO: September; $NO_2$: August).

The maximum hourly reduction in pollutant concentrations due to trees across the study area ranged from 0.007 percent for CO to 1.3 percent for $SO_2$ (Table 6). Average hourly reduction in concentrations during the in-leaf season ranged from 0.002 percent for CO to 0.4 percent for PM10. In large areas of 100-percent tree cover, reductions in concentrations due to trees likely reached 7 percent for sulfur dioxide (Table 6).

Under typical in-leaf daytime conditions in 1991, a hectare of urban tree cover would be expected to remove 0.0008 kg/hr (0.0007 lb/acre/hr) of CO, 0.0041 kg/hr (0.0037 lb/acre/hr) of $SO_2$, 0.0045 kg/hr (0.004 lb/acre/hr) of $NO_2$, 0.0056 kg/hr (0.005 lb/acre/hr) of PM10, and 0.0123 kg/hr (0.011 lb/acre/hr) of $O_3$. For concentrations at the NAAQS level, a hectare of tree cover would be expected to remove 0.007 kg/hr (0.006 lb/acre/hr) of CO (at 8-hr NAAQS); 0.067 kg/hr (0.06 lb/acre/hr) of $SO_2$ (at 24-hr NAAQS); 0.012 kg/hr (0.01 lb/acre/hr) of $NO_2$ (at annual NAAQS); 0.031 kg/hr (0.028 lb/acre/hr) of PM10 (at 24-hr NAAQS); and 0.046 kg/hr (0.041 lb/acre/hr) of $O_3$ (at 1-hr NAAQS). These removal rates should be considered high and of relatively short term.

Large individual trees have the greatest estimated pollution removal due to their relatively large leaf surface area. Trees larger than 76 cm (30 inches) in diameter at breast height (d.b.h. at 1.37 m or 4.5 ft) removed an estimated 1.4 kg (3.1 lb) of pollution in 1991; trees less than 8 cm (3 inches) in d.b.h. removed approximately 0.02 kg (0.05 lb) (Table 7).

The monetary value of pollution removal in 1991 was approximately $1 million in Chicago ($151/ha of tree cover/yr; $61/acre of tree cover/yr); $5.8 million in suburban Cook County ($137/ha of trees/yr; $55/acre of trees/yr); $2.4 mil-

Table 3.—Total pollutant removal (t/yr) and removal per hectare of land (kg/ha/yr) in Chicago, suburban Cook County, DuPage County, and study area (multiply t by 1.102 to convert to tons; divide kg/ha by 1.12 to convert to lb/acre)

| Pollutant | Chicago Total | Chicago per ha | Cook County Total | Cook County per ha | DuPage County Total | DuPage County per ha | Study area Total | Study area per ha |
|---|---|---|---|---|---|---|---|---|
| CO | 15 | 0.3 | 147 | 0.8 | 61 | 0.7 | 223 | 0.7 |
| $SO_2$ | 84 | 1.4 | 520 | 2.8 | 102 | 1.2 | 706 | 2.1 |
| $NO_2$ | 89 | 1.5 | 470 | 2.5 | 248 | 2.9 | 806 | 2.4 |
| PM10 | 212 | 3.5 | 1,179 | 6.3 | 449 | 5.2 | 1,840 | 5.5 |
| $O_3$ | 191 | 3.1 | 1,328 | 7.1 | 481 | 5.6 | 2,000 | 6.0 |
| Total | 591 | 9.7 | 3,644 | 19.4 | 1,340 | 15.5 | 5,575 | 16.7 |
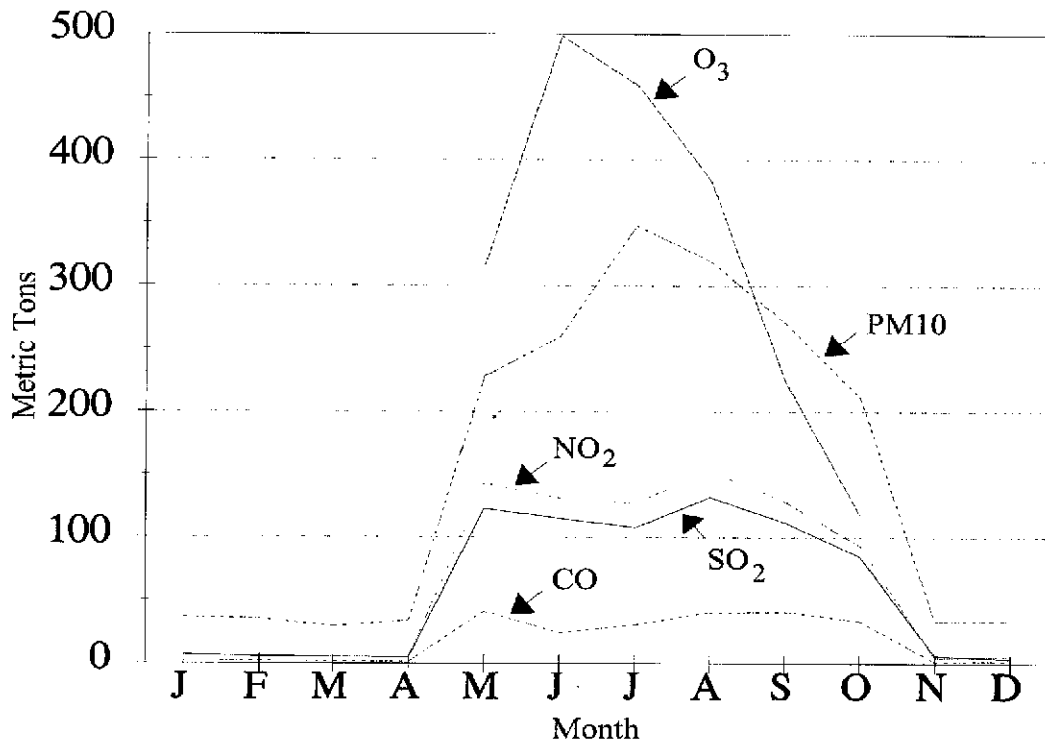
Figure 6. —Monthly estimates of pollution removal by trees in study area in 1991. Ozone removal estimates are for May-October only. Particulate removal assumes 50 percent resuspension back to the atmosphere.
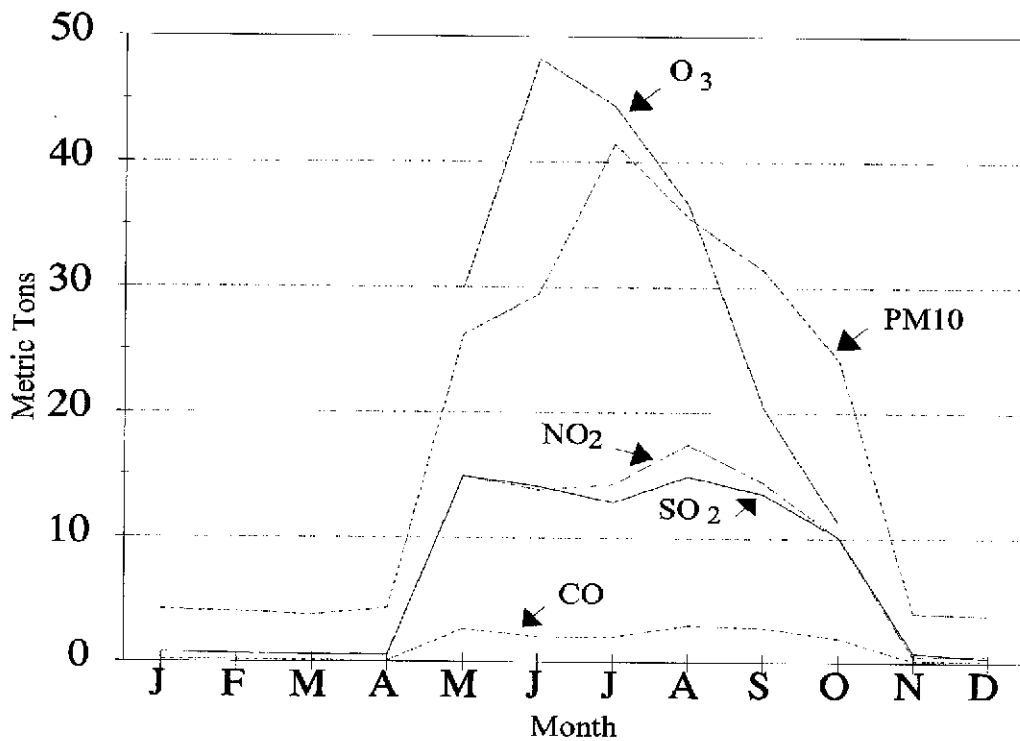


Figure 7. —Monthly estimates of pollution removal by trees in Chicago in 1991. Ozone removal estimates are for May-October only. Particulate removal assumes 50 percent resuspension back to the atmosphere.
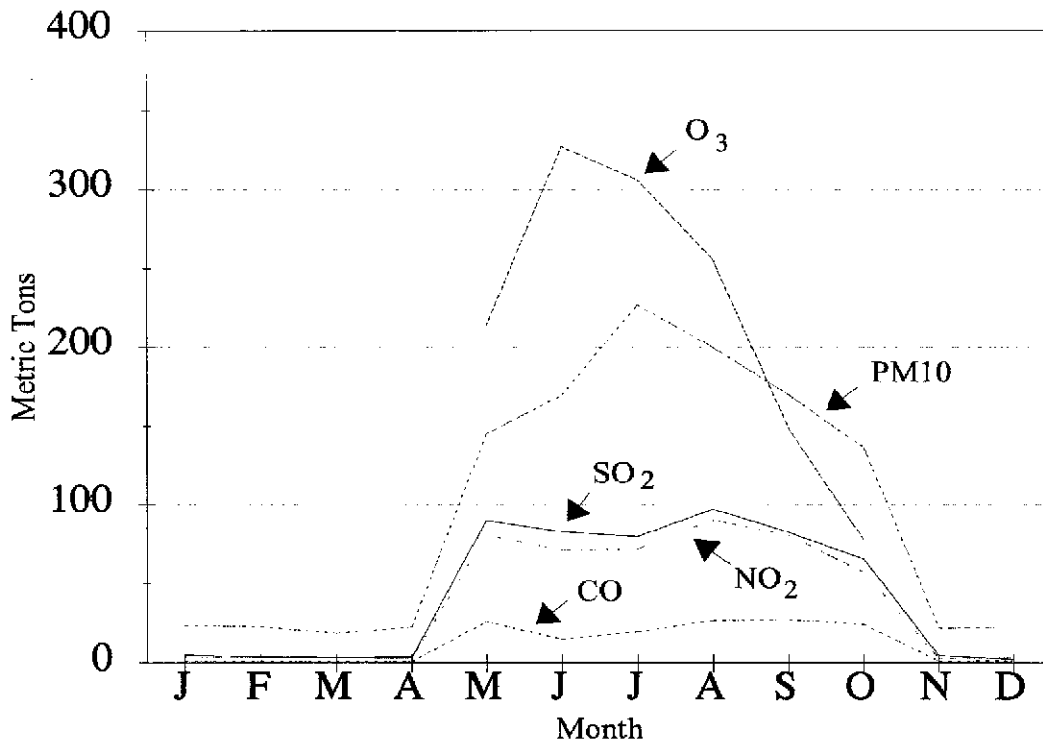
Figure 8. —Monthly estimates of pollution removal by trees in suburban Cook County in 1991. Ozone removal estimates are for May-October only. Particulate removal assumes 50 percent resuspension back to the atmosphere.
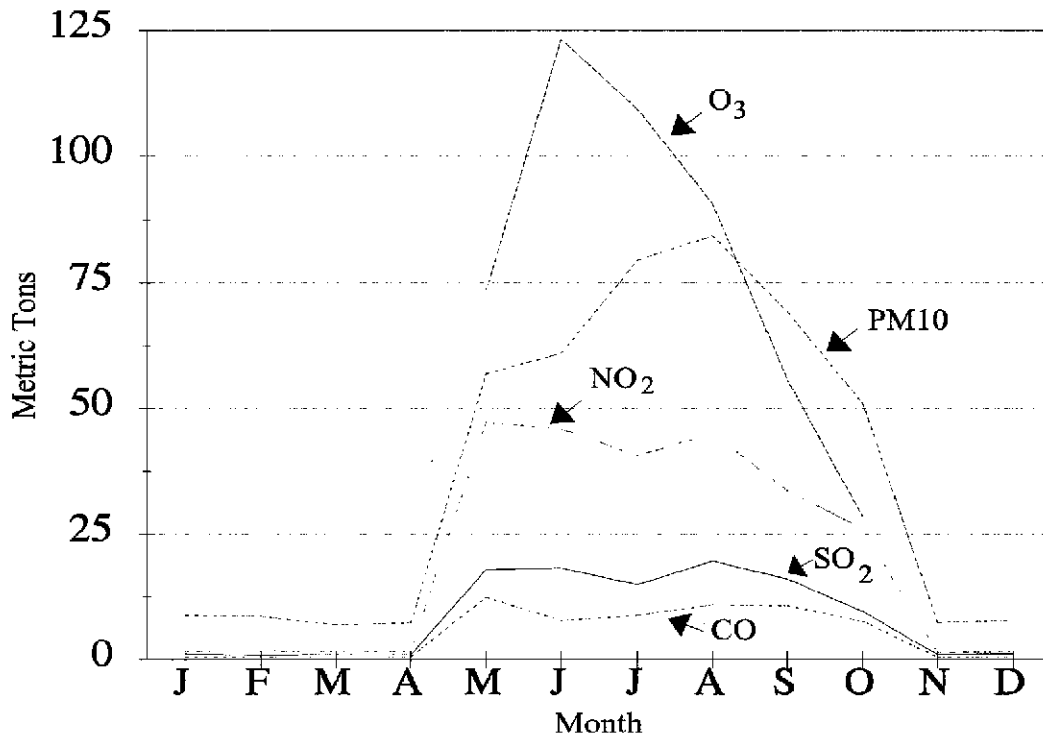


Figure 9. —Monthly estimates of pollution removal by trees in DuPage County in 1991. Ozone removal estimates are for May-October only. Particulate removal assumes 50 percent resuspension back into the atmosphere.

Table 4.—Total monthly removal rates (t/month) for pollutants by study area sector in 1991 (multiply t by 1.102 to convert to tons)

| Month | CO | $SO_2$ | $NO_2$ | PM10 | $O_3$ |
|---|---|---|---|---|---|
| **CHICAGO** | | | | | |
| January | 0.2 | 0.8 | 0.7 | 4.2 | na |
| February | 0.2 | 0.7 | 0.6 | 4.0 | na |
| March | 0.1 | 0.6 | 0.6 | 3.7 | na |
| April | 0.1 | 0.6 | 0.5 | 4.4 | na |
| May | 2.7 | 14.9 | 14.9 | 26.2 | 30.0 |
| June | 2.1 | 14.1 | 13.8 | 29.5 | 48.2 |
| July | 2.1 | 12.8 | 14.3 | 41.5 | 44.5 |
| August | 3.0 | 14.9 | 17.5 | 35.6 | 36.6 |
| September | 2.8 | 13.5 | 14.4 | 31.3 | 20.4 |
| October | 2.0 | 10.1 | 10.0 | 24.2 | 11.1 |
| November | 0.2 | 0.8 | 0.5 | 4.0 | na |
| December | 0.1 | 0.4 | 0.6 | 3.8 | na |
| **SUBURBAN COOK COUNTY** | | | | | |
| January | 1.1 | 5.0 | 3.8 | 23.7 | na |
| February | 1.2 | 4.0 | 3.4 | 22.7 | na |
| March | 1.2 | 3.6 | 3.3 | 18.9 | na |
| April | 1.0 | 3.6 | 3.0 | 22.6 | na |
| May | 26.1 | 89.7 | 80.3 | 144.7 | 213.2 |
| June | 15.0 | 82.3 | 71.0 | 169.3 | 327.0 |
| July | 19.8 | 79.7 | 71.8 | 226.7 | 305.9 |
| August | 26.9 | 97.1 | 90.0 | 199.7 | 255.6 |
| September | 27.4 | 82.3 | 80.2 | 170.0 | 148.7 |
| October | 24.3 | 65.3 | 57.1 | 136.3 | 77.8 |
| November | 1.4 | 4.8 | 3.0 | 22.1 | na |
| December | 1.5 | 2.6 | 3.4 | 22.4 | na |
| **DUPAGE COUNTY** | | | | | |
| January | 0.5 | 1.0 | 1.8 | 8.9 | na |
| February | 0.4 | 0.8 | 1.7 | 8.7 | na |
| March | 0.5 | 0.8 | 1.6 | 6.9 | na |
| April | 0.4 | 0.8 | 1.5 | 7.3 | na |
| May | 12.4 | 17.9 | 47.1 | 56.8 | 73.5 |
| June | 7.8 | 18.2 | 45.9 | 60.9 | 123.2 |
| July | 8.9 | 14.9 | 40.5 | 79.5 | 109.2 |
| August | 11.0 | 19.6 | 45.0 | 84.4 | 90.7 |
| September | 10.8 | 16.1 | 33.6 | 69.2 | 55.6 |
| October | 7.7 | 9.6 | 26.0 | 50.9 | 28.4 |
| November | 0.4 | 0.9 | 1.3 | 7.3 | na |
| December | 0.5 | 1.0 | 1.5 | 7.9 | na |
| **STUDY AREA** | | | | | |
| January | 1.7 | 6.8 | 6.3 | 36.7 | na |
| February | 1.8 | 5.4 | 5.7 | 35.4 | na |
| March | 1.8 | 5.0 | 5.5 | 29.5 | na |
| April | 1.6 | 5.1 | 5.1 | 34.2 | na |
| May | 41.2 | 122.5 | 142.3 | 227.7 | 316.7 |
| June | 24.9 | 114.7 | 130.7 | 259.7 | 498.4 |
| July | 30.7 | 107.5 | 126.6 | 347.7 | 459.6 |
| August | 40.8 | 131.6 | 152.5 | 319.6 | 382.8 |
| September | 41.0 | 111.9 | 128.2 | 270.5 | 224.7 |
| October | 33.9 | 85.0 | 93.2 | 211.3 | 117.2 |
| November | 1.9 | 6.5 | 4.9 | 33.4 | na |
| December | 2.1 | 4.0 | 5.5 | 34.2 | na |

na - not analyzed.

Table 5.—Average daily pollutant removal during in-leaf and out-of-leaf seasons (kg/day); total yearly removal per hectare of tree canopy cover (kg/ha/yr); and average daily pollutant removal during in-leaf and out-of-leaf seasons per hectare of tree canopy cover (kg/ha/day) in Chicago, suburban Cook County, DuPage County and entire study area (multiply kg by 2.204 to convert to pounds; divide kg/ha by 1.12 to convert to lb/acre)

| Sector | Average daily removal | | Removal per hectare of tree cover | | |
| | In-leaf [a] | Out-of-leaf [b] | Total year | In-leaf [a] | Out-of-leaf [b] |
|---|---|---|---|---|---|
| **CO** | | | | | |
| Chicago | 79 | 5 | 2.3 | 0.012 | 0.0007 |
| Cook County | 757 | 40 | 3.5 | 0.018 | 0.0009 |
| DuPage County | 318 | 15 | 3.8 | 0.020 | 0.0009 |
| Study Area | 1,155 | 60 | 3.4 | 0.018 | 0.0009 |
| **$SO_2$** | | | | | |
| Chicago | 437 | 21 | 12.6 | 0.065 | 0.0031 |
| Cook County | 2,697 | 131 | 12.3 | 0.064 | 0.0031 |
| DuPage County | 524 | 30 | 6.3 | 0.033 | 0.0019 |
| Study Area | 3,657 | 182 | 10.9 | 0.056 | 0.0028 |
| **$NO_2$** | | | | | |
| Chicago | 462 | 20 | 13.3 | 0.069 | 0.0030 |
| Cook County | 2,448 | 110 | 11.1 | 0.058 | 0.0026 |
| DuPage County | 1,294 | 52 | 15.4 | 0.081 | 0.0032 |
| Study Area | 4,205 | 182 | 12.4 | 0.065 | 0.0028 |
| **PM10** | | | | | |
| Chicago | 1,023 | 134 | 31.8 | 0.153 | 0.0201 |
| Cook County | 5,688 | 733 | 27.9 | 0.134 | 0.0173 |
| DuPage County | 2,183 | 260 | 27.9 | 0.136 | 0.0162 |
| Study Area | 8,894 | 1,127 | 28.3 | 0.137 | 0.0173 |
| **$O_3$** | | | | | |
| Chicago | 1,032 | na | 28.6 | 0.155 | na |
| Cook County | 7,185 | na | 31.4 | 0.170 | na |
| DuPage County | 2,602 | na | 29.9 | 0.162 | na |
| Study Area | 10,819 | na | 30.7 | 0.166 | na |

[a]May - October; kg/day
[b]November - April; kg/day

Table 6.—Estimated maximum and average in-leaf reduction in hourly pollution concentration (in percent) by trees in the Chicago area in 1991

| Pollutant | Study area | | 100-percent forested area | |
| | Maximum | Average | Maximum | Average |
|---|---|---|---|---|
| CO | 0.007 | 0.002 | 0.03 | 0.01 |
| $NO_2$ | 0.8 | 0.2 | 4.2 | 1.1 |
| $SO_2$ | 1.3 | 0.3 | 6.7 | 1.6 |
| PM10[a] | 0.5 | 0.4 | 2.5 | 2.1 |
| $O_3$ | 1.0 | 0.3 | 5.2 | 1.6 |

[a] daily percent reduction

lion in DuPage County ($147/ha of trees/yr; $59/acre of trees/yr); and $9.2 million in the study area ($141/ha of trees/yr; $57/acre of trees/yr) (Table 8). The highest value was for $NO_2$ removal (43 percent of total monetary value), followed by PM10 (29 percent), $SO_2$ (14 percent), $O_3$ (12 percent) and CO (2 percent). Monetary values for individual trees in the study area ranged from $0.04/tree/yr for small trees to $2.31/tree/yr for large trees (Table 7) .

The proposed tree-planting scenario that would fill available grass and soil space on various land uses from 0 to 25 percent with trees would increase overall tree cover in the study area by 4.1 percent (from 19.4 to 23.5 percent tree cover). This additional cover likely would have removed an additional 1,180 t (1,300 tons) of pollution in 1991 (CO: 45 t, 50 tons; $SO_2$: 150 t, 165 tons; $NO_2$: 170 t, 185 tons; PM10: 390 t, 430 tons; $O_3$: 425 t, 470 tons) and reduced pollution concentrations by another 0.05 percent.

# Discussion

The removal estimates in this paper are approximations based on computations that incorporate measured local urban tree canopy surface, local pollution concentrations, and local meteorology in diurnal and annual patterns. Average in-leaf pollution removal per hectare of tree cover per day for 1991 in the Chicago area was significantly less than estimated by DeSanto et al. (1976a) for all pollutants (from 11 to 32 times less for particles to 400 to 1,300 times less for $SO_2$). The estimates of DeSanto et al. are higher than those for the Chicago area because of high pollution concentrations in some of the studies used to determine removal rates and because diurnal leaf stomatal functions were disregarded. In-leaf daily removal of $SO_2$ per hectare of tree cover in the Chicago area was about half of that estimated by Murphy et al. (1977) and Lorenz and Murphy (1985) for equal pollutant concentration.

Results for the Chicago area improve on earlier estimates of pollution removal for urban trees. However, there remain many limitations to the Chicago results that have unknown bounds on the error of estimation. Thus, the results should be considered first-order approximations of pollution removal by urban trees. Additional research is needed to better determine various aspects of the calculations, and to test results under urban field conditions.

## Factors Influencing Pollution Removal Estimates

Because tree-canopy resistances generally decrease from morning to midday and then increase until night (Grimmond and Oke 1991), the use of average in-leaf daytime $R_c$ values likely overestimates pollution removal during the early morning and late evening, and underestimates removal during midday. Unfortunately, it is not known where the average $R_c$ value from the literature falls within the diurnal resistance cycle. Research is needed to evaluate the diurnal cycle of tree canopy resistances to pollution deposition in urban areas.

The overall removal rate for trees is greater than reported in this study as results were limited to dry deposition. In periods

after rain or during periods when dew collects on vegetation removal rates for urban trees increase as trees offer a large wet surface area upon which water-soluble pollutants can readily dissolve (e.g., $SO_2$, $NO_2$).

Estimates of particle removal also may be conservative as the model assumed 50 percent resuspension of deposited pollutants. This rate was estimated as a midvalue based on limited literature. Zinke (1967) estimated that retention of airborne materials ranged from 17 to 57 percent in pine stands and 82 to 86 percent in hardwood stands. For the Chicago area's urban forest, which is approximately 90 percent hardwoods, a resuspension rate of 20 percent would be reasonable given Zinke's estimates. However, due to the more open nature of urban forests relative to more natural forest stands, higher resuspension would be expected due to the increased probability of wind resuspension in tree canopies. Research is needed on the resuspension of particles in urban areas.

Average canopy-resistance values obtained from the literature probably are too high (leading to conservative deposition velocities) for $SO_2$ (average in-leaf daytime $R_c = 1.9$ sec/cm) and $O_3$ (average in-leaf daytime $R_c = 1.7$ sec/cm). Daytime tree-canopy resistances could be as low as 0.5 sec/cm for $SO_2$ and 0.4 sec/cm for $O_3$.[3] Average daytime in-leaf deposition velocities for forests and trees in the literature typically range from 0.2 to 2 cm/sec and average around 1.0 cm/sec for $SO_2$ (e.g., Garland 1977; McMahon and Denison 1979; Fowler and Cape 1983; Lovett and Lindberg 1984; Fowler 1985; Lorenz and Murphy 1985; Murphy and Sigmon 1990). Daytime deposition velocities for $O_3$ in the literature normally range from 0.3 to 1 cm/sec and average around 0.7 cm/sec (e.g., Greenhut 1983; Colbeck and Harrison 1985; Davidson and Wu 1990).

The deposition velocities used in this study were lower than averages in the literature (study $SO_2$ average in-leaf daytime $V_d = 0.52$ cm/sec; $O_3$ average in-leaf daytime $V_d = 0.55$ cm/sec) and are thought to be conservative (Wesely 1993, pers. commun.). Through the use of average $R_c$ values, deposition velocities and pollution removal may be underestimated by a factor of 1.9 for $SO_2$ and a factor of 1.3 for $O_3$. Research is needed on improving $R_c$ and $V_d$ estimates for urban vegetation and other urban surfaces. The average deposition velocity of $NO_2$ was within the range of velocities in the literature.

The location of pollution monitors in the city can lead to an overestimation of pollution removal by urban trees. These monitors tend to be located in areas that are expected to have relatively high concentrations of pollution. Thus, extrapolations of these concentrations to larger areas may result in inflated concentration estimates. Detailed variations

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[3] Based on minimum stomatal and mesophyll resistance of $r_s D_{H_2O}/D_x + r_{mx}$ where $r_s$ is minimum stomatal resistance, $D_{H_2O}$ is the molecular diffusivity of water vapor, $D_x$ is the molecular diffusivity of gas $x$ in air, and $r_{mx}$ is mesophyll resistance of gas $x$ (Wesely 1989). Minimum stomatal resistance was assumed to be 1.5 sec/cm (Baldocchi 1988). Leaf area index of urban forests was estimated to be 6 (see Nowak 1994: Chapter 2, this report).

Table 7.—Estimated removal rate per tree by d.b.h. class (kg/yr) and total annual dollar value per tree for removal of pollutants (see Table 8); particulate removal assumes 50 percent resuspension back to the atmosphere (multiply kg by 2.204 to convert to pounds)

| D.b.h. class | CO | $SO_2$ | $NO_2$ | PM10 | $O_3$[a] | Total | Dollars |
|---|---|---|---|---|---|---|---|
| 0-7 cm | 0.001 | 0.003 | 0.003 | 0.007 | 0.008 | 0.021 | 0.04 |
| 8-15 cm | 0.003 | 0.008 | 0.009 | 0.021 | 0.023 | 0.064 | 0.10 |
| 16-30 cm | 0.007 | 0.021 | 0.024 | 0.055 | 0.060 | 0.166 | 0.27 |
| 31-46 cm | 0.017 | 0.054 | 0.062 | 0.141 | 0.153 | 0.428 | 0.70 |
| 47-61 cm | 0.033 | 0.104 | 0.118 | 0.270 | 0.294 | 0.819 | 1.34 |
| 62-76 cm | 0.043 | 0.136 | 0.155 | 0.355 | 0.385 | 1.074 | 1.76 |
| 77+ cm | 0.056 | 0.178 | 0.204 | 0.465 | 0.505 | 1.409 | 2.31 |

[a] May-October only.

Table 8.—Total yearly monetary value (thousands of dollars) of pollutant removal and average daily monetary value (dollars) during in-leaf season for Chicago, suburban Cook County, DuPage County, and entire study area; estimated tons of pollutant removed by trees was multiplied by 1990 cost of preventing emission of similar amount of pollutant using current emission control strategies ($/t): CO = 1,014; $SO_2$ = 1,801; $NO_2$ = 4,863; PM10 = 1,441; $O_3$ = 540 (California Energy Commission 1992)

| Pollutant | Chicago | | Cook County | | DuPage County | | Study area | |
|---|---|---|---|---|---|---|---|---|
| | Total | Day | Total | Day | Total | Day | Total | Day |
| CO | 16 | 80 | 149 | 770 | 62 | 320 | 227 | 1,170 |
| $SO_2$ | 152 | 790 | 937 | 4,860 | 183 | 940 | 1,272 | 6,590 |
| $NO_2$ | 431 | 2,250 | 2,287 | 11,910 | 1,204 | 6,290 | 3,922 | 20,450 |
| PM10 | 306 | 1,470 | 1,699 | 8,190 | 646 | 3,140 | 2,651 | 12,800 |
| $O_3$ | 103 | 560 | 717 | 3,880 | 260 | 1,410 | 1,080 | 5,850 |
| Total | 1,008 | 5,150 | 5,789 | 29,610 | 2,355 | 12,100 | 9,152 | 46,860 |

in pollution concentrations across a city need to be investigated more fully to better understand the limitations of extrapolating concentrations from limited monitoring points.

*Boundary Layer*
Current estimates of percent reduction in pollution concentrations in the Chicago area likely are conservative due to the effect of the breeze off Lake Michigan and the assumption of a well-mixed boundary layer. The lake breeze reduces mixing depths (Lyons and Olsson 1973), thus, increasing the relative effect of trees in reducing air pollution. The assumption of a well-mixed unstable atmosphere presumed little variation in pollution concentration with height (e.g., Colbeck and Harrison 1985). However, there are times, particularly at night, when there is limited mixing (van Dop et al. 1977; Colbeck and Harrison 1985). During these times of limited mixing, the effect of trees and other surfaces in removing pollutants is concentrated in the lower boundary layer, so trees have a greater relative effect on pollution reduction near the ground.

This effect is of particular importance as this is the layer in which humans reside.

The depth of the boundary layer has an immense effect on the percent reduction in pollution concentration. Maximum tree effects occurred in early morning when stomates were assumed open and transpiring and the boundary-layer height still was relatively low. Research is needed on variations in stomatal resistances and boundary-layer heights in the Chicago region to improve the estimates of reductions in pollution concentration by Chicago's trees.

*Emission Effects*
Another factor that is not considered in estimates of pollution removal is that trees emit compounds that can increase local concentrations of pollution. These emissions offset some of the removal effects of trees. The relatively low removal of CO by trees likely is offset by their emission of volatile organic compounds, which can increase CO concentrations. It is

possible that urban trees may be an overall source of CO; this sink/source relationship in urban areas needs further study. If trees are a source of CO, the source amount probably would be insignificant relative to automobile emissions.

Emissions of volatile organic compounds by trees can contribute to the formation of $O_3$ (Brasseur and Chatfield 1991). However, because these emissions are temperature dependent and trees generally lower air temperatures, it is believed that increased tree cover would lower overall volatile organic emissions and $O_3$ levels in urban areas (Cardelino and Chameides 1990).

Pollen emissions by trees can contribute significantly to local concentrations of total particles. However, tree pollen often is greater than 10 μm (Smith 1990) and likely contributes little to PM10 concentrations. Inhalation of noninfectious allergens can cause disease, the major response being allergic rhinitis, including seasonal hay fever and bronchial asthma (Smith 1978). Emissions of $H_2S$ by trees generally occur in connection with moderate to high concentrations of sulfur in the atmosphere or soil. Thus, removal of $SO_2$ by trees under moderate to high $SO_2$ concentrations likely will be offset some by sulfur emissions by trees to the atmosphere.

Depending on their configuration around buildings, trees can increase or decrease building energy use. Trees generally conserve energy use in the summer but often increase use in the winter in colder climates (e.g., tree branches shade residences). This change in energy use alters pollutant emissions from local power plants. Thus, there are many interactive factors involving urban trees and air quality that remain to be investigated to more fully understand the impact of urban trees on air quality.

Model estimates of pollution removal by trees are specific to 1991 conditions in the Chicago area. Extrapolations to other years or other cities must consider specific pollution concentrations, tree configuration, and local meteorology.

## Management Considerations

The majority of pollution removal by trees occurs under in-leaf daytime conditions as this is the time when leaf surfaces are actively transpiring and pollution concentrations can reach their maximum. The size of individual trees also affects total removal per tree. Large trees can remove 60 to 70 times more pollution a year than small trees. Thus, to maximize pollution removal by trees and other environmental benefits (e.g., reductions in air temperature), it is important to sustain healthy, functional (i.e., transpiring) trees, particularly large ones.

Future tree plantings can further enhance the air quality benefits of the urban forest and should be concentrated in polluted areas. When pollution concentrations become high, it is likely that stomates partially or fully close, reducing or eliminating most of the potential for pollution reduction of urban trees. However, tree response to pollutants varies by species and pollutant. Pollution-tolerant species (Kozlowski 1980) should be selected to enhance survival and subsequent air quality benefits.

Planting to reduce building energy use (McPherson 1994: Chapter 7, this report) also will improve air quality by reducing power plant emissions. Mass plantings can act as buffers from pollution sources (McCurdy 1978). Ample water should be supplied to enhance stomatal removal of pollution. Conifers should be planted to enhance particle removal, particularly in winter.

## Monetary Value

Typical monetary values per tree are relatively small, ranging from $0.04/yr for small trees to more than $2/yr for large trees. These estimates are based on the cost of preventing the emission of a similar amount of pollutant with current control strategies. It is important to note that emission controls prevent pollution from entering the air while deposition to trees removes air pollutants already in the air. Using emission-control values likely overestimates the value generated by reducing pollutant concentrations after emission because once the pollutant is emitted, it can increase atmospheric concentrations and pollution effects around all surfaces, adversely affecting human health, materials, and visibility before being removed.

These estimates also do not fully incorporate the effects of trees on human health, materials, or visibility received through improvements in air quality. Other benefits and detriments not considered in this monetary valuation include possible lower concentrations of $O_3$ due to lower air temperatures, altered power plant emissions due to changes in building energy use, and changes in human perceptions of air quality. Perceptions can change through the production of pleasant odors, screening views from polluted air, and vegetation damage from pollution.

## Research Issues

Continued research and field studies are needed to better evaluate and quantify aerodynamic and quasi-laminar boundary-layer resistances in urban areas. The $R_a$ and $R_b$ estimates in this study are minimal and in the range expected for forests (Fowler 1985). Considering that the stomatal influence on pollution removal is large, additional research is needed to investigate urban evapotranspiration (e.g., Grimmond and Oke 1991), particularly, urban tree transpiration, tree-canopy resistances to various pollutants, and the effect of pollutants on stomatal functioning (e.g., Baldocchi et al. 1987). Although advances are being made continually in these areas, particularly for forests and agricultural crops, field studies are needed to quantify pollution deposition in urban areas to begin to understand how various urban surfaces and combinations of surfaces influence pollution deposition and concentrations.

The study calculations are the first in a series to be developed to estimate pollution deposition in urban areas. Future calculations will incorporate all urban surfaces in a multi-layer model (e.g., Baldocchi 1988). Field measurements of urban tree stomatal resistance are planned to help improve these estimates. In addition, eddy-correlation estimates of pollutant deposition in urban areas are planned to test the removal estimates under summer field conditions.

## Conclusion

Urban trees can improve air quality, removing approximately 590 metric tons (650 tons) of pollution in Chicago and 5,600 metric tons (6,100 tons) in Cook and DuPage Counties in 1991. These amounts relate to an average air quality improvement of approximately 0.3 percent, peaking at around one percent. These removal estimates are likely conservative, particularly for $SO_2$ and $O_3$. Further air quality improvement (reaching 5 to 10 percent or greater) can be obtained by increasing and sustaining healthy tree cover, particularly under stable atmospheric conditions. The majority of pollution removal by trees occurs during daylight in-leaf hours with the greatest overall removal effects for PM10 and $O_3$. Relatively minor removal was estimated for CO and urban trees may be an overall source of CO via tree volatile organic emissions. Research is needed to investigate the interactive relationships of pollution removal, trace-gas emissions, and air temperature and building energy use effects of urban trees on overall air quality.

Providing ample water to facilitate tree transpiration is critical to maximizing gaseous pollutant removal. Maximum percent reduction in pollution concentrations near the ground can be expected when trees are transpiring under stable atmospheric conditions and/or the boundary-layer height is relatively low. Trees offer both an active (via transpiration) and passive surface for gaseous and particulate pollutant removal, decreasing the amount of pollution inhaled by humans, deposited on anthropogenic material and available to decrease visibility. Trees should not be viewed as a substitute for emission controls, but rather as a supplement. Reduction of pollution emissions prevents possible pollution damage, reduction in ambient concentrations (e.g., via trees) only reduces the likelihood of possible damage. The effect of typical urban tree configurations on pollution emissions from both anthropogenic and biogenic sources remains to be investigated.

## Acknowledgments

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# Chapter 6

# Atmospheric Carbon Dioxide Reduction by Chicago's Urban Forest

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## Abstract

In terms of reducing atmospheric carbon dioxide ($CO_2$), trees in urban areas offer the double benefit of direct carbon storage and the avoidance of $CO_2$ production by fossil-fuel power plants through energy conservation from properly located trees. In the City of Chicago, trees store an estimated 855,000 metric tons (t) of carbon (942,000 tons), and trees throughout the study area of Cook and DuPage Counties store about 5.6 million t (6.1 million tons). Carbon storage by shrubs is approximately 4 percent of the amount stored by trees. Total carbon storage and annual sequestration are greatest on 1-3 family residential lands, institutional lands dominated by vegetation (e.g., parks, forest preserves) and vacant lands. Net carbon sequestration in the study area is estimated at 140,600 t (155,000 tons). Carbon storage by urban forests nationally likely is between 400 and 900 million t (440 to 990 millions tons).

Storage by individual trees is up to 1,000 times greater in large than in small trees, with sequestration rates up to 90 times greater for healthy large than healthy small trees. Estimated carbon emissions avoided annually due to energy conservation from existing trees throughout the study area is approximately 11,400 t (12,600 tons). Total carbon stored by trees in the study area, which took years to store, is equivalent to the amount of carbon emitted from the residential sector in the study area during a 5-month period. Net annual sequestration equals the amount of carbon emitted from transportation use in the study area in 1 week. The amount of carbon sequestered annually by one tree less than 8 cm (3 inches) in trunk diameter (d.b.h.) equals the amount emitted by one car driven 16 km (10 mi). Reasonable additional tree planting, in conjunction with efforts to sustain existing tree cover could increase carbon storage in the study area by another 1.2 million t (1.3 million tons), or the amount of carbon emitted by transportation use in the study area in less than 2 months. The advantages and limitations of urban trees in reducing atmospheric $CO_2$ are discussed.

## Introduction

Increasing levels of atmospheric carbon dioxide ($CO_2$) and other "greenhouse" gases (e.g., methane, chlorofluorocarbons, nitrous oxide) are thought by many to be contributing to an increase in atmospheric temperatures by the trapping of certain wavelengths of heat in the atmosphere. Climate models indicate that the probable doubling of $CO_2$ within the next century would increase average global surface temperatures by 1.5° to 4.5°C (2.7° to 8.1°F) (U.S. National Research Council 1983). While no single gas is likely to have the direct impact on climate expected from $CO_2$, the sum of the radiative effects from other trace gases could effectively double the climatic impact of projected $CO_2$ increases (Wuebbles et al. 1989).

The observed increases in atmospheric concentrations of $CO_2$, methane ($CH_4$), chlorofluorocarbons (CFC's), and nitrous oxide ($N_2O$) during the 1980's, which resulted from human activities, contributed to the greenhouse effect by 56, 15, 24 and 5 percent, respectively (IPCC 1991). During this period, the contribution of different human activities to the change in the greenhouse effect is an estimated 46 percent from energy production and use; 24 percent from the production and use of CFC's and other halocarbons (e.g., from refrigerants, aerosol sprays); 18 percent from deforestation, biomass burning, and other changes in land use practices; 9 percent from agriculture (e.g., methane from rice cultivation and livestock and $N_2O$ release from nitrogenous fertilizers); and 3 percent from other sources (e.g., methane from landfills) (IPCC 1991).

## Urban Trees and Carbon Dioxide

Increased atmospheric $CO_2$ is attributable mostly to fossil fuel combustion (about 75 percent) and deforestation (Schneider 1989). Atmospheric carbon is estimated to be increasing by approximately 2.6 billion metric tons (t) (2.9 tons) annually (Sedjo 1989). By storing carbon through their growth process, trees act as a sink for atmospheric $CO_2$. Thus, increasing the number of trees can potentially slow the accumulation of atmospheric carbon (e.g., Moulton and Richards 1990).

In reducing atmospheric $CO_2$, trees in urban areas offer double benefits. First, they directly sequester and store atmospheric carbon. Second, when located properly, urban trees conserve energy, which results in lower $CO_2$ emissions from fossil-fuel power plants. Properly located trees shade residences in summer (reducing air-conditioning energy use), but also allow solar access and/or block winds in winter to reduce heating needs (Heisler 1986). Tree transpiration also reduces local air temperatures, which can affect local energy use. There has been little research on the amount of carbon that urban forests store, or on the effect of energy conservation by trees on the amount of carbon released to the atmosphere.

Biomass (dry weight) of trees in Shorewood, Wisconsin, a suburb of Milwaukee, has been estimated at 35.7 t per hectare (ha) of above-ground biomass (15.9 tons/acre) (Dorney

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et al. 1984). Biomass was calculated using a generalized formula from Whittaker et al. (1974). This biomass estimate converts to approximately 22.8 t/ha of carbon (10.2 tons/acre) (above and below ground). Shorewood's tree cover has been liberally estimated at 39 percent, with approximately 67 percent of the trees less than 15 cm (6 inches) in trunk diameter (d.b.h.) at 1.37 m (4.5 ft) (Dorney et al. 1984). Estimated carbon storage by trees in Oakland, California, (21 percent tree cover) is 145,800 t or 11.0 t/ha (160,700 tons or 4.9 tons/acre) (Nowak 1993).

Carbon storage by urban forests in the United States has been estimated at 350 to 750 million t (385 to 825 million tons) (Rowntree and Nowak 1991; Nowak 1993). It has been estimated that the establishment of 10 million urban trees annually over the next 10 years would sequester and offset the production of 363 million t (400 million tons) of carbon over the next 50 years, 77 million t (85 million tons) due to direct sequestration and 286 million t (315 million tons) due to avoided carbon emissions from power plants (Nowak 1993). This estimate assumes that the 100 million trees survive the 50-year period and were planted in optimal positions for energy conservation. Even so, this total is less than 1 percent of the amount of carbon emissions projected for the United States over the same 50-year period.

The purpose of this paper was to estimate total carbon storage, annual carbon sequestration, and carbon emissions avoided from power plants through energy conservation by trees in the Chicago area.

## Methods

### Ground Sampling of Trees

Data on 8,996 trees were collected on 652 randomly located plots throughout the study area (see Figure 1 in Chapter 2). 0.04-ha (0.1 acre) plots were used for all land uses except 1-3 family residential, where information on the entire residential lot was collected. Tree data collected included d.b.h., tree height, and species. Total shrub area was measured on each plot; on every tenth plot, diameters for individual shrubs were measured at 15 cm (6 inches) above groundline (see Nowak 1994: Chapter 2, this report).

### Carbon and Tree Biomass

Biomass for each measured tree was calculated using allometric equations from the literature (Table 1). If no allometric equation could be found for an individual species, the genera average was substituted. If no genera equations were found, biomass was computed separately for each hardwood and conifer equation and the average result from the hardwood or conifer group was used.

To help determine whether allometric equations for forest-grown trees were applicable for urban trees, above-ground total fresh-weight biomass was collected for 30 street trees in Oak Park, Illinois. As the trees were removed, tree limbs were chipped and bagged and larger stems cut into logs. Logs and chips were weighed using a truck scale. Decay

was evident in 10 trees but was not considered significant (Mike Stankovich, 1993, Village of Oak Park, pers. commun.). Measured trees ranged in d.b.h. from 20 to 99 cm (8 to 39 inches). Included were nine silver maple, eight American elm, four Norway maple, three ash, two pin oak, one elm, one linden, one tulip poplar and one sugar maple. Measured weight was matched against predicted weight using appropriate allometric equations. A pair-wise t-test was used to determine if significant differences existed between actual and predicted weights.

Measured biomass from street trees in Oak Park was significantly lower than that predicted from allometric equations from natural forest stands (alpha = 0.05). Biomass estimates of more open-grown trees were multiplied by a factor 0.8 to account for the discrepancy. No adjustment was made for trees found in more natural stand conditions (e.g., on vacant lands or in forest preserves).

Biomass equations differ in the portion of tree biomass that is calculated; whether fresh or oven-dry weight is estimated, and in the diameter ranges used to devise the equations (Table 1). Below-ground biomass of trees averages approximately 22 percent of total tree biomass (Bray 1963; Ovington 1965; Young and Carpenter 1967; Whittaker and Woodwell 1968; Andersson 1970; Woodwell and Botkin 1970; King and Schnell 1972; Whittaker and Marks 1975; Harriss et al. 1977; Hermann 1977; Husch et al. 1982; Raile and Jakes 1982; Czapowskyj et al. 1985; Harmon et al. 1990; Little and Shainsky 1992).

Average biomass per square meter of shrub cover was estimated for each land-use type by calculating the above-ground biomass (kg) using formulas in Smith and Brand (1983) and dividing the calculated biomass by individual shrub cover (m²).

Below-ground biomass of small shrubs averaged approximately 61 percent of total shrub biomass (Whittaker 1962; Whittaker and Woodwell 1968; Woodwell and Botkin 1970). Many shrubs in the study area were larger than found in the literature, so a more conservative estimate of 40 percent of total biomass was used in converting above-ground shrub biomass to total shrub biomass. Equations that compute above-ground biomass were divided by 0.78 for trees and 0.6 for shrubs to convert to total biomass.

Equations that compute fresh-weight biomass were multiplied by species or genera specific conversion factors to yield dry-weight biomass. These conversion factors, derived from average moisture contents of species given in the literature, averaged 0.48 for conifers and 0.56 for hardwoods (U.S. Dept. Agric. 1955; Young and Carpenter 1967; King and Schnell 1972; Wartluft 1977; Stanek and State 1978; Wartluft 1978; Monteith 1979; Clark et al. 1980; Ker 1980; Phillips 1981; Husch et al. 1982; Schlaegel 1984a-d; Smith 1985).

For dead and dying trees, leaf biomass was removed from the estimate of total tree biomass using leaf biomass formulas derived as part of the Chicago Urban Forest Climate Project. Total biomass of dead trees was reduced by approximately 4 percent.

Table 1.—Attributes of biomass equations used to calculate tree biomass

| Species | Tree part[a] | Weight[b] | D.b.h. range[c] | Reference |
|---|---|---|---|---|
| American beech | Above | Dry | 3-56 | Tritton and Hornbeck 1982 |
| American beech | Above | Dry | 3-66 | Tritton and Hornbeck 1982 |
| American beech | Above | Dry | 5-51 | Tritton and Hornbeck 1982 |
| Aspen | Above | Dry | 3-56 | Tritton and Hornbeck 1982 |
| Aspen | Total | Fresh | 3-51 | Wenger 1984 |
| Balsam fir | Total | Dry | 3-41 | Stanek and State 1978 |
| Balsam fir | Above | Dry | 3-51 | Tritton and Hornbeck 1982 |
| Balsam fir | Total | Fresh | 3-51 | Wenger 1984 |
| Black cherry | Above | Dry | 5-51 | Tritton and Hornbeck 1982 |
| Black oak | Total | Dry | 28-86 | King and Schnell 1972 |
| Chestnut oak | Above | Dry | 5-51 | Tritton and Hornbeck 1982 |
| Douglas-fir | Total | Dry | 3-122 | Wenger 1984 |
| Eastern hemlock | Total | Fresh | 15-38 | Stanek and State 1978 |
| Eastern hemlock | Above | Dry | 3-56 | Tritton and Hornbeck 1982 |
| Eastern hemlock | Above | Dry | 3-51 | Tritton and Hornbeck 1982 |
| Eastern hemlock | Above | Dry | 5-51 | Tritton and Hornbeck 1982 |
| Eastern hemlock | Total | Fresh | 3-51 | Wenger 1984 |
| Eastern white-cedar | Above | Dry | 3-30 | Ker 1980 |
| Green ash | Ab-lf | Dry | 3-79 | Schlaegel 1984a |
| Hickory | Total | Fresh | 5-71 | Wenger 1984 |
| Hickory | Above | Dry | 5-51 | Tritton and Hornbeck 1982 |
| Jack pine | Above | Dry | 3-33 | Stanek and State 1978 |
| Jack pine | Total | Fresh | 3-33 | Wenger 1984 |
| Lodgepole pine | Total | Dry | 10-33 | Stanek and State 1978 |
| Longleaf pine | Total | Fresh | 15-48 | Wenger 1984 |
| Norway spruce | Above | Dry | 13-41 | Jokela et al. 1986 |
| Overcup oak | Ab-lf | Dry | 3-86 | Schlaegel 1984b |
| Paper birch | Total | Fresh | 15-28 | Stanek and State 1978 |
| Paper birch | Above | Dry | 3-51 | Tritton and Hornbeck 1982 |
| Pin cherry | Above | Dry | 3-23 | Tritton and Hornbeck 1982 |
| Red maple | Above | Dry | 3-56 | Tritton and Hornbeck 1982 |
| Red maple | Above | Dry | 3-66 | Tritton and Hornbeck 1982 |
| Red maple | Above | Dry | 5-51 | Tritton and Hornbeck 1982 |
| Red oak | Ab-lf | Dry | 15-66 | Clark et al. 1980 |
| Red oak | Above | Dry | 3-56 | Tritton and Hornbeck 1982 |
| Red oak | Above | Dry | 5-51 | Tritton and Hornbeck 1982 |
| Red pine | Above | Dry | 3-51 | Tritton and Hornbeck 1982 |
| Red pine | Total | Fresh | 3-51 | Wenger 1984 |
| Red/white spruce | Total | Fresh | 3-66 | Wenger 1984 |
| Scarlet oak | Ab-lf | Dry | 13-51 | Clark et al. 1980 |
| Shortleaf pine | Total | Fresh | 15-51 | Wenger 1984 |
| Slash pine | Total | Fresh | 15-53 | Wenger 1984 |
| Spruce | Above | Dry | 3-56 | Tritton and Hornbeck 1982 |
| Spruce | Above | Dry | 3-66 | Tritton and Hornbeck 1982 |
| Sugarberry | Ab-lf | Dry | 3-56 | Schlaegel 1984c |
| Sugar maple | Above | Dry | 3-56 | Tritton and Hornbeck 1982 |
| Sugar maple | Above | Dry | 3-66 | Tritton and Hornbeck 1982 |
| Sugar maple | Total | Fresh | 3-66 | Wenger 1984 |
| Sweetgum | Ab-lf | Dry | 3-84 | Schlaegel 1984d |
| Tulip-poplar | Ab-lf | Dry | 15-71 | Clark and Schroeder 1977 |

Table 1.—continued

| Species | Tree part[a] | Weight[b] | D.b.h. range[c] | Reference |
|---|---|---|---|---|
| Tulip-poplar | Above | Dry | 3-51 | Tritton and Hornbeck 1982 |
| Tulip-poplar | Above | Dry | 5-51 | Tritton and Hornbeck 1982 |
| Western redcedar | Above | Dry | 3-119 | Stanek and State 1978 |
| White ash | Above | Dry | 5-51 | Tritton and Hornbeck 1982 |
| White oak | Above | Dry | 5-51 | Tritton and Hornbeck 1982 |
| White pine | Above | Dry | 3-56 | Tritton and Hornbeck 1982 |
| White pine | Above | Dry | 3-66 | Tritton and Hornbeck 1982 |
| White pine | Total | Fresh | 3-66 | Wenger 1984 |
| Yellow birch | Above | Dry | 3-56 | Tritton and Hornbeck 1982 |
| Yellow birch | Above | Dry | 3-66 | Tritton and Hornbeck 1982 |
| Yellow birch | Above | Dry | 5-51 | Tritton and Hornbeck 1982 |
| Yellow birch | Total | Fresh | 3-66 | Wenger 1984 |

[a]Above = above-ground biomass; Ab-lf = above ground biomass excluding leaves; Total = total tree biomass (including roots).
[b]fresh or oven-dry weight.
[c]in cm

Total tree and shrub dry-weight biomass was converted to total stored carbon by multiplying by 0.5 (For. Prod. Lab. 1952; Millikin 1955; Ovington 1957; Reichle et al. 1973; Pingrey 1976; Ajtay et al. 1979; Chow and Rolfe 1989; Koch 1989). Total carbon storage by trees and shrubs was calculated by land-use type for each sector of the study area.

Because of a lack of information on errors in the basic formulas from which the projections were made and the various adjustment factors that were used, standard errors report sampling error rather than the error of estimation. Sampling errors underestimate the actual standard errors.

## Urban Tree Growth and Carbon Sequestration

To estimate the amount of carbon sequestered annually by trees, urban tree-growth was estimated from measurements of radial growth increments. Sections cut at d.b.h. were obtained for 543 trees — 223 elms, 171 maples, 78 ash, 13 poplar, and 58 other (10 species) removed from Chicago, Oak Park, Glen Ellyn, and Bloomingdale during 1991-92. A radial line was marked across the section where average growth occurred (not compressed or elongated tree rings). To avoid measuring tree growth that might be affected by the condition of the removed trees (i.e., many trees were declining or dead), radial growth and tree cumulative radius to 0.05 cm (1/50 inch) were measured for each ring developed between 1965 and 1985. Average annual growth by diameter class was calculated for major genera. Average diameter growth from the appropriate genera and diameter class was added to the existing tree diameter (year $x$) to estimate tree diameter in year $x+1$. Average height growth was assumed to be 0.15 m/ yr (0.48 ft/yr) (Fleming 1988). The difference in estimates of carbon storage between year $x$ and year $x+1$ is the amount of carbon sequestered annually.

Tree death will lead to the eventual release of stored carbon. This release is hastened when wood is burned or allowed to decay (e.g., not stored in durable wood products or landfills). To calculate the potential release of carbon due to tree death, estimates of annual mortality rates by diameter class were derived from a study of street-tree mortality (Nowak 1986). Annual mortality was estimated as 2.9 percent for trees 0 to 7 cm (0 to 3 inches) in diameter; 8 to 15 cm (3.1 to 6 inches) = 2.2 percent; 16 to 46 cm (6.1 to 18 inches) = 2.1 percent; 47 to 61 cm (18.1 to 24 inches) = 2.9 percent; 62 to 76 cm (24.1 to 30 inches) = 3.0 percent; and 77+ cm (30+ inches) = 5.4 percent. The amount of carbon sequestered due to tree growth was reduced by the amount lost due to tree mortality to estimate the net carbon sequestration rate.

## Energy Conservation

Total distribution of residential natural gas in Chicago in 1992 was 4.16 billion m³ (147 billion ft³) (Peoples Energy Corp. 1993). In Dupage County, residential gas use in 1991 was 861 million m³ (30.4 billion ft³) (Northern Illinois Gas, 1992, pers. commun.). Cook County's estimated natural gas use, based on per capita consumption in Chicago and DuPage County, is 3.27 billion m³ (115.6 billion ft³). Natural gas consumption was converted to heating energy use by multiplying by 0.78 (Peoples Gas, 1992, pers. commun.); thousand m³ of natural gas was converted to million Btu by multiplying by 36.55 (Energy Information Administration 1993). Total carbon emissions from natural gas were estimated based on the rate of 14.2 t (15.7 tons) of carbon per billion Btu for natural gas (Citizens Fund 1992). Total conservation of heating energy due to existing tree configurations (i.e., shading, wind modification) at 50 residences in Chicago has been estimated at 0.04 percent (Jo and Wilkin,1994). This

value was used to estimate carbon emissions avoided due to the effects of existing trees on heating energy.

Total electrical energy generation by Commonwealth Edison in 1992 was 79.9 billion kWh with $CO_2$ emissions of 15.0 million t (16.5 million tons) (Commonwealth Edison, 1993, pers. commun.). Considering that 68 percent of Commonwealth Edison sales are in Cook and Dupage Counties (McPherson et al. 1993), 26.7 percent of sales are to residences (Commonwealth Edison, 1993, pers. commun.) and approximately 15 percent of residential energy use is for air conditioning (Greg McPherson, 1993, pers. commun.), it is estimated that air-conditioning energy use in the study area is 2.2 billion kWh. Commonwealth Edison's $CO_2$ emission rate is 0.051 t (0.056 tons) of carbon/MWh. Total conservation of air-conditioning energy use due to existing tree configurations at 50 residences in Chicago has been estimated at 8.4 percent (Jo and Wilkin 1994). This value was used to estimate carbon emissions avoided due to the effect of existing trees on air conditioning energy use.

### Future Tree Planting

To analyze the potential effect of future tree plantings, available growing space (grass and soil area) was analyzed by land-use type throughout the study area. A reasonable tree-planting scenario assumes that none of the available space in agricultural or other transportation (predominantly airport) uses would be planted with trees due to land-use limitations. Five percent of available space could readily be planted and covered with trees on large commercial-industrial areas and institutional land dominated by vegetation such as parks, cemeteries, golf courses, and forest preserves. Ten percent of available space could be planted and covered with trees

on institutional lands dominated by building such as schools, 15 percent in residential areas, 20 percent in landscaped commercial complexes, and 25 percent on vacant lands and along freeways.

## Results

Total carbon storage by trees in the study area was about 5.6 million t or 85.7 t/ha of tree cover (6.1 million tons or 38.2 tons/acre). Trees in Chicago store 0.9 million t of carbon or 128.0 t/ha of tree cover (0.9 million tons or 57.1 tons/acre); suburban Cook County trees store 3.2 million t or 75.5 t/ha of tree cover (3.5 million tons or 33.7 tons/acre) and DuPage County trees store 1.5 million t or 95.0 t/ha of tree cover (1.7 million tons or 42.4 tons/acre) (Table 2). The most carbon stored by trees was on residential land and the least on agricultural lands. Total carbon stored by shrubs in the study area is estimated at 216,000 t (238,000 tons).

Tree carbon stored per ha in the study area averaged 16.7 t (7.4 tons/acre) and ranged from 14.1 t/ha (6.3 tons/acre) in Chicago to 17.7 t/ha (7.9 tons/acre) in DuPage County (Table 3). The highest carbon storage per ha was on institutional lands dominated by vegetation and least on agricultural lands (Table 3).

Average carbon storage by individual trees was 3 kg (7 lb) for a tree less than 8 cm (3 inches) d.b.h. to more than 3,100 kg (7,000 lb) for a tree greater than 76 cm (30 inches) d.b.h. (Figure 1, Table 4). Average carbon sequestration by individual trees ranged from 1.0 kg/yr (2.3 lb/yr) for a tree less than 8 cm d.b.h. to 93 kg /yr (204 lb/yr) for a tree greater than 76 cm d.b.h. (Figure 2, Table 4).

Table 2.—Total carbon stored (in thousands of metric tons) in Chicago, suburban Cook County, DuPage County, and entire study area (multiply thousands of metric tons by 1.102 to convert to thousands of tons)

| Land use | Chicago | | Cook Co. | | DuPage Co. | | Study area | |
|---|---|---|---|---|---|---|---|---|
| | Total | SE | Total | SE | Total | SE | Total | SE |
| Agriculture | 0.0 | 0.0 | 0.0 | 0.0 | 2.9 | 2.6 | 2.9 | 2.6 |
| Commercial[a] | 0.2 | 0.2 | 8.9 | 5.1 | 8.6 | 4.9 | 17.7 | 7.1 |
| Transportation[b] | 40.5 | 25.5 | 0.0 | 0.0 | 19.7 | 19.7 | 60.2 | 32.2 |
| Institutional (bldg.)[c] | 28.7 | 25.9 | 0.0 | 0.0 | 42.1 | 31.6 | 70.7 | 40.9 |
| Multiresidential[d] | 100.9 | 87.8 | 24.0 | 11.6 | 7.0 | 1.7 | 131.9 | 88.5 |
| Vacant | 66.2 | 25.9 | 191.1 | 128.8 | 198.3 | 68.6 | 455.5 | 148.2 |
| Institutional (veg.)[e] | 198.2 | 46.1 | 1,308.4 | 192.6 | 310.6 | 66.4 | 1,817.2 | 208.9 |
| Residential[f] | 420.1 | 69.6 | 1,659.8 | 210.2 | 936.8 | 146.6 | 3,016.7 | 265.6 |
| Total | 854.8 | 129.1 | 3,192.2 | 313.1 | 1,525.9 | 178.9 | 5,572.9 | 383.0 |

SE = standard error (based on sampling error, not the error of estimation. Sampling errors underestimate the actual standard errors).
[a]Commercial/industrial.
[b]Airport, freeways, etc.
[c]Institutional lands dominated by buildings, e.g., schools, churches.
[d]Apartments with four or more units.
[e]Institutional lands dominated by vegetation, e.g., parks, cemeteries, forest preserves, golf courses.
[f]1-3 family residential buildings.

Table 3.—Carbon storage per hectare (metric tons) in Chicago, suburban Cook County, DuPage County, and entire study area (divide t/ha by 2.24 to convert to tons/acre)

| Land use | Chicago Total | Chicago SE | Cook Co. Total | Cook Co. SE | DuPage Co. Total | DuPage Co. SE | Study area Total | Study area SE |
|---|---|---|---|---|---|---|---|---|
| Agriculture | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.1 | 0.1 |
| Commercial | 0.0 | 0.0 | 0.3 | 0.2 | 1.0 | 0.7 | 0.3 | 0.1 |
| Transportation | 7.2 | 4.5 | 0.0 | 0.0 | 9.0 | 9.0 | 3.5 | 1.9 |
| Institutional (bldg.) | 9.7 | 8.8 | 0.0 | 0.0 | 14.5 | 10.9 | 5.1 | 3.0 |
| Multiresidential | 17.3 | 15.0 | 5.7 | 2.8 | 3.2 | 0.8 | 10.8 | 7.3 |
| Vacant | 34.2 | 13.4 | 15.6 | 10.5 | 25.0 | 8.6 | 20.6 | 6.7 |
| Institutional (veg.) | 35.8 | 8.3 | 44.2 | 6.5 | 33.9 | 7.2 | 41.0 | 4.7 |
| Residential | 17.2 | 2.9 | 22.5 | 2.9 | 25.7 | 4.0 | 22.4 | 2.0 |
| All uses | 14.1 | 2.1 | 17.0 | 1.7 | 17.7 | 2.1 | 16.7 | 1.1 |

Table 4.—Average carbon stored (kg/tree) and sequestered (kg/tree/yr) in study area by d.b.h. class (multiply kg by 2.204 to convert to pounds)

| D.b.h. class (cm) | Carbon stored Mean | Carbon stored SE | Carbon sequestered Mean | Carbon sequestered SE |
|---|---|---|---|---|
| 0-7 | 3 | 0.05 | 1.0 | 0.02 |
| 8-15 | 24 | 0.3 | 4.4 | 0.05 |
| 16-30 | 105 | 1.4 | 9.4 | 0.1 |
| 31-46 | 399 | 6 | 19.1 | 0.3 |
| 47-61 | 962 | 19 | 34.6 | 0.8 |
| 62-76 | 1,808 | 51 | 55.3 | 1.8 |
| 77+ | 3,186 | 153 | 92.7 | 4.0 |
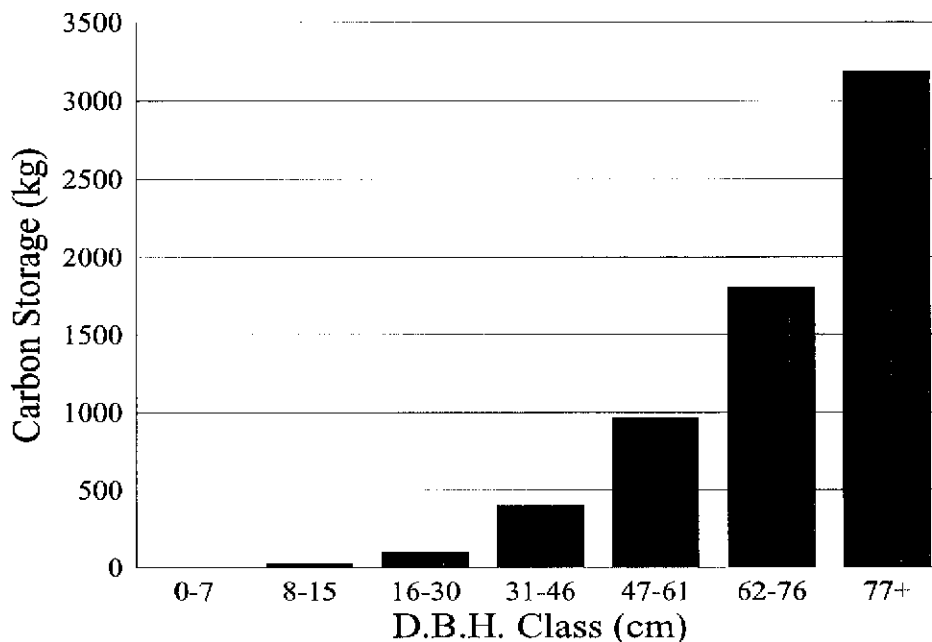


Figure 1. —Average carbon stored in individual urban trees by d.b.h. class (kg).
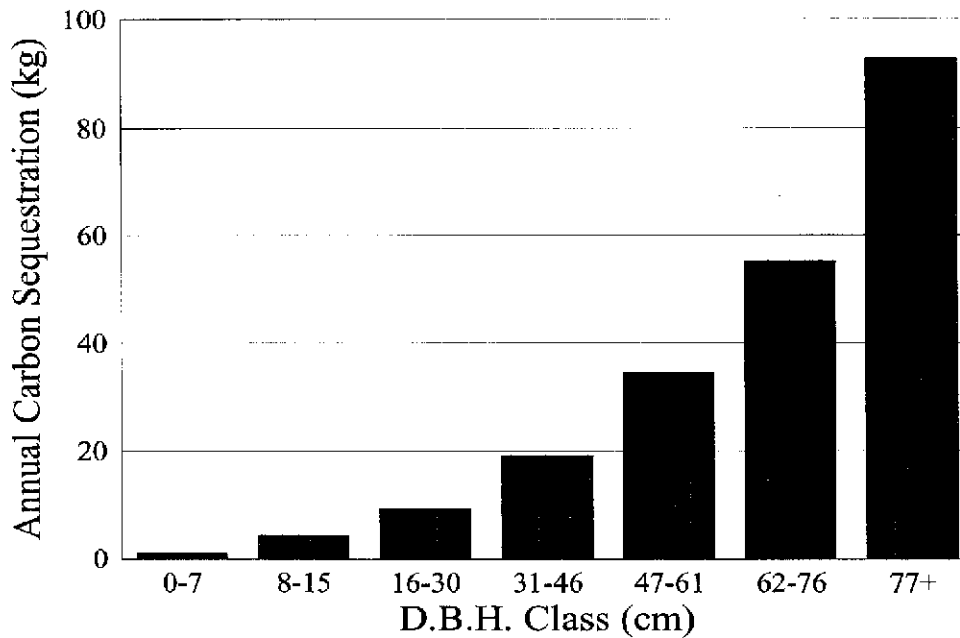
Figure 2. —Average annual carbon sequestration by individual urban trees by d.b.h. class (kg/year).

Average urban tree growth ranged from 0.78 to 1.02 cm/yr (0.31 to 0.40 inch/yr) (Table 5). Maximum total sequestration by trees in the study area (no tree mortality) is estimated at 315,800 t (348,000 tons) of carbon, ranging from 40,100 t (44,200 tons) in Chicago to 186,500 t (205,500 tons) in suburban Cook County (Table 6). Loss of carbon due to tree mortality in the study area (2.6 percent average annual mortality rate) is estimated at 175,200 t (193,000 tons) — 55 percent of the carbon sequestered — for a net sequestration rate of 140,600 t (155,000 tons) of carbon. This amounts to 0.4 t/ha of land and 2.2 t/ha of tree cover (0.2 ton/acre and 0.9 tons/acre). At an average mortality rate greater than 4.8 percent per year (assuming the same relative difference in mortality rates among the d.b.h. classes), more carbon would be lost due to tree mortality than would be sequestered by existing living trees.

Carbon emissions due to heating energy use in the study area total about 3.3 million t/yr (3.7 million tons/yr). Avoided carbon emissions due to savings in heating energy use from existing trees are estimated at 1,300 t/yr (1,500 tons/yr). Total carbon emissions due to air-conditioning use in the study area are approximately 109,900 t/yr (121,100 tons/yr). Avoided carbon emissions due to savings in air-conditioning use from existing trees are estimated at 10,100 t/yr (11,100 tons/yr).

If 0 to 25 percent of the available grass and soil space on various land uses were planted with trees, overall tree cover in the study area would increase from 19.4 to 23.5 percent. This planting assumes a tree-diameter structure comparable to what exists today and probably would take 40 to 80 years to become established. This tree establishment likely would store an additional 1.2 million t (1.3 million tons) of carbon. These trees also could reduce carbon emissions from power

plants by lowering air temperatures through transpiration and by properly shading buildings and blocking winter winds.

## Discussion

There are limitations to estimating carbon storage and sequestration by urban trees. Preliminary indications are that biomass equations derived from forest stands overestimate biomass from open-grown urban trees by a factor of 1.25. Open-grown trees typically are shorter but often have larger, more branchy crowns than forest-grown trees (Spurr and Barnes 1980). However, urban tree crowns often are pruned, which removes stored carbon. These differences in tree height and pruning likely contribute to the discrepancy between forest derived equations and measured biomass of urban trees. Pruning practices vary by location but street trees usually are well maintained; thus, the biomass equation adjustment factor (derived from street trees) likely is near maximum. Research is needed to further test the applicability of existing biomass equations to urban trees, and on how biomass-equation estimates vary by land-use type and associated maintenance practices.

D.b.h. ranges for biomass equations used in this study generally ranged from 3 to 66 cm (1 to 26 inches). The degree of error in predicting biomass outside of regression formula d.b.h. ranges is unknown, but visual inspection of biomass estimates for large trees (greater than 66 cm d.b.h.) indicates the estimates appear reasonable. Research is needed on root-shoot relationships of open-grown urban trees.

In U.S. forest ecosystems, 59 percent of the total carbon stored is in soils (Birdsey 1990). Estimates of carbon storage

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Table 5.—Average tree-diameter growth rates (cm/yr), from a sample of street trees in the Chicago area, used for estimating carbon sequestration; dead and dying trees were given a growth rate of 0.0 cm/yr (divide cm by 2.54 to convert to inches)

| Genera | D.b.h. class (cm) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0-7 | 8-15 | 16-30 | 31-46 | 47-61 | 62-76 | 77+ |
| Ash | 0.90 | 0.99 | 0.85 | 0.64 | 0.68 | 0.70 | 0.44 |
| Elm | 0.96 | 1.15 | 1.08 | 0.89 | 0.83 | 0.83 | 1.03 |
| Maple | 0.81 | 0.92 | 0.79 | 0.68 | 0.66 | 0.72 | 1.11 |
| Other | 0.80 | 1.10 | 0.87 | 0.73 | 0.73 | 0.71 | 0.42 |
| Poplar | 0.64 | 1.06 | 0.98 | 0.94 | 1.49 | 1.61 | 1.87 |
| Average | 0.85 | 1.02 | 0.90 | 0.79 | 0.78 | 0.84 | 0.95 |

Table 6.—Total carbon sequestered annually (in thousands of metric tons) in Chicago, suburban Cook County, DuPage County, and entire study area; estimates of sequestration are high because they do not account for tree mortality (multiply thousands of metric tons by 1.102 to convert to thousands of tons)

| Land use | Chicago | | Cook Co. | | DuPage Co. | | Study area | |
|---|---|---|---|---|---|---|---|---|
| | Total | SE | Total | SE | Total | SE | Total | SE |
| Agriculture | 0.0 | 0.0 | 0.0 | 0.0 | 0.8 | 0.7 | 0.8 | 0.7 |
| Commercial | 0.1 | 0.1 | 2.2 | 1.4 | 0.7 | 0.3 | 2.9 | 1.4 |
| Transportation | 2.5 | 1.6 | 0.0 | 0.0 | 0.7 | 0.7 | 3.1 | 1.8 |
| Institutional (bldg.) | 1.2 | 1.0 | 0.0 | 0.0 | 1.7 | 1.1 | 3.0 | 1.5 |
| Multiresidential | 3.1 | 2.2 | 2.0 | 0.8 | 0.9 | 0.2 | 6.1 | 2.4 |
| Vacant | 4.4 | 1.6 | 13.5 | 5.9 | 21.3 | 6.6 | 39.2 | 9.0 |
| Institutional (veg.) | 10.7 | 2.2 | 94.4 | 12.4 | 17.9 | 3.4 | 123.0 | 12.8 |
| Residential | 18.2 | 2.7 | 74.4 | 8.0 | 45.1 | 6.3 | 137.7 | 10.5 |
| Total | 40.1 | 4.9 | 186.5 | 16.0 | 89.2 | 9.9 | 315.8 | 19.4 |

Table 7.—Average carbon stored (metric tons) per hectare of land in Oakland, CA, Chicago, suburban Cook County, and DuPage County; Oakland estimate is adjusted to meet same assumptions of biomass and carbon used in Chicago area estimates; land-use classes are combined to allow for equal comparison with Oakland estimates (Nowak 1993) (divide t/ha by 2.24 to convert to tons/acre)

| Land use | Oakland | Chicago | Cook County | DuPage County |
|---|---|---|---|---|
| Commercial | 0.6 | 0.0 | 0.3 | 1.0 |
| Transportation | 0.8 | 7.2 | 0.0 | 9.0 |
| Residential[a] | 10.4 | 17.2 | 21.6 | 24.4 |
| Institutional/Wildland[b] | 26.0 | 27.8 | 21.9 | 15.0 |
| All uses | 12.5 | 14.1 | 17.0 | 17.7 |

[a]Includes street trees that were categorized separately in Oakland.
[b]Wildlands, institutional and miscellaneous land uses, including agriculture.

for the Chicago area's urban forest include only carbon stored by trees and shrubs. Research is needed on carbon storage by soil, grass, and other components of the urban-forest ecosystem. Carbon storage by shrubs in the study area is approximately 4 percent of the amount stored by trees.

Estimates of carbon storage for the Chicago area differ from those for Oakland, California (Table 7). There are various factors that contribute to the differences observed among Oakland, Chicago, and Cook and DuPage Counties. One factor is the difference in land-use distribution among these areas. Oakland is relatively high in transportational land uses while Chicago is relatively high in commercial-industrial uses, and DuPage County is relatively high in agricultural use. As land-uses change, so does the amount of trees and associated tree biomass.

Land-use distribution affects overall tree density. Chicago had the lowest tree density with 68 trees/ha (28 trees/acre), followed by Oakland with 120 trees/ha (49 trees/acre), suburban Cook County with 169 trees/ha (68 trees/acre) and DuPage County with 173 trees/ha (70 trees/acre) (Table 3, Chapter 2). The greater the tree density, the more biomass that is stored per ha given an equal diameter distribution.

Other factors that greatly influence carbon storage are tree species and diameter distribution. Tree species will differ in growth characteristics, so estimates of carbon storage can vary among trees of the same diameter. Chicago had relatively more large trees than other urban areas: 7.5 percent of Chicago's trees were larger than 46 cm (18 inches) d.b.h. compared with 4.5 percent for Oakland, 4 percent for DuPage County, and 3.5 percent for suburban Cook County. Cook and DuPage Counties had relatively more small trees with 78.7 and 76.7 percent of the trees less than 15 cm (6 inches) d.b.h. respectively. This compares with 63.5 percent in Chicago and 60.9 percent for Oakland (Table 9, Chapter 2).

Carbon stored per ha of tree cover was highest in Chicago at 128 t/ha (57 tons/acre), followed by DuPage County at 95.0 t/ha (42 tons/acre), suburban Cook County at 75.5 t/ha (34 tons/acre), and Oakland at 59.6 t/ha (27 tons/acre). Both tree density per ha of tree cover and tree-diameter distribution affect estimates of carbon storage per ha of tree cover. DuPage County had the highest density per ha of tree cover at 927 (375 trees/acre), followed by Cook County at 752 (304 trees/acre), Chicago at 619 (250 trees/acre), and Oakland at 571 (231 trees/acre). The estimate for Chicago may be too high due to the probability of a conservative estimate of tree cover from aerial photographs. The large amount and size of buildings in Chicago obscure small trees, so tree cover likely is underestimated and the amount of carbon stored per ha of tree cover probably is overestimated.

U.S. forest ecosystems store approximately 52.5 billion t (57.9 billion tons) of carbon, with 31 percent in live trees (Birdsey 1990). This estimate converts to 55 t of carbon/ha (24.5 tons/acre) of land in live trees in U.S. forests — 3 to 4 times greater than storage estimates for urban forests. This live-tree forest estimate of 55 t/ha is less than urban forest carbon storage estimates per ha with 100 percent tree cover because the former estimate is not based on 100 percent

tree cover and the latter estimate includes dead trees (about 3 percent of total biomass). In the Chicago area, total carbon and residential carbon storage per ha appears to decrease with an increase in the density of urban development.

Carbon storage in urban forests nationally (28 percent tree cover) is estimated at 600 to 900 million t (660 to 990 million tons). This estimate falls at the upper end and beyond the estimated range (350 to 750 million t) of total carbon storage by U.S. urban forests (Nowak 1993).

## Carbon Sequestration by Urban Trees

Total carbon stored by trees in the study area (5.6 million t), which took years to store, equals the amount of carbon emitted from the residential sector (including transportation use) in the study area during a 5-month period.[1] Net annual sequestration for all trees in the study area (140,600 t of carbon) equals the amount of carbon emitted from transportation use in the study area in one week.[2] The amount of carbon sequestered annually by one tree less than 8 cm d.b.h. is equivalent to the amount of carbon emitted by driving one car 16 km (10 mi). Annual sequestration by one tree greater than 77 cm d.b.h. is equivalent to driving one car approximately 1,460 km (900 mi).[3]

Carbon storage by individual trees is as much as 1,000 times greater in large than small trees, with sequestration rates as much as 90 times greater for healthy large than healthy small trees. Thus, to maximize carbon storage and sequestration from urban trees, it is necessary to ensure the survival and vigor of large trees and establish small ones.

The net sequestration rate is highly sensitive to mortality as tree death ultimately leads to the release of $CO_2$. An annual mortality rate of 2.6 percent was assumed in the estimate of net sequestration. This mortality rate is relatively low compared to that for newly planted street trees (Nowak et al. 1990). However, there is limited information on urban tree mortality, particularly for larger trees and nonstreet trees. If actual annual mortality of urban trees exceeds approximately 5 percent in the Chicago area (with no replacement plantings), it is likely that the urban forest will be a source of atmospheric $CO_2$. There will be a delay in the emission of $CO_2$ depending on the method of tree disposal (e.g., burning facilitates early emissions of $CO_2$). Trees removed today will contribute to $CO_2$ levels in the future, just as trees removed in the past are contributing to concentrations of $CO_2$ today. The cycle of carbon emissions due to urban tree removal needs further investigation.

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[1] 2.24 t (2.47 tons) of carbon were emitted in 1991 from the residential sector (including transportation use) per capita in Illinois (Citizens Fund 1992). With 5.88 million people in the study area, an estimated 13.2 million t (14.5 million tons) of carbon are released annually from residences.

[2] 1.30 t (1.43 tons) of carbon were emitted on average in 1991 from all transportation uses per capita in Illinois (Citizens Fund 1992). With 5.88 million people in the study area, an estimated 7.6 million t (8.4 million tons) of carbon are released annually due to transportation use.

[3] 0.0636 kg of carbon emitted per vehicle km (0.226 lb/mi) (Citizens Fund 1992).

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Average diameter growth of urban trees in this study ranged from 0.78 to 1.02 cm/yr (0.31 to 0.40 in/yr), within the range of average growth rates for street trees in New Jersey (0.58 to 1.09 cm/yr; 0.23 to 0.43 inch/yr) (Fleming 1988) but higher than those for trees in New York's Central Park (0.36 to 0.86 cm/yr; 0.14 to 0.34 inch/yr) (deVries 1987). The rates also are higher than those for forest trees in Illinois, which average 0.38 cm/yr (0.15 inch/yr) (Smith and Shifley 1984). Thus, the net sequestration rate is likely liberal as trees in more closed-canopy positions have slower growth rates than those in this study.

### Energy Effects of Urban Trees

Estimated carbon emissions avoided annually due to energy conservation from existing trees throughout the study area total 11,400 t (12,600 tons). This amounts to about 8 percent of the net carbon sequestration rate. However, the heating energy conservation value (0.04 percent) likely is conservative as most of the sample buildings analyzed for energy use had a north-south orientation. Shading from trees on the south side of residences can increase winter heating use (Heisler 1986). If heating energy savings reached 3 percent (McPherson 1994: Chapter 7, this report), 113,600 t (125,200 tons) of carbon emissions would be avoided annually. More research is needed to evaluate the effect of existing tree configurations on residential energy use. Most studies to date have evaluated optimal tree configurations. A national average ratio of 4:1 carbon emissions avoided to carbon sequestered by urban trees has been estimated for optimal locations of urban trees (Nowak 1993). The actual ratio for existing urban tree configurations in the study area is probably much lower. Ratios can be higher in regions with little winter heating needs, but also can be negative in certain locations due to increased energy consumption from shading of homes in winter.

Avoided carbon emissions due to savings in air-conditioning energy use probably would be higher in other cities given the same energy savings as 83 percent of the study area's electricity is generated from nuclear sources.

### Maximizing $CO_2$ Reduction with Urban Trees

There are two primary strategies for maximizing the effect of urban trees on atmospheric $CO_2$. The first is to sustain or enhance existing tree health to maximize sequestration while minimizing losses due to tree mortality. The net effect of existing trees is relatively minimal. However, due to the large amount of carbon stored in trees, existing trees could become a source of $CO_2$ through increased tree mortality in conjunction with minimal replanting to offset tree losses. A loss of urban trees without replacement is a net source of carbon to the atmosphere both directly and indirectly (loss of energy conservation around buildings).

The second strategy is to establish more properly chosen and located urban trees in available planting spaces. Planting trees to maximize building energy conservation will yield the greatest relative carbon benefit. A reasonable tree-planting program in conjunction with efforts to sustain existing tree cover could increase carbon storage in the study area by another 1.2 million t (1.3 million tons). This additional storage, which will take years to accrue, is the amount of carbon emitted through transportation use in the study area in less than 2 months. Future tree plantings must survive to ensure that they act as carbon sinks and not sources, that is, trees must live long enough to compensate for the $CO_2$ emitted due to planting and maintenance. Research is needed to analyze the carbon budget of urban trees.

Because trees are only a short term reservoir of carbon, future planting structures must be sustained to ensure that newly treed areas remain long-term carbon sinks. Although the benefit of carbon sequestering by trees will eventually be lost and the trees will need to be replanted, $CO_2$ emissions avoided by properly located urban trees are avoided forever.

## Conclusion

Average carbon storage by trees in the Chicago area is between 14 and 18 t/ha (6 and 8 tons/acre), with more intensely urbanized areas having lower carbon storage. Estimates of carbon storage vary widely by land-use type and city depending on urban forest structure (e.g., species composition, tree density, diameter distribution). Estimates of carbon storage by urban forests nationally likely is between 400 and 900 million t (440 and 990 million tons). However, research is needed to refine this estimate and investigate urban forest characteristics and their influence on atmospheric $CO_2$. This research would include understanding variations in urban forests across the United States, carbon cycling and anthropogenic carbon emissions due to vegetation management, tree energy/carbon emission effects, and urban tree growth, mortality, and biomass. Although urban trees can help in reducing atmospheric $CO_2$, their effect is minimal relative to the magnitude of emissions in urban areas. The principal ways to decrease $CO_2$ emissions are increasing energy conservation and efficiency and converting to non-carbon or low-carbon fuels.

## Acknowledgments

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## Chapter 7
# Energy-Saving Potential of Trees in Chicago

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## Abstract

Parametric 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 in the City of Chicago. Prototypical buildings included one-, two-, and three-story brick buildings similar to residences in the Chicago area, 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 percent (corresponding to about three trees per building) could reduce total heating and cooling energy use by 5 to 10 percent ($50 to $90). On a per-tree basis, annual heating energy can be reduced by about 1.3 percent ($10, 2 MBtu), cooling energy by about 7 percent ($15, 125 kilowatt-hours), and peak cooling demand by about 6 percent (0.3 kilowatts). Simulation results were used in a 20-year economic analysis of costs and benefits associated with a hypothetical shade-tree program. Benefit-cost ratios of 1.35 for trees planted around typical two-story residential buildings and 1.90 for trees near energy-efficient wood-frame buildings indicate that a utility-sponsored shade-tree program could be cost-effective for both existing and new construction in Chicago.

## Introduction

This study provides information to utilities, policy makers, planners, urban foresters, arborists, and landscape professionals in the Chicago area on the potential impacts of trees on energy use for residential space conditioning. Based on results of computer simulations, the cost-effectiveness of tree planting for energy conservation around typical residential buildings is evaluated and landscape design guidelines are presented. These findings can be used to: 1) evaluate energy-efficient landscape design incentives for new and existing residential construction; 2) conduct a broader analysis of benefits and costs associated with tree planting and care; and 3) educate residents and landscape professionals regarding energy-efficient landscape design. Effects of tree shade, cooler summertime temperatures due to evapotranspirational (ET) cooling, and reduced windspeeds were simulated using Chicago weather data and two computer programs: the Shadow Pattern Simulator and Micropas 4.01. Energy savings were calculated for three brick buildings (one, two and three story) typical of residences in the City of Chicago and older suburban communities, as well as two wood-frame buildings (one

and two story) representative of housing products built in suburban Chicago. This study builds on previous simulations of potential energy savings from trees in Chicago (Akbari et al. 1988; Huang et al. 1990) by incorporating additional building types, a variety of tree sizes and locations, and ET cooling effects.

## Background

Chicago area residents spend about $660 million annually for natural gas to heat their homes, and $216 million for air conditioning (McPherson et al. 1993). Approximately 93 percent of all households use natural gas for space heating, 40 percent use electricity for central air conditioning, and 38 percent use electricity for room air conditioning (Bob Pendlebury, Peoples Gas, 1994, pers. commun.; Tom Hemminger, Commonwealth Edison, 1991, pers. commun.). Each year, the typical Chicago household with central air conditioning pays $755 for heating (151 million Btu or MBtu) and $216 for cooling (1,800 kilowatt-hours or kWh).

The need for summertime cooling is greatest in Chicago's most densely developed areas, where paving and buildings absorb and trap heat to create mini-heat islands. Air temperatures can be 5° to 10°F (2° to 6°C) warmer in these "hot spots" than in cooler park or rural areas (Landsberg 1981). A study of air temperatures measured at Midway Airport and rural Argonne National Laboratory found temperature differences between city and rural sites of 5.4°F (3°C) or more in August 20 percent of the time (Ackerman 1985). A substantial amount of air conditioning is required just to offset increased temperatures associated with localized heat islands (Akbari et al. 1992).

The potential of trees to mitigate urban heat islands and conserve heating and cooling energy has not been well documented in Chicago, but studies have been conducted in other cities with a similar climate (Akbari et al. 1992; Akbari and Taha 1992; McPherson and Rowntree 1993). Large numbers of trees and parks can reduce local air temperatures by 1° to 9°F(0.5° to 5°C), and the advection of this cool air can lessen the need for air conditioning. Results of computer simulations of three trees around an unshaded well-insulated house in Chicago showed that shade alone reduced annual and peak cooling energy use by 31 percent (583 kWh) and 21 percent (0.67 kW), respectively (Akbari et al. 1988). ET by trees lowers air temperatures and results in additional cooling energy savings. There is considerable uncertainty as to the magnitude of this ET cooling effect, but findings from several simulation studies suggest that it can produce savings greater than those from direct shade of buildings (Huang et al. 1987; McPherson and Rowntree 1993).

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Scattered trees throughout a neighborhood increase surface roughness, thereby reducing windspeeds by as much as 50 percent (Heisler 1990). Trees and shrubs located slightly upwind of buildings provide additional protection that reduces the amount of cold outside air that infiltrates. Lower windspeed results in reduced infiltration of outside air. Reduced infiltration is beneficial during both the heating and cooling seasons. However, lower windspeed is detrimental during the cooling season when natural ventilation can reduce reliance on air conditioning. Reduced infiltration from wind shielding by three trees around a well-insulated Chicago residence was simulated to reduce heating energy use by 16 percent (16.8 MBtu) or about $84 (Huang et al. 1990). In the same study, wind shielding reduced annual air-conditioning energy use by 9 kWh (0.03 GJ), suggesting that the benefit from reduced infiltration is slightly greater than the detrimental effect of lower windspeeds on natural ventilation. Other computer simulations and building energy measurements confirm that windbreaks can reduce annual heating costs by 10 to 30 percent (DeWalle et al. 1983, Heisler 1991). Proper placement and tree selection is critical in Chicago because winter shade on south-facing surfaces increases heating costs in mid- and high-latitude cities (Heisler 1986a; McPherson and Rowntree 1993; Sand and Huelman 1993; Thayer and Maeda 1985).

# Methods

## Building Energy Analysis

Micropas and the Shadow Pattern Simulator (SPS) were the two computer programs used to project the effects of trees on heating and cooling energy use (McPherson and Dougherty 1989; McPherson and Rowntree 1993; McPherson and Sacamano 1992). Micropas 4.01 provides hour-by-hour estimates of building energy use based on the building's thermal characteristics, occupant behavior, and specific weather data (Nittler and Novotny 1983). It is used widely by engineers, architects, and utilities to evaluate building energy performance. Micropas algorithms have been validated and found to agree closely with data from occupied houses and passive test cells (Atkinson et al. 1983). The California Energy Commission (1992) has certified Micropas for checking building compliance with state energy-efficiency standards.

In this study, Micropas simulations used Chicago weather data for each unshaded base case building. Two additional simulations use a modified weather file and adjusted shielding class to account for energy savings due to the reductions in air temperature and windspeed associated with trees. Information on how Micropas estimates solar heat gains, infiltration, natural ventilation, and internal heat gains is contained in the footnote to Table 1.

SPS quantifies the effects of each shading scenario on solar-heat gains (McPherson et al. 1985). SPS uses sun-plant-building geometry, tree size, shape, and crown density to compute hourly surface shading coefficients for the 21st day of each month. Micropas was modified to accept output from the SPS files to account for tree shade on each of eight possible building surfaces (four wall and four roof orienta-

tions). Micropas multiplies the hourly shading coefficients by direct and diffuse radiation values to reduce solar-heat gains on opaque and glazing surfaces.

Energy savings are calculated as the difference between the unshaded base case and results from each of the shading, ET cooling, and windspeed-reduction scenarios. Standardized reports in Appendixes C and D include the following information:

—Heating, cooling, and total annual energy use (kBtu/sf).
—Total annual electricity (kWh) use for air conditioning.
—Summer peak (kW) energy use for air conditioning.
—Total annual natural gas (MBtu) use for space heating.
—Hours of air conditioning use.

## Base Case Buildings

Energy simulations are applied to five base case buildings: three brick buildings typical of construction in Chicago and nearby communities, and two wood-frame buildings characteristic of suburban residential development. The brick buildings are one, two, and three stories and the wood-frame houses are one and two stories. Because Chicago streets are laid out in a grid pattern and building orientation influences energy use, brick buildings are modeled with their long walls facing north-south and east-west. This was not necessary for the wood-frame buildings because the window area is identical for all walls. The following characteristics of each base case building are detailed in Table 1.

1. One-story brick. One family and three occupants, 2,125 ft$^2$ (197 m$^2$) of floor area, constructed during 1950's with 8-inch (20-cm) brick walls (gypsum lath and plaster, plus 1-inch blanket insulation) (R-7), gypsum lath (3/8 inch) and plaster ceiling below an unheated attic with 6 inches (15 cm) of attic insulation (R-19), wood floor over enclosed unheated basement with 4 inches (10 cm) of insulation (R-4), double-hung, wood-sash, single-pane windows with storms, and moderately efficient heating and cooling equipment.

2. Two story brick. Two households and six occupants, 3,562 ft$^2$ (331 m$^2$) of floor area (1,781 ft$^2$ per household), constructed during the 1950's with materials and equipment similar to the one-story brick building.

3. Three story brick. Six households, 18 occupants, 6,048 ft$^2$ (562 m$^2$) of floor area (1,008 ft$^2$ per household), constructed during the 1930's with materials similar to those for the one- and two-story brick buildings, but no storm windows, loose construction, and relatively inefficient heating (e.g., boiler instead of furnace) and cooling equipment.

4. One-story wood frame. One household, three occupants, 1,500 ft$^2$ (139 m$^2$) of floor area, constructed during 1950's with 2 by 4-inch (5 by 10-cm) studs on 16-inch (40 cm) centers, hardboard siding, sheathing, and drywall (R-7), drywall ceiling below an unheated attic with 6 inches of attic insulation (R-19), wood floor over enclosed unheated basement with 4 inches of insulation (R-4), single-pane metal slider windows with storms, and moderately efficient heating and cooling equipment.

Table 1.—Base case building characteristics and Micropas simulation assumptions

| Building feature | 1 Story | 2 Story | 3 Story | 1 Story | 2 Story |
|---|---|---|---|---|---|
| Construction type | Brick | Brick | Brick | Wood | Wood |
| Date built | 1950-60 | 1950-60 | 1930 | 1950-60 | 1990 |
| No. units (occupants) | 1 (3) | 2 (6) | 6 (18) | 1 (3) | 1 (3) |
| Floor area (ft$^2$) | 2,125 | 3,562 | 6,048 | 1,500 | 1,761 |
| Volume (ft$^3$) | 19,125 | 33,858 | 54,432 | 12,500 | 15,588 |
| Front orientation | North (East) | South (East) | South (East) | South | West |
| Window area (ft$^2$) | | | | | |
| North | 79 (28) | 136 (105) | 90 (200) | 75 | 75 |
| East | 96 (79) | 105 (98) | 200 (200) | 75 | 75 |
| South | 67 (96) | 98 (214) | 200 (200) | 75 | 75 |
| West | 28 (67) | 214 (136) | 200 (90) | 75 | 75 |
| Total | 270 | 553 | 690 | 300 | 300 |
| floor area (%) | 12.7 | 15.5 | 11.4 | 20.0 | 17.0 |
| Window panes (No. and u-value) | 2, 0.60 | 2, 0.60 | 1, 0.88 | 1, 0.88 | 2, 0.44 |
| Window shading coef.[a] | | | | | |
| Glass only | 0.88 | 0.88 | 1.00 | 1.00 | 0.88 |
| Drapes or blinds | 0.78 | 0.78 | 0.78 | 0.78 | 0.78 |
| Duct insulation (R-value) | | | | | |
| Duct | 4.2 | 2.0 | 4.2 | 4.2 | 4.2 |
| CVCrawl | 4.2 | 4.2 | 4.2 | 4.2 | 4.2 |
| Wall insulation (R-value)[b] | 7 | 7 | 7 | 7 | 13 |
| Attic insulation (R-value)[b] | 19 | 19 | 19 | 19 | 30 |
| Crawlspace/basement | | | | | |
| Floor (R value) | 4 | 4 | 4 | 4 | 11 |
| Stem wall (R value) | 5 | 5 | 5 | 5 | 5 |
| Air exchange | | | | | |
| Ventilation (ach)[c] | 1.39 | 2.80 | 2.32 | 2.17 | 2.66 |
| Infiltration (ach)[d] | 0.58 | 0.62 | 0.75 | 0.67 | 0.48 |
| Local shielding class[d] | 3 | 3 | 3 | 3 | 3 |
| Latent heat fraction | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Glazing obstruction[a] | 0.7 | 0.75 | 0.75 | 0.75 | 0.75 |
| Wind correction factor[e] | 0.25 | 0.4 | 0.5 | 0.25 | 0.4 |
| Internal gain (Btu/day)[f] | 51,875 | 73,430 | 210,720 | 42,500 | 46,415 |
| Gas furnace efficiency | 0.6 | 0.58 | 0.5 | 0.7 | 0.78 |
| Air conditioner (SEER) | 7.8 | 6.7 | 6.5 | 7.5 | 10 |
| Thermostat settings | No setback | No setback | No setback | No setback | Setback |
| Summer cooling | 78 | 80 | 78 | 78 | 78 |
| Winter heating | 70 | 72 | 70 | 70 | 68 day, 60 night |

[a] Shading coefficients are fraction of irradiance transmitted. Micropas simulations assume drapes are drawn when air conditioning was on the previous hour. Glazing obstruction is a shading coefficient that applies at all times to all windows to approximate irradinace reductions from shade cast by nearby buildings and vegetation (Enercomp 1992).

[b] Solar absorptance of walls and roof assumed to be 0.5 corresponding to a medium gray color.

[c] Micropas simulations assume that the buildings are naturally cooled and ventilated by opening the windows whenever the outside temperature and windspeeds allow such natural cooling to occur. The average hourly ventialtion rate during summer (June-August) is shown as air changes per hour (ach).

[d] The hourly infiltration rate is simulated to vary with outdoor air temperature and windspeed and is calculated using estimates of the building's total effective leakage area (ASHRAE 1989). Local shielding classes are used to account for windspeed reductions associated with increased tree cover (see text). The average hourly infiltration rate during winter (November-April) is shown as air changes per hour (ach).

[e] The wind-reduction factor is a fraction of airport windspeed that accounts for windspeed differences between the building site and measurement instrument, which is typically 30 feet above the ground.

[f] Daily internal heat gains are assumed constant year round. Hourly gains are simulated using a research-based schedule (CEC 1992).

5. <u>Two-story wood frame</u>. One household, three occupants, 1,761 ft$^2$ (164 m$^2$) of floor area, constructed during 1990's with 2 by 4-inch (5 by 10-cm) studs on 16-inch (40 cm) centers, hardboard siding, sheathing, insulation, and drywall (R-13), drywall ceiling below an unheated attic with 6 inches of attic insulation (R-30), wood floor over enclosed unheated basement with 4 inches of insulation (R-11), double-pane metal slider windows with storms, and very efficient heating and cooling equipment.

## Calibration

To ensure that the energy performance of each base case building is reasonably similar to actual buildings in Chicago, building performance targets were established with data from real reference buildings. A close match between building performance of the base case building and its reference indicates that simulations produce realistic data on energy use. To achieve similitude, various input parameters for each base case building are adjusted in an iterative process. Comparisons of similitude are made using a Heating Performance Index (HPI) and Cooling Performance Index (CPI) that partially normalize for different weather conditions and building sizes (Mahajan et al. 1983). The HPI and CPI are calculated as:

$$HPI = Btu / HDD / FA \qquad CPI = Wh / CDD / FA$$

where Btu = British thermal units of natural gas consumed for space heating, Wh = watt-hours of electricity consumed for air conditioning, HDD = heating degree-days—(one HDD accumulates for every degree that the mean outside temperature is below 65°F (18.3°C) for a 24-hr period), CDD = cooling degree days—(one CDD accumulates for every degree that the mean outside temperature is above 65°F (18.3°C) for a 24-hr period) and FA = conditioned floor area (ft$^2$).

Indices for target building performance for the one-and two-story brick buildings were calculated using metered data from a sample of 18 residences in a two-block area in Chicago (Wilkin and Jo 1993). These buildings are part of another Chicago Urban Forest Climate Project study, and are representative of the brick bungalows and two-story houses that were built throughout Chicago soon after World War II. Data on monthly metered electricity and bimonthly natural gas, as well as data on heating and cooling degrees were obtained with the residents' approval from the local utilities for April 1991 through March 1993. Energy consumed for space heating (SH) and cooling (SC) for each bimonthly and monthly period was estimated by the base-load method (Linaweaver et al. 1967):

$$SH = TG - BLG \qquad SC = TE - BLE$$

where TG and TE are total metered gas and electric consumption, respectively, and BLG and BLE are base-load gas and electric consumption. BLG is defined as the lowest consumption of natural gas during the summer cooling season (May through September); BLE is defined as the lowest consumption of electricity during the winter heating season (October through April). Use of base loads to calculate SH and SC assumes that base-load consumption remains constant throughout the year. Base loads can vary monthly and seasonally (e.g., less electricity used for lighting during summer than winter due to shorter nights). Another limitation

to the base load method is that the use of degree-days may not fully normalize energy use for different weather conditions. For example, when there are high amounts of wind or irradiance, the temperature-based cooling degree-day approach becomes a less accurate indicator of heating and cooling energy use. Also, the assumption of constant base loads becomes increasingly less tenable as weather conditions deviate from normal (e.g., during very hot periods people may use less electricity for cooking). Annual HDD and CDD from 1991 to 1992 and from 1992 to 1993 indicate that while HDD for both periods are within 10 percent of the 30-year normal for Chicago, there are 56 percent more CDD than normal during the first year and 39 percent fewer than normal during the second year (Table 2). Although average annual HDD and CDD for the 2-year period (1991-93) are within 10 percent of normal, the extremely warm summer of 1991 and cool summer of 1992 are likely to reduce the reliability of estimates of air-conditioning energy use. Although these building performance indices provide only rough approximations of energy consumed for space heating and air conditioning, they serve as a basis for simulating effects of vegetation on building energy performance in Chicago.

Separate average monthly CPI's and HPI's for the 2 years were calculated for the one-and two-story brick buildings using data from the four one-story and 14 two-story reference buildings. Separate target CPI's and HPI's were established for the one-and two-story buildings using the mean values for each building type. The one and two story brick buildings with building performance indices closest to the overall mean were selected for use as the base case buildings in this study. To gather information for modeling energy use of these buildings, an informal energy audit was conducted by the Center for Neighborhood Technology and detailed building measurements were taken.

Because there are no three-story buildings in the sample of actual houses, building features and performance targets were based on results of numerous energy audits of three-story and four-story buildings conducted by the Center for Neighborhood Technology (John Katrakis 1993, pers. commun.).

To facilitate comparisons of potential energy savings from trees in Chicago with studies in other cities, the characteristics of the two wood-frame buildings used in this study are similar to those used in previous simulations (McPherson and Rowntree 1993). The base cases were calibrated so that their performance indices are similar to the target indices of reference buildings used in a previous simulation study for Chicago conducted by scientists at Lawrence Berkeley Laboratory (LBL) (Huang et al. 1990). LBL developed two wood-frame reference buildings, the "pre-1973 house" had little insulation and was not energy efficient, while the "1980's house" was highly efficient. The CPI and HPI of the LBL reference buildings served as targets for evaluating the energy performance of the two wood-frame base case buildings used in this study.

## Shading Scenarios

Two sets of shading scenarios account for different tree-building juxtapositions in Chicago and suburban areas. In Chicago, front yards and narrow side yards seldom have

Table 2.—Number of heating and cooling degree-days for Chicago

| Period | Heating degree-days | Cooling degree-days |
|---|---|---|
| April 1991 - March 1992 | 5,928 | 1,154 |
| April 1993 - March 1993 | 6,746 | 457 |
| Average annual (1991-93) | 6,337 | 806 |
| 30-year normal | 6,455 | 740 |

trees. Therefore, street trees located 20 to 35 ft (6 to 11 m) from the front of buildings are a major source of shade. In suburban areas, larger lots and wider side yards provide more opportunities for locating trees to optimize summer shade. This section describes one set of shading scenarios applied to the brick buildings typically found in Chicago, and a second set of scenarios applied to the wood-frame buildings often seen in suburban Chicago.

### Brick Buildings
Shading scenarios were developed to estimate the positive and negative impacts of shade from trees of different sizes, at different distances from the building, and at different aspects around the building. Tree heights of 24, 36, and 50 feet (7.3, 11.0, 15.3 m) roughly correspond with sizes of trees at 20, 30, and 45 years (Table 3). All trees are assumed to be deciduous, blocking 85 percent of total irradiance during summer (May-October) and 25 percent during winter (November-April). Tree crowns are assumed to have a paraboloid shape.

Trees are located at three distances from the building walls: 12, 22, and 34 feet (3.7,6.7,10.4 m). A distance of 12 feet usually is about as close to a building that a tree is placed. Distances of 22 and 34 feet correspond with potential locations of backyard and street trees. In Chicago, street trees are seldom farther than 34 feet from the front of buildings because of building setback and right-of-way configurations. Four shading scenarios account for these tree size and distance factors:

—One 24-foot-tall tree sequentially located 12 feet from the east, south, and west walls.
—One 36-foot-tall tree sequentially located 22 feet from the east, south, and west walls.
—One 50-foot-tall tree sequentially located 22 feet from the east, south, and west walls.
—One 50-foot-tall tree sequentially located 34 feet from the east, south, and west walls

To account for shade from trees located at different aspects around the building, the four scenarios listed are repeated for trees centered and opposite the east, south, and west walls of each brick building. These scenarios allow a comparison of cooling savings associated with trees opposite west- and east-facing walls, as well as of increased heating costs associated with reduced winter solar-heat gain from trees opposite south-facing walls. Fifteen shading scenarios are run for each base case building orientation. Because the orientation of each brick building is rotated 90 degrees

to account for dissimilar window distributions, 90 shading scenarios are simulated.

### Wood-Frame Buildings
Shading scenarios for the wood-frame buildings were developed to supply information to utilities interested in evaluating the cost-effectiveness of yard trees for demand-side management (DSM). Cost-effectiveness analysis for DSM options usually require's annual estimates of energy savings over a 20-year period (McPherson 1993). Shading scenarios should reflect near optimum tree placement for energy savings, i.e., if trees are not cost-effective in the best locations, they will not be cost-effective elsewhere.

To provide data for annual estimates of energy savings, shading scenarios occur at 5-year intervals for 20-years. Tree dimensions at years 5, 10, 15, and 20 are based on a typical growth curve for a deciduous tree assumed to be 6 feet (1.8 m) tall when planted (Table 3). The rate of growth reaches a maximum of 1.5 feet (0.5 m) per year several years after planting, then slows until a height and spread of 25 feet (7.6 m) is obtained 20 years after planting. Crown density, shape, and foliation periods are assumed to be the same as for trees shading the brick buildings (Table 3).

Computer simulation results suggest that in mid- and high-latitude cities like Chicago, tree shade on west walls is beneficial but detrimental on the south walls because increased heating costs outweigh cooling savings (Thayer and Maeda 1985; Heisler 1986a). Shade from trees to the east may increase heating, but net savings are likely due to substantial cooling benefits. Therefore, four shading scenarios were developed to assess potential energy savings from trees opposite east and west walls: one tree opposite the west wall; two trees opposite west wall; one tree opposite east wall; and three trees, two opposite the west wall and one the east wall.

Single trees are placed opposite the middle of the wall to maximize the area shaded. All trees are 12-feet from the walls (Figure 1).

### ET Cooling and Reduction in Windspeed
Reductions in windspeed and summertime air temperatures cannot be simulated as accurately as the effects of direct shade on buildings. The former reflect the aggregate effect of trees in the local area, which makes it difficult to isolate

Table 3.—Tree dimensions for shading scenarios in feet

| Building | Crown diameter | Bole height | Crown height | Tree height |
|---|---|---|---|---|
| Brick buildings | | | | |
| Small | 12 | 6 | 18 | 24 |
| Medium | 24 | 8 | 28 | 36 |
| Large | 36 | 12 | 38 | 50 |
| Wood buildings | | | | |
| Yr. 5 | 13 | 4 | 9 | 13 |
| Yr. 10 | 19 | 6 | 13 | 19 |
| Yr. 15 | 24 | 6 | 18 | 24 |
| Yr. 20 | 25 | 6 | 19 | 25 |
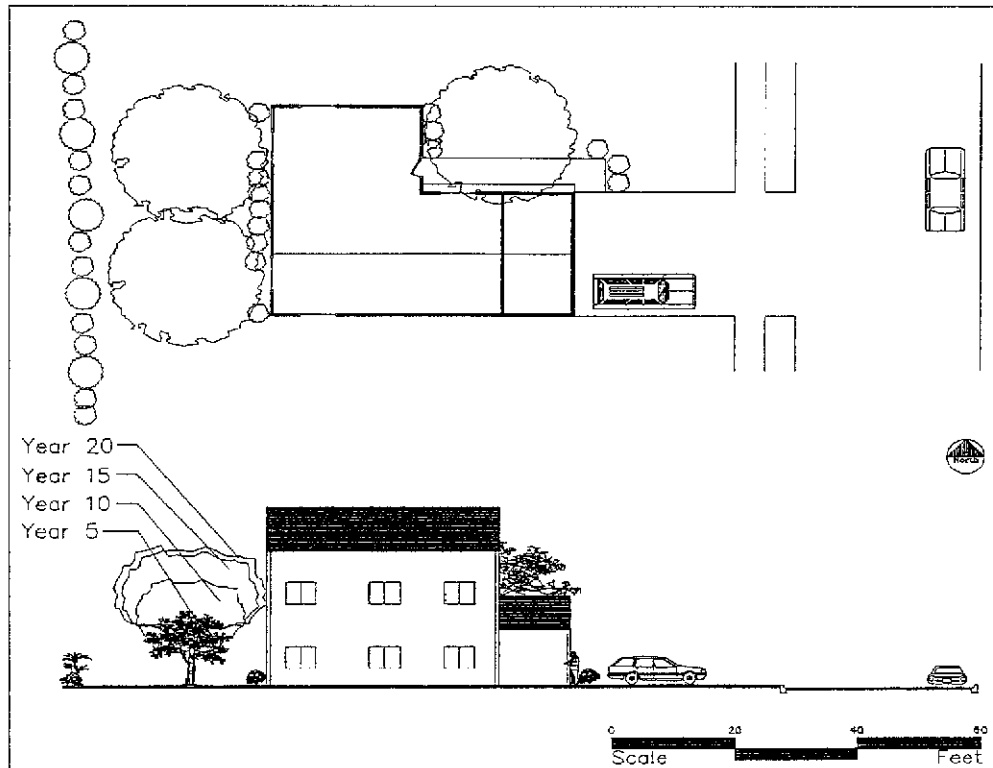


Figure 1.—Plan view and section showing simulated tree growth over the 20-year period for two trees opposite the west wall and one opposite the east wall of the two-story wood-frame base case building.

the role of any single tree. Yet, they are important because their effect can be substantial (Akbari et al. 1992; Huang et al. 1987; McPherson 1993). Further analysis of weather data collected at backyard locations throughout Chicago will reduce uncertainty about the relative impact of reductions in windspeed and summertime air temperature.

## Reductions in Air Temperature

The method used by Huang et al. (1987) was followed to ascribe cooling energy savings associated with modeled reductions in air temperature for individual trees. Assuming a typical lot size of 7,000 ft$^2$ (650 m$^2$), each tree (24-foot crown diameter) adds 7-percent tree cover to the lot (450 ft$^2$ per tree). Adding three trees around the residence increases tree cover by about 20 percent, but in reality the presence of other trees on or near the lot diminishes the marginal contribution of each new tree. Therefore, it is conservatively assumed that the simulated cooling savings associated with three trees is due to about half of the new tree cover they represent, or 10 percent.

To determine how a 10-percent increase in tree cover influences outside air temperatures in Chicago, limited data from local measurements, previous studies, and the literature were consulted. Measurements of air temperature taken between 12 noon and 5 p.m. during a summer day in Chicago were 1° to 2°F (0.5° to 1.0°C) cooler in a city block with 59-percent tree cover than in a nearby block with 36-percent tree cover (Wilkin and Jo 1993). A similar cooling effect was found in Bloomington, Indiana, where midday temperatures measured under the canopy of trees over grass were 1.3° to 2.3°F (0.7° to 1.3°C) cooler than at an open reference site (Souch and Souch 1993). Other findings (Huang et al. 1987; Profous 1992) suggest that there is a 1° to 2°F (0.5° to

1.0°C) decrease in temperature for every increase of 10-percent in vegetation cover. On the basis of these data, an empirical model was developed that reduced hourly summertime temperatures in a graduated manner to account for diurnal differences. Nighttime temperatures are altered the least because evapotranspiration is small, while mid-afternoon temperatures are reduced by as much as 1.8 percent (Figure 2). In all cases, winter temperatures are unaltered. Thus, a maximum hourly reduction in temperature of 2°F (1.1°C) is modeled that corresponds to what might be associated with an increase in local tree cover of about 10 percent.

## Reductions in Windspeed

Results from studies of wind reduction in residential neighborhoods suggest that a 10-percent increase in tree canopy cover is associated with a reduction in wind speed of 5 to 15 percent (Heisler 1990; Myrup et al. 1993). The magnitude of windspeed reduction associated with a 10-percent increase in tree cover is greater for neighborhoods with relatively low tree canopy cover than for areas with high tree cover.

Micropas uses local shielding classes to incorporate the effects of buildings and vegetation on air infiltration rates in houses. Reductions in windspeed of approximately 5 to 15 percent are simulated by modifying the building shielding class from 3 or moderate local shielding (some obstructions within two house heights, thick hedge, solid fence, or one neighboring house) to 4 or heavy shielding (obstructions around most of perimeter, buildings or trees within 30 feet in most directions; typical suburban shielding). Savings in heating energy associated with increased shielding are conservatively attributed to the aggregate effects of three trees on site or a 10-percent increase in local tree cover.
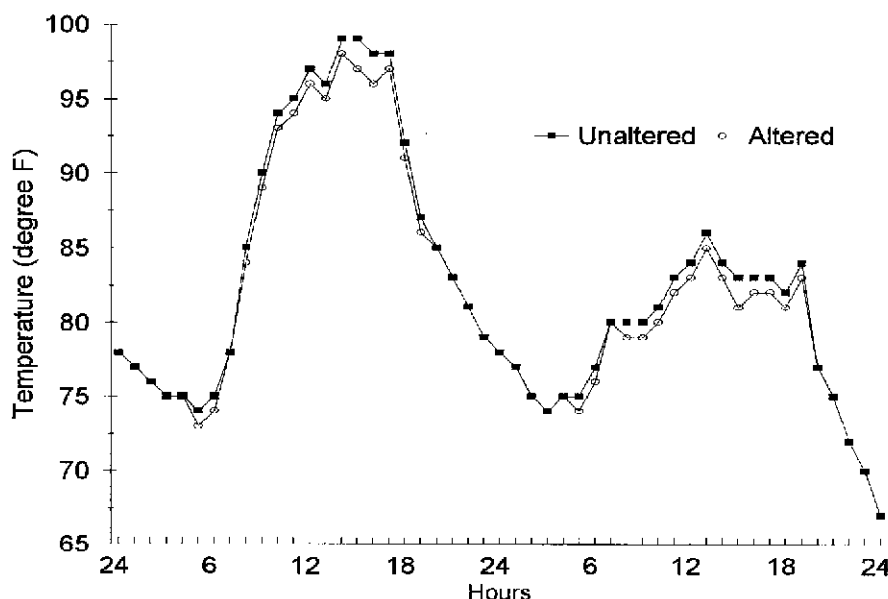


Figure 2.—Modeled outside air temperature reductions associated with a 10-percent increase in neighborhood tree-canopy cover are shown as the altered temperature curves for July 1 and 2. ( In the simulation model, 4 p.m. on July 1 is when peak air-conditioning energy demand occurs.)

## Micropass Simulations

Effects of air temperature and reductions in windspeed are simulated separately with Micropas. The combined savings due to direct and indirect effects of trees is calculated by adding the savings due to shade, ET cooling, and wind reductions. Simulations were run to determine if there were interactions among these three factors, but none were observed. The presence of tree shade had little effect on the indirect effects and indirect effects did not alter the impact of shade. Savings due to ET cooling and wind shielding are calculated on a per-tree basis as one-third of the savings attributed to a 10-percent increase in tree cover associated with the addition of three trees. Savings from shade cast by a tree on the west wall is added to the ET cooling and wind shielding savings to calculate total savings per tree.

# Results and Discussion

## Base Case Building Validation

To determine if simulated energy use is realistic the HPI's and CPI's of the base case buildings were compared with those of their respective reference buildings. The HPI's of the base case buildings are within 6 percent of their respective targets except for the two-story wood-frame building, which is less energy efficient than the LBL reference building (Table 4). Although less efficient than its reference, the two-story wood-frame base case consumes less than one-half the amount of natural gas used to heat a typical Chicago residence (151 MBtu). The CPI's of the base case buildings also are within 7 percent of their respective targets except for the one-story brick building, which is about 15 percent less energy efficient (Table 4). However, total electricity used to air condition this building is similar to that of typical Chicago households (1,800 kWh).

Relations among annual energy costs for heating and cooling each base case building are shown in Figure 3. Because

the two- and three-story brick buildings contain two and six households, respectively, costs for the typical Chicago household are multiplied by 2 and 6 as a basis for comparison with the base cases. Total costs for the one-story brick building are similar to those of the typical Chicago household ($971). Costs for the two-story brick buildings, each containing two dwelling units, are about $400 (20 percent) greater than the costs of a building containing two households with typical energy consumption for heating and cooling. Annual costs for the three-story base case containing six dwelling units are about $1,400 (24 percent) less than projected for six typical households. This result is not surprising because smaller households often use less energy than larger households and the average dwelling unit size in the six-unit base case is only 1,008 ft2 (94 m2). Energy costs for the poorly insulated one-story wood-frame building are $30 (3 percent) greater than for the typical household. Annual costs for the single-family, two-story wood-frame building are $390 (40 percent) less than the typical residence due to its insulative properties and tight construction.

## Effects of Tree Shade

Effects of tree shade on heating and cooling energy use vary with building type, building orientation, and tree type and location. Results from simulations using more than 100 shading scenarios provide a basis for examining relations among these variables.

### Building Type and Orientation

Street trees are a major source of building shade within Chicago (Nowak 1994: Chapter 2, this report). Therefore, relations among building type, building orientation, and energy savings are shown for a large street tree (50-feet-tall and 36-feet-wide) located 34 feet (10 m) from the east, south, and west walls of each brick-base case building (Figure 4). Because winter irradiance is primarily from the south, street trees to the south reduce solar-heat gain and increase

Table 4.—Targeted and base case building performance indices

| Item | One-story brick[a] | | Two-story brick[b] | | Three-story brick[c] | | One-story wood[d] | | Two-story wood[d] | |
|------|------|------|------|------|------|------|------|------|------|------|
| Heating | HPI[e] | MBtu | HPI | MBtu | HPI | MBtu | HPI | MBtu | HPI | MBtu |
| Target | 13.3 | | 17.2 | | 18.0 | | 14.2 | | 5.3 | |
| N-S facing | 13.3 | 173.4 | 17.6 | 385.1 | 19.1 | 711.7 | 14.0 | 129.7 | | |
| E-W facing | 13.0 | 170.1 | 17.1 | 375.5 | 19.2 | 715.6 | | | 6.6 | 71.5 |
| Cooling | CPI[e] | kWh | CPI | kWh | CPI | kWh | CPI | kWh | CPI | kWh |
| Target | 0.82 | | 1.06 | | 1.20 | | 1.71 | | 0.94 | |
| N-S facing | 0.92 | 1,795 | 1.12 | 3,682 | 1.29 | 7,199 | 1.75 | 2,941 | | |
| E-W facing | 0.98 | 1,928 | 1.13 | 3,725 | 1.25 | 6,970 | | | 0.94 | 1,853 |

[a] Targets based on whole-house metered data for four Chicago residences.
[b] Targets based on whole-house metered data for 14 Chicago residences.
[c] Targets based on energy audit results from the Center for Neighborhood Technology.
[d] Targets based on performance of similar Chicago buildings in Huang et al. 1990.
[e] Units for HPI and CPI are: Btu/heating degree-day/ft$^2$ conditioned floor area and Wh/cooling degree-day/ft$^2$ conditioned floor area.
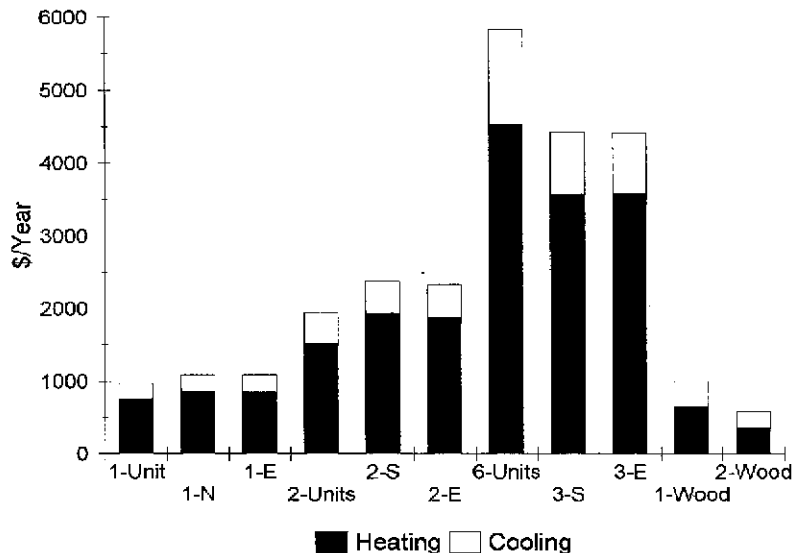
Figure 3.—Simulated annual heating and cooling costs are shown for each base case building, where the number corresponds to the number of stories and the letter corresponds to the brick building's front orientation (e.g., 1-N is one-story brick building facing north, 1-Wood is the one-story wood-frame base case). For comparison, average costs per Chicago household have been extrapolated for buildings with one, two, and six dwelling units.

heating costs (Figure 4a). Street trees usually are too far from the building to block much summer irradiance, so cooling savings do not offset increased heating costs (Figure 4b). Trees to the south are projected to increase total annual heating and cooling costs by $5 to $13 compared to unshaded base cases. These results suggest selecting trees with open crowns during the leaf-off period and/or species that drop their leaves relatively early during the fall and leaf out in late spring. These traits minimize the obstruction of irradiance during the heating season. Tree species identified as "solar friendly" and well adapted to growing conditions in the Chicago area are listed in Appendix B. Information in Appendix B was adapted from Watson (1991) and Ames (1987). It should be noted that energy penalties from trees south of buildings can be offset to some extent by other energy benefits such as shading of streets, ET cooling, and wind shielding.

Annual energy savings from a large street tree to the east range from $7 to $13, while savings from a tree to the west range from $5 to $26 (Figure 4a). Differences in savings among buildings are largely due to differences in the relative amount of window area shaded by the tree. For example, energy savings from a tree to the east of the one-story brick building facing north are more than twice that from a tree to the west, but the building has 96 ft2 (8.9 m2) of window area facing east and only 28 ft2 (2.6 m2) facing west. When the building is rotated 90 degrees (facing east), 79 ft2 (7.3 m2) of window area face east and 67 ft2 (6.2 m2) face west. Given this comparable distribution of window area, the savings from a tree to the east and west are nearly equal. Similarly, when the three-story building is rotated to face east, the

west-facing window area decreases from 200 to 90 ft2 (19 to 8 m2) and savings from a west tree drops from $21 to $14.

When only the beneficial aspects of shade on annual air-conditioning energy use are considered, a large street tree to the east or west provides savings of 2 to 8 percent in total cooling energy use (Figure 4b). Cooling savings are greatest (6 to 8 percent) for a tree to the east of the one-story brick buildings and west of the two-story building facing south. A tree opposite the three-story building provides the least cooling savings on a percentage basis, but the most savings on an absolute basis (kWh) due to overall building size.

Air-conditioning energy use at the building peak (4 p.m., July 1) is not influenced by shade from trees to the east and south. A large tree to the west reduces peak cooling energy demand by 2 to 6 percent (Figure 4c). Savings are greatest for buildings with relatively large amounts of west-facing window area.

## Tree Size and Distance from Building
Energy savings are related to the amount of window and wall area that a tree shades. Generally, larger trees produce more building shade than smaller trees in the same location. Also, the closer a tree is to a building the more wall area it shades. Using the two-story brick building facing south as an example, shade from the 50-foot-tall tree (large) located 22 feet from the building walls produces greater total annual energy savings than the other shading scenarios (Figure 5). Savings are about 40 percent less for the same size tree located 34 feet away from the buildings, the typical distance of a street tree in Chicago. The 36-foot-tall tree (medium)

Chapter 7

**4a**

$/Year Saved (y-axis: -20 to 30)

x-axis: 1-North, 1-East, 2-South, 2-East, 3-South, 3-East
Brick Buildings

▨ Tree to East  ☐ Tree to South  ■ Tree to West

**4b**

Percent kWh (y-axis: 0 to 8)

x-axis: 1-North, 1-East, 2-South, 2-East, 3-South, 3-East
Brick Buildings

**4c**

Percent kW (y-axis: 0 to 7)

x-axis: 1-North, 1-East, 2-South, 2-East, 3-South, 3-East
Brick Buildings
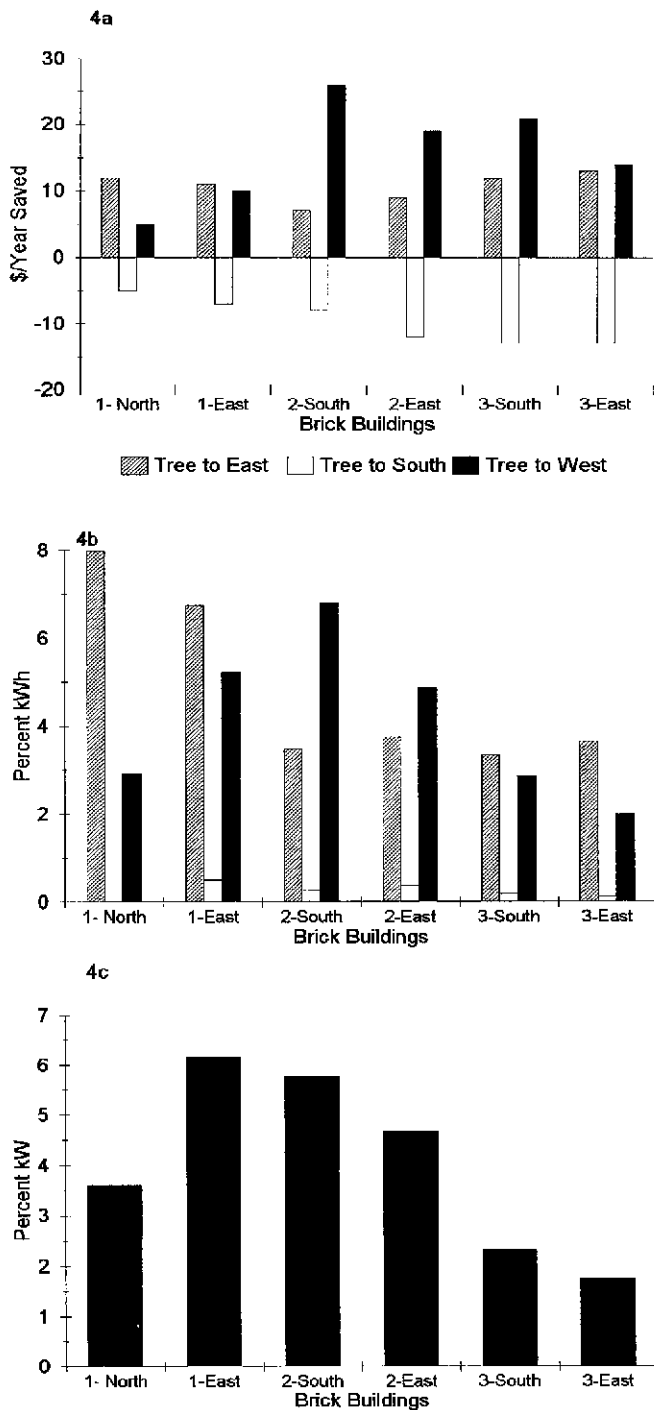
Figure 4.—Annual savings in space conditioning savings due to shade from a single deciduous tree (50 feet tall and 36 feet wide) located 34 feet from each brick building. The shading scenario is representative of a mature street tree in Chicago. Figures 4b and 4c show the simulated effects of tree shade as percentages of annual and peak air-conditioning savings.

located 22 feet from the building produces about one-third the savings as the 50-foot tree at the same location. Savings from the 24-foot tree (small) located 12 feet away from the west wall are about half the savings produced by the 36-foot tree at 22 feet. The 24-foot tree opposite the east wall produces no net savings because cooling savings are offset by increased heating costs due to winter shading. These relations between energy savings and tree size and distance are consistent across building types.

Annual cooling savings divided by heating costs produces a ratio with a value greater than 1.0 when savings from tree shade exceed costs. Ratios for trees to the south are less than 1.0 for all size-distance combinations (Figure 6). Ratios for trees to the east range from 1.0 to 2.2, while ratios for trees to the west range from 4.5 to 7.5. Lower ratios for trees to the east are due to shade during the spring-fall transition months when large amounts of irradiance strike the east wall, but nighttime temperatures are cool and heating is required. Early morning shade extends the hours of heating demand, whereas shade in the late afternoon from a tree to the west may be beneficial because air has warmed and cooling is needed. These data suggest that for similar buildings in Chicago, a tree located to the west provides about 2 to 4 times greater net energy savings than a similar tree located to the east. The use of solar friendly trees to the east can increase their cooling-heating ratio and net energy savings produced.

### Tree Growth

Tree growth influences the amount of wall area shaded and resulting cooling and heating energy savings. In shading scenarios for the wood-frame buildings, wall area shaded increases with tree age. As expected, the incremental increase in energy savings follows the incremental increase in crown size and area of wall surface that is shaded (Figure 7a). For all shading scenarios, savings increase most from years 5 to 15 when crown diameters increase from 13 feet at year 5 to 19 feet at year 10 to 24 feet at year 15. The marginal savings from years 15 to 20 result from a small increase in tree growth (24 to 25 feet) and area shaded. Thus, growth rate has a direct influence on the rate of return on investment provided that tree shape and location are such that increased size results in greater building shade.

Annual heating and cooling energy savings from the 25-foot-tall tree on the west are $20 and $13 for the one- and two-story buildings, respectively. Marginal savings from the second 25-foot tree on the west are $14 and $7, respectively. Hence, marginal savings per tree diminish by about 30 to 50 percent for the second tree opposite the west wall compared to savings from the first tree (Figure 7a). Adding the second tree results in more overall shade, but each tree is less efficient because it shades more nonbuilding surface than when centered opposite the wall as a single tree. Energy savings from the 25-foot tree opposite the east wall are $16 and $9 for the one- and two-story buildings, respectively, or 20 to 30 percent less than savings from the same tree to the west.

Smaller absolute savings from tree shade are noted for the energy-efficient two-story building than the inefficient one-story base case. The former consumes 42 percent less

energy each year for space heating and cooling, and receives 30 to 45 less energy savings from shade. Despite differences in energy consumption and absolute savings between the two building types, savings in air-conditioning energy as a percentage are similar (Figure 7b). Single 25-foot trees to the west and east reduce annual cooling energy use by about 7 and 5 percent, respectively. Two trees on the west lower annual air-conditioning energy use by about 11 percent. Electricity savings for peak cooling also are similar for the two buildings, though the savings are about double those noted for annual cooling (Figure 7c). Analogous per-centage cooling savings for the two wood-frame buildings are not surprising since they have similar ratios of window area to floor area, and window area is distributed equally on each wall (Table 1).

### Maximum Air-Conditioning Energy-Savings

If trees are not cost-effective when they are located optimally and near mature size, they will not be cost-effective when smaller and in less optimal sites. The maximum savings in air-conditioning due to shade from a single tree is listed in Table 5 for each base case building. Maximum savings for
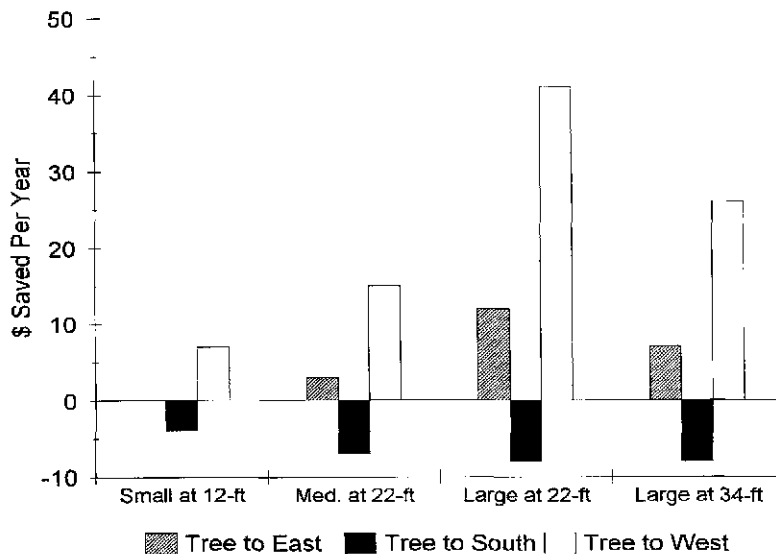


Figure 5.—Effects of shade from trees of different size and location on annual energy savings are for two-story brick building facing south.
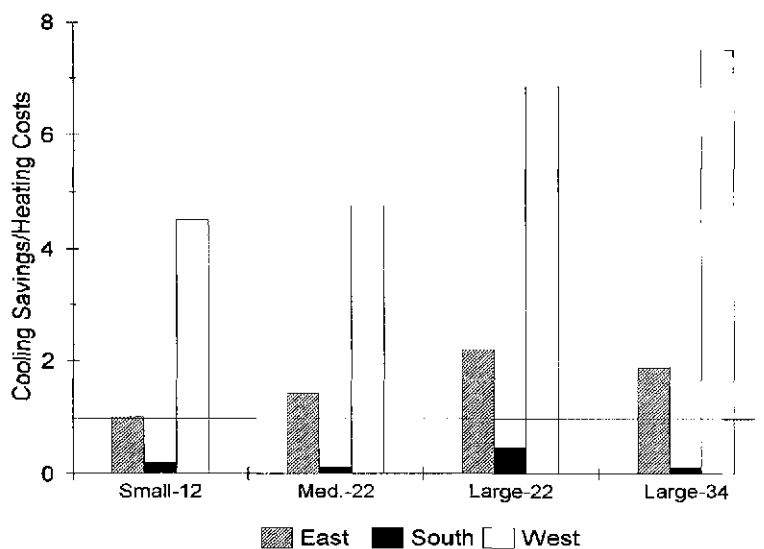


Figure 6.—Ratios depict net impact of energy penalties from tree shade during winter and savings from shade during summer on annual heating and cooling energy costs for two-story brick building facing south.

7a

7b

7c

▨ Yr. 5 (13 ft)  ■ Yr. 10 (19 ft) ☰ Yr. 15 (24 ft) ☐ Yr. 20 (25 ft)
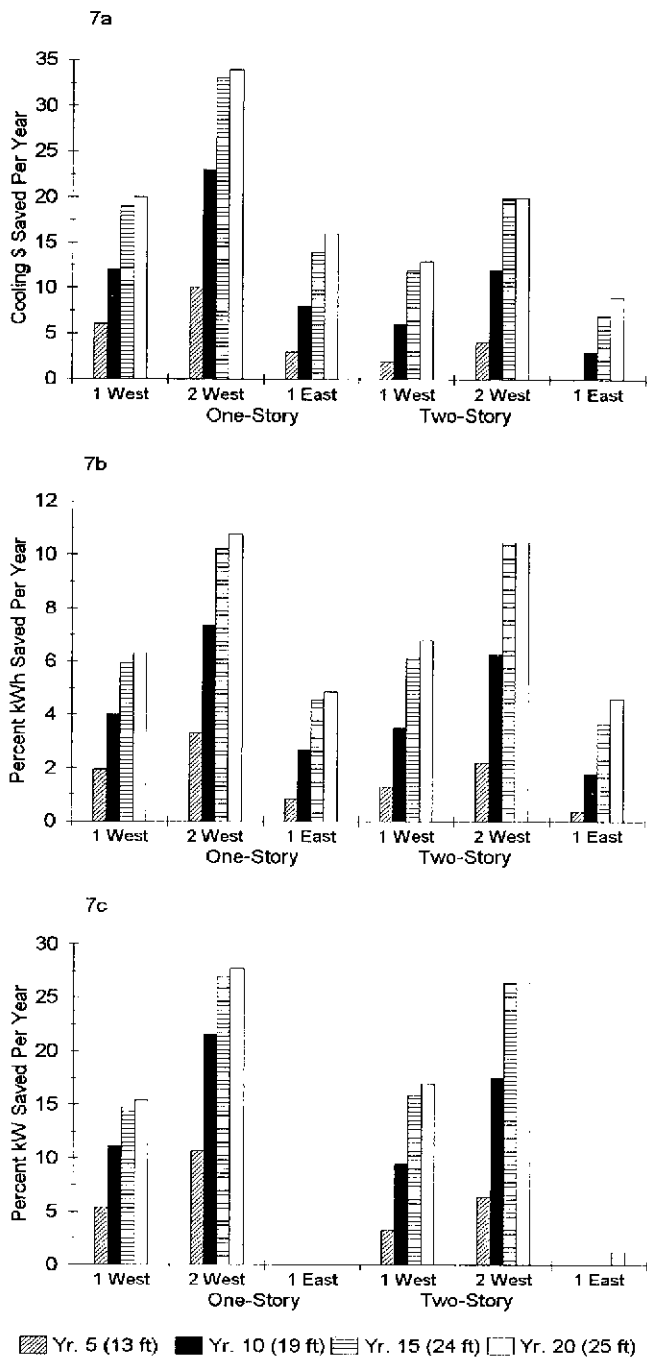
Figure 7.—Annual savings in space conditioning savings due to shade from deciduous trees (25 feet tall and 25 feet wide) located 12 feet from one- and two-story wood-frame buildings. Shading scenarios are one tree to the west, one tree to the east, and two trees to the west. Figures 7b and 7c show the simulated effects of tree shade as percentages of annual and peak air-conditioning savings.

the brick buildings resulted from a large tree (50 feet and 36 feet wide) located 22 feet from the west wall, while a 25-foot tree located 12 feet from the west wall produced maximum savings for the wood-frame buildings.

Annual savings in air-conditioning energy range from 126 to 399 kWh (0.45 to 1.43 gigajoules, GJ) per tree ($15 to $49). Absolute savings are greatest for the two- and three-story buildings. However, percentage savings, which range from 3 to 11, are least for the three-story buildings, probably because a relatively large amount of the wall area is unshaded by the single tree. Peak cooling savings range from 0.3 to 1.3 kW per tree (4 to 17 percent). Percentage peak cooling savings vary among building types, increasing in buildings with relatively large amounts of west-facing glass and high ratios of window to floor area. Solar-heat gain through windows accounts for the greatest proportion of heat gain in all buildings, but is especially important in the wood-frame and two-story brick buildings, which have ratios of window to floor area ranging from 16 to 20 percent (Table 1). Since solar gain has a strong influence on the demand for peak cooling, tree shade on the buildings with large amounts of west-facing glass results in a relatively greater percentage savings in peak cooling energy than was observed for the other buildings.

## Effects of Air Temperature and Reductions in Wind Speed

Cooler summertime (outside) air temperatures due to ET cooling and lower windspeeds associated with increased surface roughness produced by trees are simulated assuming effects associated with a 10-percent increase in neighborhood tree-canopy cover. The savings from these indirect effects plus shade produced by a 25-foot wide tree opposite the west wall are shown on a per-tree basis in Figures 8a-c and Table 6.

Annual heating savings per tree from wind shielding range from $5 (0.96 MBtu, 1.3 percent) for the well-insulated wood frame-building to $52 (10.3 MBtu, 1.5 percent) for the loosely constructed three-story brick buildings (Figure 8a). Although savings in heating energy vary little on a percentage basis per tree, absolute savings increase with size of the brick building (Table 6). Annual savings in space heating due to wind shielding increase from $13 (2.5 MBtu) to $26 (5.1 MBtu) to $52 (10.3 MBtu) per tree for the one-, two-, and three-story buildings, respectively. Shade on the west wall results in a small penalty in heating energy (up to 0.7 MBtu or $3.50), there is virtually no savings or penalty from ET cooling during the heating season.

Annual cooling savings per tree from wind shielding range from $1 (5 kWh, 0.3 percent) for the wood-frame building to $3 (29 kWh, 0.4 percent) for the three-story brick buildings (Figure 8b). Given the building characteristics and modeling assumptions used here, this result confirms that cooling savings due to reduced infiltration in summer can offset increased reliance on mechanical cooling due to lower windspeeds and reduced natural ventilation.

Table 5.—Per-tree maximum annual savings in air-conditioning (AC) from tree shade[a]

| Base case buildings | Base case AC | | | AC saved | | | Peak AC saved | |
|---|---|---|---|---|---|---|---|---|
| | kWh | $ | Peak kW | kWh | % | $ | kW | % |
| 1-story brick north facing | 1,795 | 215 | 4.2 | 187 | 10.4 | 22.85 | 0.3 | 6.2 |
| 1-story brick east facing | 1,928 | 231 | 4.5 | 149 | 7.7 | 18.21 | 0.5 | 10.5 |
| 2-story brick south facing | 3,682 | 442 | 10.6 | 399 | 10.8 | 48.76 | 1.3 | 12.3 |
| 2-story brick east facing | 3,725 | 447 | 10.1 | 297 | 8.0 | 36.29 | 1.0 | 9.7 |
| 3-story brick south facing | 7,199 | 864 | 16.7 | 345 | 4.8 | 42.16 | 1.0 | 5.8 |
| 3-story brick east facing | 6,970 | 836 | 16.1 | 245 | 3.5 | 29.94 | 0.7 | 4.4 |
| 1-story wood poorly insulated | 2,941 | 353 | 7.4 | 187 | 6.4 | 22.85 | 1.1 | 15.5 |
| 2-story wood well insulated | 1,858 | 223 | 5.1 | 126 | 6.8 | 15.40 | 0.9 | 17.1 |

[a] Savings for brick buildings due to shade from one 50-foot-tall and 36-foot-wide tree at 22 feet from the west wall and savings for wood-frame buildings due to shade from one 25-foot-tall and 25-foot-wide tree at 12 feet from the west wall.

Table 6.—Per-tree annual savings in heating and cooling energy from shade, ET cooling and reductions in windspeed[a]

| Base case buildings | Heating | | Cooling | | Total | | Peak Cooling | |
|---|---|---|---|---|---|---|---|---|
| | MBtu | % | kWh | % | $ | % | kW | % |
| 1-story brick east base case | 170.1 | | 1928 | | 1082 | | 4.49 | |
| Shade | -0.33 | -0.2% | 74 | 3.8% | 7.23 | 0.7% | 0.2 | 4.5% |
| ET cooling | 0 | 0.0% | 46 | 2.4% | 5.57 | 0.5% | 0.08 | 1.8% |
| Wind-shield | 2.54 | 1.5% | 7 | 0.4% | 13.47 | 1.2% | 0.03 | 0.7% |
| Total | 2.21 | 1.3% | 127 | 6.6% | 26.27 | 2.4% | 0.31 | 6.9% |
| 2-story brick south base case | 385.1 | | 3682 | | 2367 | | 10.60 | |
| Shade | -0.71 | -0.2% | 160 | 4.3% | 15.69 | 0.7% | 0.39 | 3.7% |
| ET cooling | 0 | 0.0% | 94 | 2.6% | 11.26 | 0.5% | 0.19 | 1.8% |
| Wind-shield | 5.13 | 1.3% | 12 | 0.3% | 27.03 | 1.1% | 0.06 | 0.6% |
| Total | 4.42 | 1.1% | 266 | 7.2% | 53.98 | 2.3% | 0.64 | 6.0% |
| 3-story brick south base case | 711.7 | | 7199 | | 4422 | | 16.69 | |
| Shade | -0.68 | -0.1% | 122 | 1.7% | 11.2 | 0.3% | 0.25 | 1.5% |
| ET cooling | 0 | 0.0% | 168 | 2.3% | 20.09 | 0.5% | 0.33 | 2.0% |
| Wind-shield | 10.34 | 1.5% | 29 | 0.4% | 55.2 | 1.2% | 0.11 | 0.7% |
| Total | 9.66 | 1.4% | 319 | 4.4% | 86.49 | 2.0% | 0.69 | 4.1% |
| 1-story wood base case | 129.7 | | 2941 | | 1002 | | 7.43 | |
| Shade | -0.48 | -0.4% | 186 | 6.3% | 19.94 | 2.0% | 1.15 | 15.5% |
| ET cooling | 0 | 0.0% | 57 | 1.9% | 6.72 | 0.7% | 0.69 | 9.3% |
| Wind-shield | 1.61 | 1.2% | 6 | 0.2% | 8.8 | 0.9% | 0.02 | 0.3% |
| Total | 1.13 | 0.9% | 249 | 8.5% | 35.46 | 3.5% | 1.86 | 25.0% |
| 2-story wood base case | 71.5 | | 1858 | | 581 | | 5.10 | |
| Shade | -0.46 | -0.6% | 126 | 6.8% | 12.88 | 2.2% | 0.87 | 17.1% |
| ET cooling | 0 | 0.0% | 39 | 2.1% | 4.54 | 0.8% | 0.05 | 1.0% |
| Wind-shield | 0.96 | 1.3% | 5 | 0.3% | 5.36 | 0.9% | 0.01 | 0.2% |
| Total | 0.5 | 0.7% | 170 | 9.1% | 22.78 | 3.9% | 0.93 | 18.2% |

[a] ET cooling and wind-shielding effects correspond to lower air temperatures and windspeeds associated with a 10-percent increase in neighborhood tree canopy cover.

Figure 8.—Annual savings in heating (a), cooling (b), and total (c) space conditioning due to shade, ET cooling, and reductions in windspeed on a per tree basis. Shading savings are from a deciduous tree opposite the west wall of each base case building. Reductions in ET cooling and windspeed are assumed to be associated with a 10-percent increase in overall neighborhood tree-canopy cover.
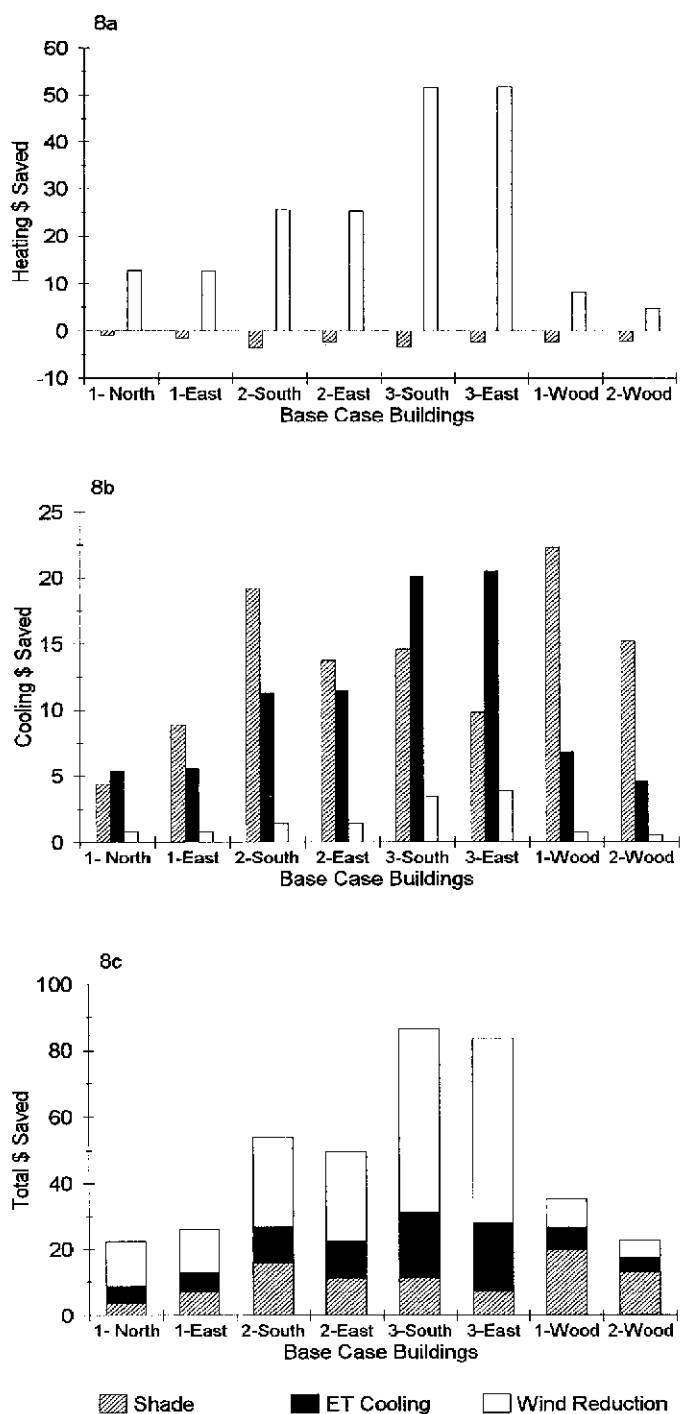
The relative magnitudes of cooling savings from shade and ET cooling vary with building type and orientation. Annual savings from shade range from $4 (37 kWh, 2 percent) per tree for the one-story brick building facing north to $22 (186 kWh, 6.3 percent) per tree for the one-story wood-frame building (Table 6). Annual savings in air-conditioning attributed to shade are 2 to 3 times greater than savings from ET cooling for buildings with large amounts of solar-heat gain through west-facing windows (i.e., wood-frame houses and two-story brick building facing south). This trend is more pronounced for savings in peak air-conditioning due in part to the influence of solar-heat gain on peak demand in late afternoon (Table 6). Annual savings in ET cooling range from $5 (39 kWh, 2.1 percent) per tree for the two-story wood-frame building to $20 (168 kWh, 2.3 percent) per tree for the three-story brick building.

Total annual savings in heating and cooling energy range from 2 to 4 percent of total heating and cooling costs, or $20 to $35 per tree for the single-family detached homes, about $50 per tree for the two-story brick buildings, and $85 per tree for the three-story brick buildings (Figure 8c). Savings due to indirect effects are considerably greater than from direct shade for the brick buildings. Indirect effects account for 70 to 90 percent ($19 to $75 per tree) of total energy savings for the brick buildings, and about 45 percent ($10 to $16 per tree) of the savings for wood-frame buildings (Table 6). This finding is in general agreement with results of other simulation studies, but differences in percentage savings attributed to each indirect effect reflect the uncertainty associated with modeling these complex meteorological processes. For example, simulation results from this study, as well as for residences in Minneapolis (Sand and Huelman 1993) and Toronto (Akbari and Taha 1992), estimate an annual heating savings from wind shielding of 1 to 1.5 percent per tree. Simulated heating savings per tree from wind shielding for a well-insulated building in Chicago was 7 percent in another study (Huang et al 1990). On a per tree basis, simulated annual ET cooling savings ranged from 7 to 8 percent for buildings in Toronto (Akabari and Taha 1992) and Minneapolis (McPherson and Rowntree 1993), but are estimated as about 3 percent in this study. Thus, indirect savings are lower end estimates compared to those from several other studies.

Simulation results suggest that in Chicago, the amount and type of energy savings associated with trees are sensitive to building characteristics. On a percentage basis per tree, total dollar savings in heating and cooling are greatest for the energy-efficient, two-story wood-frame building ($23, 4 percent). This indicates that shade trees could be cost-effective as an energy conservation measure associated with new home construction. Also, it is important to reiterate that the magnitude of annual and peak cooling savings, as well as heating costs associated with direct shading by trees, depends largely on the relative area and orientation of windows that are shaded. In absolute dollar savings, substantial savings ($75 per tree) for the three story brick buildings is attributed to ET cooling and wind shielding because trees reduce heat exchange by conduction and infiltration, the primary heat transfer pathways in these large, old buildings. Savings in heating energy from wind protection is especially large because of the buildings' relatively loose construction,

high rates of air infiltration, and inefficient heating equipment (Table 1). This means that trees in Chicago not only can mitigate summer heat islands but also provide sizable annual savings in heating energy, especially for older buildings in areas where tree cover is relatively sparse. Since nearly every household in Chicago is heated with natural gas, substantial heating savings could result from neighborhood tree plantings that increase tree cover by 10 percent or more.

## Effect of Trees on Peak Demand

Trees can help defer the construction of new electric generating facilities by reducing the peak demand for building air conditioning and shifting the hour of building peak to reduce the total system peak. Commonwealth Edison is a summer peaking utility, with electricity demand usually greatest in July or August. In 1992, peak demand for electricity occurred on July 22 (Claire Saddler, Marketing, Commonwealth Edison, 1993, pers. commun.). Electricity demand by residential customers peaked from 6 to 7 p.m. (7.64 GW), while the total system peak occurred at 4 p.m. (17.73 GW) (Figure 9). Midday peaking by commercial and industrial users shifted the system peak from late to mid-afternoon.

The simulated peak demand for air conditioning for the two-story brick building is 10 to 11 kW between 3 and 5 p.m. Direct shading and indirect effects associated with a 10 percent increase in cover reduce the peak demand by 2 kW (19 percent) at 5 p.m. The effect of trees is to shave the peak between 4 and 6 p.m. and to shift the building peak from 5 to 3 p.m., or 1 hour before the system peak. A similar peak savings is noted for the two-story wood-frame base case. Trees reduce the peak by 1 kW (20 percent) at 5 p.m., but the time of building peak remains 5 p.m. The brick building's

responsiveness to tree shade and dry-bulb temperature depression between 4 and 6 p.m. is largely due to its relatively large amount of west-facing window area (25 percent of net wall area) and low amount of insulation compared to the wood-frame building.

## Cost-Effectiveness of Shade Trees in Chicago

Utilities apply economic analyses to determine if conservation measures such as shade trees can meet their need for clean and efficient power as cost-effectively as other supply-side and demand-side options. Tree planting and care programs sponsored by electric utilities in Washington, D.C., Minnesota, Iowa, Arizona, and California suggest that shade-tree programs can be cost-effective in certain markets. Simulation results for Chicago indicate that trees near residential buildings can produce substantial energy savings if selected and located judiciously. Although an exhaustive accounting of all benefits and costs associated with a utility-sponsored shade tree program in Chicago is beyond the scope of this study, an initial analysis is undertaken.

### Assumptions

This simplified analysis accounts for selected costs and benefits over 20 years associated with the planting and 3-year follow-up care of "typical" trees near two "typical" buildings. The annual stream of benefits is derived from energy savings previously modeled around the two-story brick building (south-facing) and the energy-efficient two-story wood-frame building. It is assumed that the annual savings for the 20-year-old tree are 266 kWh (0.96 GJ) and 0.64 kW for the brick building and 169 kWh (0.61) and 0.93 kW for the wood building. The energy-savings pattern is linked to tree growth using an S-shaped growth curve for
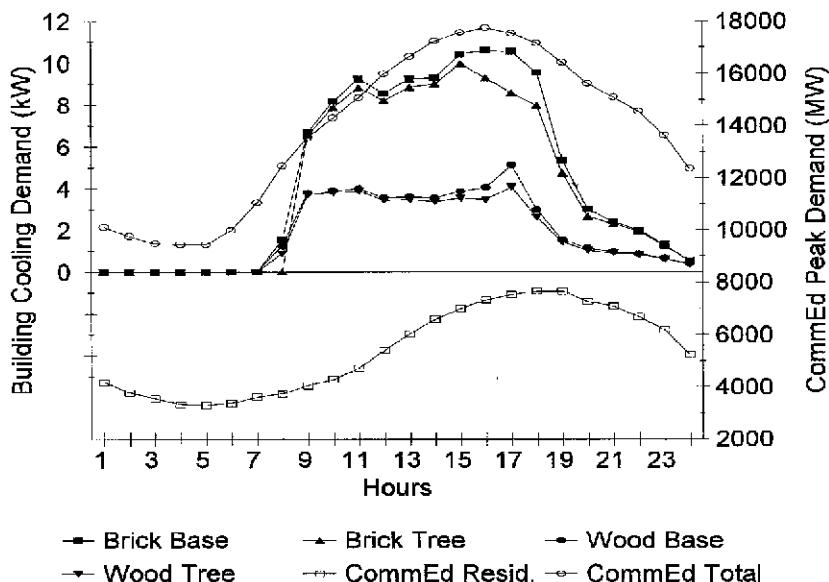


Figure 9.—Commonwealth Edison profiles residential and total peak summer demand for July 22, 1992, as well as simulated peak-day cooling electricity demand (July 1) for two-story brick (south facing) and two-story wood-frame base case buildings, with and without a deciduous tree.

years 1 to 20 (Appendix E). It is assumed that one typical tree is planted for energy savings near each typical building in 1993, with a total of 10,000 trees shading 10,000 brick buildings, and 10,000 trees shading 10,000 wood buildings. The typical tree is 3 feet tall and wide when planted and costs $50 to plant. This includes the cost of the tree, stakes and other planting materials, program administration, overhead, and 3 years of follow-up care and public education. It also assumes that the residents plant the trees. As a comparison, the estimated costs of the Sacramento Tree Foundation's Shade Tree Program to the Sacramento Municipal Utility District (SMUD) have dropped from $49 per tree planted in 1990-91 to $35 per tree in 1993-94 (Richard Sequest, SMUD, 1993, pers. commun.).

Two adjustments are made to estimates of avoided energy and capacity. First, it is assumed that trees die at a rate of 5 percent a year during the first two years of establishment. A 1-percent annual mortality rate is assumed for the remaining 18 years. Over the 20-year planning horizon, 25 percent of the planted trees are expected to die. Second, it is assumed that only half of the houses that receive a tree have a space cooling device. Both of these adjustments reduce estimated energy savings.

The analysis assumes Commonwealth Edison's current avoided energy and capacity costs of $0.015 per kWh and $89 per kW yr$^{-1}$, as well as the 11-percent discount rate and 4.5 percent inflation rate typically used in their economic analyses (Gary Rehof, Commonwealth Edison, 1994, pers. commun.).

### Results

Cost-effectiveness is evaluated by comparing the present value of estimated program costs with estimated benefits. The net present value, or benefits minus costs, is $176,928 for the brick building and $447,588 for the wood building. Capacity benefits account for more than 90 percent of the total benefits in both cases. The benefit-cost ratio, or benefits divided by costs, is 1.35 for the brick building, and 1.90 for the wood building (Appendix E). Both measures indicate that the benefits derived from such a shade-tree program would outweigh costs incurred to Commonwealth Edison.

This analysis assumes a single tree located optimally to shade each building. Benefits per tree would be less if several trees were planted for each building, as noted in results from the multiple-tree shading simulations for the wood-frame buildings. However, program costs may be less if fewer customers are receiving trees. Also, this analysis does not incorporate the value of other benefits that shade trees can provide, such as removal of atmospheric carbon and other air pollutants, heating energy savings, reduced stormwater runoff, and increased property values, scenic beauty, and biological diversity. The following chapter explores these benefits, as well as many other costs associated with the planting and care of trees in Chicago.

## Energy-Efficient Landscape Design

There are a number of good references on the topic of energy-efficient landscape design that Chicagoans can use to save energy dollars (Akbari et al. 1992; Foster 1978; Heisler 1986b; McPherson 1984; Moffat and Schiler 1981;

Robinette 1977; Sand 1991; Sand 1993a; Sand 1993b). In this section, general guidelines for energy-efficient residential landscape design in the Chicago area are summarized. Appendix B contains information on recommended trees.

Generally, the best place to locate the first (and perhaps second) tree for energy savings is opposite west-facing windows and walls. This suggests that a tree to the west provides the greatest peak cooling energy savings, and greater net annual energy savings than a tree to the east unless large amounts of window area face east. Also, trees to the west provide the most protection from winter winds, which prevail from the west and northwest during the coldest months (Sand and Huelman 1993). Select evergreens if space permits, or low branching deciduous trees with broad crowns for extensive shading during summer (Figure 10). Locate trees within 30 feet (9 m) of the building to increase the amount of shade. Evergreen vines and shrubs are good plants for solar control on west walls (Hudson and Cox 1985; Parker 1987). Where feasible, shading the air conditioner improves its efficiency and can save electricity.

The next best place for a tree in Chicago is opposite the east wall, where shade reduces annual cooling demand and does not obstruct winter solar gain as much as a tree to the south. Select solar friendly deciduous trees with broad spreading crowns and relatively short foliation periods (May-October rather than April-November) for east shade. Keep trees pruned high to maximize the flow of cool breezes during summer, which prevail from the south and southwest except near Lake Michigan, where breezes move inland from the east.
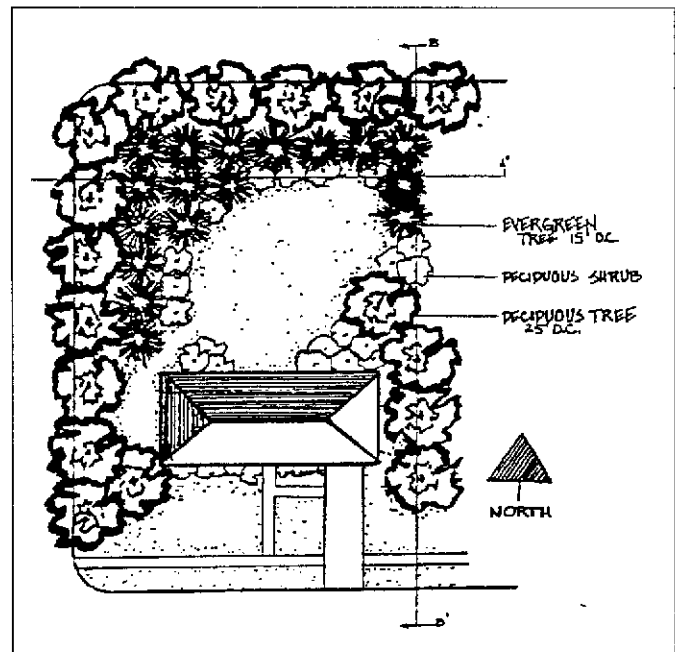


Figure 10.—Energy-efficient residential landscape design with east and west shade as well as wind protection to the west and northwest (from Sand and Huelman 1993).

Deciduous vines and shrubs can provide both summer shade and winter solar access.

South shade can reduce summer peak cooling demand more than east shade, especially for taller residential and commercial buildings (McPherson and Sacamano 1992). However, shade from trees located south of buildings in Chicago usually increases heating costs more than it reduces air-conditioning costs. If trees are required to the south, select large solar friendly ones that will eventually branch above the windows to provide winter solar access and summer shade (McPherson 1984). South trees should be located fairly close (8 to 20 feet) to the building for optimum energy savings.

Cool breezes can improve comfort and reduce cooling energy use during hot muggy days if natural ventilation is used and outside temperatures are below 90°F (32°C) (Givoni 1981). Whether you live near Lake Michigan or further inland will influence the direction of cooling breezes, but in either case avoid hedges that restrict natural ventilation. Dense plantings to the west are needed to protect from winter winds and summer solar-heat gain. Windbreak plantings located 30 to 50 feet upwind of the building can provide savings once they grow about as tall as the building (Heisler 1984). Select trees that will grow to about twice the height of the building they protect, and plant staggered rows where possible. Windbreak plantings should be longer than the building for protection as wind directions shift. Because cooling breezes are from the east and southeast while winter winds usually are from the west and northwest, it is possible to use shade trees and evergreen windbreaks for wind and solar control without obstructing solar access to the south side of buildings (Figure 10).

## Summary and Conclusion

The following are key findings of this study.

—Shade trees in Chicago can provide substantial energy savings. A single 25-foot tree is estimated to reduce annual heating and cooling costs by 2 to 4 percent, or $23 to $86. Three such trees located for maximum summer shade and protection against winter wind could save a typical Chicago homeowner about $50 to $90 per year (5 to 10 percent of the typical $971 heating and cooling bill).

—Results of an economic analysis indicate that a utility-sponsored shade-tree program could be cost-effective in Chicago. Benefit-cost ratios of 1.35 for trees planted near typical two-story brick buildings and 1.90 for trees planted near energy-efficient wood-frame buildings suggest that avoided energy and capacity benefits can outweigh costs incurred.

—Street trees are a major source of building shade within 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 percent (138 to 205 kWh or $17 to $25) and peak cooling demand by 2 to 6 percent (0.16 to 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 can slightly increase heating

costs. Shade from large street trees to the south increase heating costs more than they decrease cooling costs for the buildings studied. Planting solar friendly trees to the south and east can minimize the energy penalty associated with blocking irradiance during the heating season.

—For typical suburban wood-frame residences, shade from three trees reduces annual heating and cooling 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 126 to 187 kWh (0.45 to 0.67 GJ) (6 to 7 percent, $15 to $23) and 0.9 to 1.1 kW (16 to 17 percent), assuming a 25-foot-tall tree opposite the west wall.

—The amount and type of energy savings associated with trees are highly sensitive to building characteristics. Effects of ET cooling and reductions in windspeed associated with increased tree cover account for an estimated 70 to 90 percent of the total annual savings for the older brick buildings, with heating savings exceeding cooling savings. Trees that provide mitigation of summer heat islands in Chicago also can provide sizable annual savings in heating energy, especially for older buildings in areas where tree cover is relatively low. Strategic landscaping for maximum shading is especially important with new construction because solar-heat gains through windows strongly influence cooling loads.

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

Although the effect of Chicago's existing urban forest on climate and energy use is difficult to quantify precisely, it appears to be substantial. Resources invested in the maintenance and upgrade of Chicago's trees will provide direct benefits to residents in energy savings and a more hospitable outdoor climate. Thus, maintaining the health and longevity of trees in areas where canopy cover is relatively high should be a top priority.

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. 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 (see section on benefits and costs of volunteered-based tree planting and care in public housing sites). Demonstration projects are needed to evaluate the long-term cost-effectiveness of public investment in tree plantings for energy conservation and other benefits. Chicago is an ideal location for innovative projects aimed at promoting energy efficiency and forging new partnerships among residents, government, utilities, and nonprofit organizations.

# Acknowledgments

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## Chapter 8
# Benefits and Costs of Tree Planting and Care in Chicago

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## Abstract

Benefit-cost analysis is used to estimate the net present value, benefit-cost ratio, and discounted payback periods of proposed tree plantings in the City of Chicago. A "typical" tree species, green ash (*Fraxinus pennsylvanica*), was located in "typical" park, residential yard, street, highway, and public housing sites. The 30-year stream of annual costs and benefits associated with planting 95,000 trees was estimated using a computer model called Cost-Benefit Analysis of Trees (C-BAT) and discount rates of 4, 7, and 10 percent. NPV were positive and projected benefit-cost ratios were greater than 1 at all discount rates. Assuming a 7-percent discount rate, a net present value of $38 million or $402 per planted tree was projected. Benefit-cost ratios were largest for trees planted in residential yard and public housing sites (3.5), and least for park (2.1) and highway (2.3) sites. Discounted payback periods ranged from 9 to 15 years. Expenditures for planting alone accounted for more than 80 percent of projected costs except at public housing sites, while the largest benefits were attributed to "other" benefits (e.g., scenic, wildlife, improved water quality, noise abatement, and social values) and energy savings. Considerations for planting and managing Chicago's urban forest to maximize return on investment are presented.

## Introduction

Trees have a long and rich tradition in Chicago. This tradition can be seen today as the formal elm bosques in Grant Park, Chicago's many majestic tree-lined boulevards, its extensive forest preserves, and the informal plantings of hawthorns, hackberry, oak, and other natives that grace its many parks (McPherson et al. 1993a). In Chicago and most surrounding communities, trees have long been recognized as valuable community assets. First-rate urban forestry programs abound as evidence of commitment to the perpetuation of healthy community forests. However, dwindling budgets for planting and care of street and park trees are creating new challenges for urban forestry. Community officials are asking if trees are worth the price to plant and care for them over the long term. 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 sap from aphids that fouls 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 is to quantify some of the benefits and costs associated with tree planting and care in Chicago. In previous sections of this report, existing and potential benefits of Chicago's urban forest have been outlined with respect to climate, air quality, atmospheric carbon, and energy used for space heating and cooling. Relations between these functions and the composition and distribution of tree species have been discussed. In this study, 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 is based upon interviews with entities responsible for much of the tree planting and care in the city and covers projected plantings between 1992 and 1997 as follows:

—12,500 trees planted and maintained in parks by the Chicago Park District.
—25,000 trees planted by residents in their yards with maintenance by professional arborists beginning 15 years after planting.
—50,000 trees planted along residential streets and maintained by the Bureau of Forestry.
—5,000 trees planted along expressways under the auspices of Gateway Green and the Illinois Department of Transportation, with maintenance by volunteers and city personnel.
—2,500 trees planted in public housing sites by local residents under the direction of the Openlands Project, with initial maintenance by residents and Openland's TreeKeepers and professional maintenance of larger trees.

Quantifying benefits and costs associated with these plantings will 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?

This analysis is complicated by incomplete information on such critical variables as tree growth and mortality rates, the value of social, aesthetic, and economic benefits that trees

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produce, and costs associated with infrastructure repair, litigation, and program administration. When data from local sources were unavailable, it was necessary to use the best available data. As a result, some variables were excluded from this analysis (e.g., costs of litter clean-up and health care benefits and costs). Estimating the value of social, aesthetic, and economic benefits, called "other benefits" in this study, is uncertain because we have yet to identify the full extent of these benefits or their implications. Additional problems emerge since many of these benefits are not exchanged in markets and it is often difficult to estimate appropriate dollar values. This lack of data required the development of several assumptions about the planting and care of a "typical" tree species in "typical" locations. To simplify the analysis it was necessary to limit its scope to the planting of trees over a 5-year period and their care over a 30-year period. Benefit-cost data were gathered in 1992 and 1993 from local contacts and used to estimate future values. Therefore, this study provides an initial approximation of those benefits and costs for which information is available. As our understanding of urban forest structure, function, and values increases, and we learn more about urban forestry programs and costs, these assumptions and the methods used to estimate benefits and costs will be improved.

# Background

Urban trees provide a range of services for community residents that can influence the quality of our environment. As illustrated elsewhere in this report, trees in the Chicago area can moderate local climate, reduce building energy use (Akbari et al. 1992), improve air quality (McPherson and Nowak 1993), and sequester and avoid carbon dioxide (Nowak 1993, Rowntree and Nowak 1991). Other studies have found that urban forests reduce stormwater runoff (Lormand 1988; Sanders 1986), increase property values (Anderson and Cordell 1988), and provide a connection to nature, relaxation, or spiritual joy (Dwyer et al. 1992). Quantifying the value of these and other benefits and the costs associated with urban trees can assist planners and managers optimize their return on investment in Chicago's urban forest.

Current efforts to determine the value of greenspace do not include the broad range of important benefits and costs or how they vary across time and location. Nor do they allow comparison of future cost-benefit relationships associated with alternative management scenarios (McPherson 1992). In response to these limitations, the Cost-Benefit Analysis of Trees (C-BAT) computer model was developed to quantify various management costs and environmental benefits. C-BAT as applied here quantifies annual benefits and costs for a 30-year period associated with the establishment and care of trees in Chicago.

# Approch

### C-BAT
C-BAT estimates annual benefits and costs for newly planted trees in different locations over a specified planning horizon. C-BAT is unique in that it directly connects tree size 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) and benefit (e.g., heating/cooling energy savings, absorption of air pollution, reduction in stormwater runoff) through direct estimation and implied valuation of benefits as environmental externalities. This makes it possible to estimate the net benefits of plantings in typical locations and with typical tree species. C-BAT incorporates the different rates of growth and mortality as well as different levels of maintenance associated with typical trees. Hence, this greenspace accounting approach "grows trees" in different locations and directly calculates the annual flow of benefits and costs as trees mature and die (McPherson 1992).

Although Chicago's urban forest is planted with many tree species (Nowak 1994a: Chapter 2, this report), the scope of this analysis is limited to planting and care of a single typical tree species, green ash (*Fraxinus pennsylvanica*), in each of five typical locations: parks, residential yards, residential streets, highways, and public housing sites. Typical locations were selected to represent the types of trees, management approaches, socio-economic situations, and growing conditions that influence tree health and productivity in Chicago. Green ash was selected as the typical species because it is one of the most widely planted and successful tree species in Chicago (Nowak 1994a: Chapter 2, this report).

In this study, trees are "planted" during the first 5 years and their growth is assumed to follow an S-shaped curve that incorporates a slow start after transplanting. As trees age, their numbers decrease. Transplanting-related losses occur during the first 5 years after planting, and age-independent losses occur over the entire 30-year analysis period. Transplanting-related losses are based on annual loss rates reported by local managers and other studies (Miller and Miller 1991; Nowak et al. 1990). Age independent losses are assumed to be equally likely to occur in any year (Richards 1979). Tree growth and mortality rates reflect rates expected for the green ash on each type of site.

Each year, C-BAT calculates total leaf area for each age class by multiplying the number of live trees times the typical tree's leaf-area (LA). LA is calculated using the typical tree's leaf-area index (LAI) and ground projection (GP) term, where GP is the area under the tree-crown dripline:

$$LA = LAI \times GP$$

The LAI of a tree varies with species, size, and condition. In this study, the LAI of green ash trees in Chicago is assumed to be 5 based on data presented in Chapter 2.

C-BAT directly connects selected benefits and costs with estimated leaf area of the planted trees. Because many functional benefits of trees are related to leaf-atmosphere processes (e.g., interception, transpiration, photosynthesis), benefits increase as leaf-surface area increases. Similarly, pruning and removal costs usually increase with tree size. To account for these time-dependent relationships, benefits and costs are assumed to vary with leaf area.

For most costs and benefits, prices are obtained for large trees (assumed to be 20-inches in d.b.h. or about 45-feet tall and wide) and estimated for trees of smaller size using

different functions (e.g., linear, sine, cosine). For parameters such as sidewalk repair, costs are small for young trees but increase relatively rapidly as tree roots grow large enough to heave pavement. For other parameters such as rainfall interception, benefits are directly proportional to leaf area (Aston 1979). In this study, a linear function is used to estimate all benefits and costs with the exception of infrastructure repair and litigation costs (cosine function) and benefits related to energy savings (sine function). These prices are divided by the tree's leaf area to derive a base price per unit LA for different tree size classes (e.g., $20/10,000 ft2 LA = $0.002/ft2 LA). C-BAT multiplies the base price times the total LA of trees in that size class to estimate the total annual nominal value of each benefit and cost. Once the nominal values are calculated for each year into the future, they can be adjusted to account for future inflation and discounted to a present value. Thus, both tree size and the number of live or dead trees influence the dollar value of each benefit and cost.

Most benefits occur on an annual basis, but some costs are periodic. For instance, street trees are pruned on yearly cycles and removed when they pose a hazard or soon after they die. C-BAT calculates tree and stump removal costs for the same year as each tree dies. Pruning costs are average annual costs based on average tree size.

Generally, benefits directly related to leaf-surface area increase yearly as trees grow larger and add more leaves each spring. However, two benefits are more directly related to the annual change in tree girth than to the increase in leaf area: "other benefits" (i.e., social, aesthetic, and other environmental benefits not explicitly accounted for); and the storage of atmospheric carbon in tree biomass. The annual value of these benefits is proportional to the increase in d.b.h. for that year. Relations between tree d.b.h., age, and crown dimensions are based on findings reported by Nowak (1994c: Chapter 6, this report) and data from Churack and Miller (1992, Univ. of Wisconsin-Stevens Point, pers. commun.), Fleming (1988), and Frelich (1992).

In this study, both direct estimation and implied valuation are used to assign values. Much of the cost data for tree management were directly estimated based on interviews with local contact persons. Findings from energy simulations

presented by McPherson (1994: Chapter 7, this report) are used in this study to directly estimate energy savings due to shading, temperature modification, and wind speed reductions from trees. Other benefits are estimated using implied valuation, which relies on the costs of required or anticipated environmental control measures or regulations. For instance, if society is willing to pay $1 per pound for current or planned air-pollution control, then the air-pollution mitigation value of a tree that absorbs or intercepts 1 pound of air pollution should be $1 (Chernick and Caverhill 1991; Graves et al. 1987).

## Tree Planting and Care

Contact persons from each organization (Table 1) were interviewed to estimate the number of trees to be planted annually over a 5-year period (1992 to 1997), growth and mortality rates, and planting and management practices and costs. Costs summarized in Table 2 and described in the section that follows are for the typical large tree (45-feet tall, 20-inch d.b.h.) and adjusted downward for smaller trees using functions noted previously.

### Trees in Parks

There are about 250,000 trees in Chicago parks that receive regular care from the Chicago Park District. On average, the Park District expects to plant 2,500 trees per year for the next 5 years. About 30 varieties will be planted, with an average planting height of 15-feet (4-inches d.b.h.). Total planting costs average $470 per tree, including $100 for watering during the establishment period. The typical green ash is assumed to have a life-span of 30 to 50 years after planting mortality and an average annual height growth rate of 0.8-feet (0.4-inch d.b.h.). It is expected to attain a height of 39 feet (16-inch d.b.h.) 30 years after planting. Mortality during the 5-year establishment period is assumed to be 16 percent, with an overall loss rate of 39 percent for 30 years.

The cost to prune a large park tree is assumed to be $160, and the typical tree is pruned four times over 30 years. Large tree and stump removal costs are assumed to be $900 and $110, respectively, with 80 percent of all dead trees and stumps removed. Sixty percent of the removed wood is recycled as mulch and the remainder is taken to a landfill, where the dumping fee is $40 per ton. Each year the Park

Table 1. —"Typical" locations, planting sizes, and organizational roles

| Tree location | Planting size[a] | Organization and assumed tree planting/care activity |
|---|---|---|
| Park | 15 ft, 4-inch caliper | Chicago Park District plant and maintain |
| Residential yard | 12 ft, 2-inch caliper | Residents plant and maintain while trees are small; arborists maintain/remove large trees |
| Residential street | 12 ft, 2-inch caliper | Bureau of Forestry plant and maintain |
| Highway | 14 ft, 3-inch caliper | Gateway Green, Illinois Dept. of Transportation, and arborists plant and maintain |
| Public housing | 13 ft, 2.5-inch caliper | Openlands, TreeKeepers, and residents plant and maintain while young; professional maintenance of larger trees |

[a] Tree height in feet and caliper (trunk diameter) in inches measured 6 inches (15 cm) above the ground.

Table 2.—Estimated tree planting and management costs

| Cost category [a] | Tree location | | | | |
| --- | --- | --- | --- | --- | --- |
| | Park | Yard | Street | Highway | Housing |
| **Planting** | | | | | |
| Cost per tree (dollars) | 470 | 250 | 162 | 250 | 150 |
| **Pruning** | | | | | |
| Cost per tree (dollars) | 160 | 196 | 97 | 150 | 160 |
| Frequency (# in 30 yrs) | 4 | 1 | 5 | 3 | 4 |
| **Tree removal** | | | | | |
| Cost per tree (dollars) | 900 | 504 | 658 | 312 | 900 |
| Frequency (% removed) | 80 | 100 | 100 | 60 | 80 |
| **Stump removal** | | | | | |
| Cost per tree (dollars) | 110 | 140 | 108 | 91 | 110 |
| Frequency (% removed) | 80 | 50 | 100 | 100 | 80 |
| **Waste disposal** | | | | | |
| Cost (dollars per ton) | 40 | na | na | na | na |
| **Infrastructure repair** | | | | | |
| (dollars per tree per year) | | | | | |
| Walk, curb, gutter cost | 0.62 | 0.62 | 2.49 | 0.25 | 0.62 |
| Sewer and water cost | 0.38 | 1.15 | 0.76 | 0.12 | 0.76 |
| **Litigation and liability** | | | | | |
| Cost (dollars per tree per year) | 0.01 | 0.50 | 1 | 0.75 | 0.07 |
| **Inspection** | | | | | |
| Cost (dollars per tree per year) | 0.19 | 0 | 0.35 | 0 | 0.19 |
| **Program administration** | | | | | |
| Cost (dollars per tree per year) | 0.94 | 0 | 0 | 2.63 | 32.78 |

[a] Cost estimates given as dollars per year per tree (45-ft tall, 20-inch d.b.h.) unless shown otherwise.

District spends about $75 per tree on the Grant Park elm program to control Dutch elm disease, but other expenditures for pest and disease control are minimal. The annual program administration cost is assumed to be $0.94 per large tree, while costs for litigation/liability and infrastructure repair are negligible.

### Residential Yard Trees
Eight local garden centers were surveyed to estimate the number of trees planted annually in Chicago's residential landscapes. Questions were asked regarding numbers of trees sold, most popular species and sizes, and average cost. Based on the response, an estimated 5,000 trees will be planted each year in residential yards at an average planting height of 12-feet ( 2-inches d.b.h.). The average cost of this size tree is assumed to be $250. The typical green ash in yards is assumed to grow at an average annual rate of 0.8 feet in height (0.4-inch d.b.h.), reaching a height of 36 feet (14-inches d.b.h.) 30 years after planting. Due to the relatively favorable growing conditions in yards, low mortality rates are expected. Only 4 percent of the transplants are assumed to die during the first 5 years; a mortality rate of 18 percent is assumed for the entire 30 years.

On average, residential yard trees are assumed to be pruned once by a paid landscape professional over the 30-year analysis period at a cost of $196 per tree. Costs for tree and stump removal are assumed to be $504 and $140 per large tree, respectively. Costs are included for removal of all trees and 50 percent of all stumps.

Tree roots can damage old sewer lines that are cracked or otherwise susceptible to invasion. Several local companies were contacted to estimate the extent to which street and yard trees damage sewer lines and repair costs. Respondents noted that sewer damage is minor until trees and sewers are more than 30 years old, and that roots from trees in yards usually are a greater problem than roots from street trees. The latter assertion may be due to the fact that sewers become closer to the root zone as they enter houses than at the street. Repair costs typically range from $100 for rodding to $1,000 or more for excavation and replacement. This study assumes that on average, 10 percent of all yard trees planted will invade sewers during the 30-year period after planting, each requiring repair at an average cost of $345. When factored over the 30-year period, this cost amounts to about $1.15 per year per tree. The annual costs for repair of sidewalks due to damage from yard trees is $0.62 per tree.

The annual litigation or liability costs associated with property damage from yard trees is assumed to be $0.50 per tree based on data from other cities (McPherson et al. 1993b).

### Residential Street Trees
Chicago's Bureau of Forestry maintains nearly a half million trees along city streets and boulevards. It anticipates planting 10,000 bare root trees each year for the next 5 years at an average planting cost of $162 each. Trees are typically 12-feet tall (2-inches d.b.h.) when planted. Along streets the typical green ash is assumed to grow at an average annual rate of 0.67 feet (0.33-inch d.b.h.), reaching a height of 32 feet (12-inches d.b.h.) 30 years after planting. It is assumed that 28 percent of the trees die during the first 5 years, with 42 percent dying over the 30-year planning horizon.

The Chicago Bureau of Forestry anticipates pruning street trees once every 6 years at an average cost of $97 per tree. All dead trees and their stumps are removed at a cost of $658 and $108 per tree, respectively. Nearly all of the removed wood is salvaged and used as mulch or compost. Roots of older street trees can cause sidewalk heaving that is costly to repair. In Chicago, costs for sidewalk repair are shared between the city and property owner. Approximately $3 million is spent annually for sidewalk repair (Ronny Eisen, City of Chicago Transportation Dept., 1993, pers. commun.). It is estimated that about $1 million is spent each year repairing sidewalk damage that is largely attributed to trees, or $2.18 each year per street tree. Data on the cost of curb and gutter repair due to tree damage are unavailable for Chicago but is asssumed to be 14 percent of sidewalk repair costs ($0.31 per tree per year) based on information from other cities (McPherson et al. 1993b). Based on data from several local sewer contractors, the estimated cost is $0.76 per year per large tree.

Data on litigation and liability costs are unavailable for Chicago, so costs are estimated as $1 annually per tree based on data from several other cities (McPherson et al. 1993b). The annual inspection cost is S0.35 per tree, while Bureau of Forestry program administration costs are included in the unit costs cited. Inspection costs cover time and expenses for personnel who regularly inspect trees, adjust staking, apply mulch, and perform other minor tree-care operations.

### Trees Along Highways
The Chicago Gateway Green Committee is a nonprofit organization that raises funds for tree planting and care. Gateway Green teams with Illinois Department of Transportation (IDOT), Hendricken The Care of Trees, City of Chicago, and local volunteers to plant and care for trees along major transportation corridors. Recent plantings along the Kennedy Expressway and at the Ohio-Ontario-Orleans triangle demonstrate the success of this collaboration. IDOT is responsible for additional tree plantings associated with the reconstruction of expressways and highways. Planting numbers vary yearly depending on the construction schedule; and trees planted within the city limits are maintained by city personnel.

From 1992 to 1997, about 1,000 trees will be planted annually along Chicago's expressways and major streets by IDOT and Gateway Green. Plantings contain many native species that are well adapted to local growing conditions. The typical green ash is assumed to be 14 feet tall (3-inches d.b.h.) with an average planting cost of $250 per tree. This $250 incorporates savings due to donated labor from Gateway Green volunteers. Green ash trees along expressways are assumed to grow at an average annual rate of 0.67 feet in height (0.33-inch d.b.h.) attaining a height of 34 feet (13-inches d.b.h.) after 30 years, which is about their typical life-span since highways are rebuilt every 25 to 30 years. It is anticipated that sixteen percent of the new trees will die during the first 5 years. A loss rate of 39 percent is expected over the 30-year period.

On average, expressway trees are pruned once every 10 years at a cost of about $150 per large tree. Costs for tree and stump removal are assumed to be $312 and $91 per tree, respectively. Sixty percent of all dead trees are removed, and all stumps are removed. Nearly all waste wood is recycled as mulch used for landscaping. Because expressway trees are not planted close to sidewalks, curbs and gutters, and other built property, damage to them from trees is minimal. Program administration costs are assumed to be $2.63 annually per tree based largely on IDOT's projected expenses.

### Trees In Public Housing Sites
Openlands Project is a nonprofit organization with an active urban forestry program called TreeKeepers, which teaches volunteers how to plant and maintain trees. Openlands plants 300 to 500 trees each year at a variety of locations throughout Chicago. About half of these trees are planted at public housing sites with participation from local residents. Other planting sites include libraries, parks, and streets. Plantings involve TreeKeepers and other volunteers. To simplify this analysis, data for tree planting and care at public housing and similar park-like sites are used.

During the next 5 years, Openlands expects to plant about 2,500 balled and burlapped trees (311 per year) averaging 13 feet in height (2.5 inches d.b.h.). It costs about $150 to plant each tree. The typical green ash is assumed to have an average annual growth rate of 0.8 feet in height (0.4-inch d.b.h.) per year and attain a height of 37 feet (14.5-inches d.b.h.) 30 years after planting. Mortality during the first 5 years is assumed to be 16 percent, and estimated as 39 percent for the entire 30 years.

TreeKeepers and other Openlands volunteers do not prune or remove trees over 10 inches d.b.h. Therefore, maintenance of maturing trees is performed by local arborists or other landscape professionals. Pruning costs are assumed to be $160 per tree, with the typical tree pruned four times over 30 years. Large tree and stump removal costs are assumed to be $900 and $110, respectively, with 80 percent of all dead trees and stumps removed. Annual program administration costs are $32.78 per tree. Administration costs cover expenses for coordinating, training, and supplying volunteers with equipment needed to plant and maintain trees.

## Energy Savings

Trees can reduce energy use for air conditioning (AC) by shading building surfaces and lowering air temperatures and

windspeed. During winter, trees can conserve energy use for heating by lowering windspeeds and associated infiltration of cold outside air. However, even bare branches of deciduous trees can block winter sunlight and increase heating energy use (Heisler 1986). Results from energy simulations for a typical two-story brick building in Chicago (McPherson 1994: Chapter 7, this report) are used in this benefit-cost analysis. Specifically, a single deciduous tree 36 feet (11 m) tall and 24 feet (7 m) wide was estimated to reduce annual air conditioning energy use by 266 kWh (0.96 GJ) and heating energy use by 4.42 MBtu (4.66 GJ). These base values represent maximum potential savings from a well-sited tree around a typical two-story residential building in Chicago. Reduction factors are applied to these base values to account for less than optimal shading and indirect effects, less than 100 percent presence of air-conditioning and natural gas heating devices, and less than mature tree size (McPherson 1991). Electricity and natural gas prices are $0.12 per kilowatt-hour (kWh) and $5 per million Btu (MBtu). About 40 percent of all households in Chicago have central air conditioning, 36 percent have room air conditioning, and 93 percent use natural gas for space heating (Thomas Hemminger and Claire Saddler, Commonwealth Edison; Bob Pendlebury, People's Gas, 1993, pers. commun.). Reduction factors that account for less than optimal tree placement with respect to buildings are based on personal observation of tree locations in Chicago and a previous study (McPherson 1993) (Table 3).

## Air Quality Improvement

Although the ability of urban greenspace to mitigate air pollution through particulate interception and absorption of gases is recognized by many, few studies have translated this environmental control function into dollars and cents. This study uses an approach similar to that used previously by Chicago Urban Forest Climate Project (CUFCP) scientists to model the value of improvements in air quality from trees in a portion of Lincoln Park (McPherson and Nowak 1993). This analysis also includes benefits from the avoided costs of residual power plant emissions control due to cooling energy savings from trees.

Pollutant uptake is modeled as the surface deposition velocity times the pollutant concentration. Deposition velocities to vegetation for each pollutant, i.e., particulate matter less than

10 $\mu$m (PM10), ozone ($O_3$), nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$), and carbon monoxide (CO) are derived from the limited literature on this subject (Davidson and Wu 1988).

Two scenarios with different pollution concentrations are used to estimate uptake rates. The first scenario uses average annual pollution concentrations during periods when National Ambient Air Quality Standard (NAAQS) levels are exceeded. The second scenario uses average pollution concentrations. Average annual pollution concentrations and the number of hours associated with each scenario are derived for in-leaf and leaf-off months from 2 years of data collected at Edgewater (gaseous pollutants) and the Chicago Avenue Pumping Station (particulates). All trees are considered to be deciduous, so annual pollutant uptake rates are calculated using in-leaf data only (May through October). Gaseous absorption is assumed to occur during daylight hours when stomates are open.

Biogenic hydrocarbon emissions from planted trees can contribute to $O_3$ pollution. However, as noted by Nowak (1994b: Chapter 5, this report), reducing city temperatures with trees can lower $O_3$ production and hydrocarbon emission. Because much research is needed before these complex interactions are understood, these costs and benefits are assumed to be offsetting.

Emissions by power plants depend on the type of technology used to generate electricity, fuel type, plant age, and other factors. Energy savings by trees will influence future emissions, and future emissions will be different as Commonwealth Edison begins to retire nuclear power plants. However, it is conservatively assumed that pollution emission rates will not change because advanced control technologies will offset an increase in the use of fossil fuels. Current emission rates provided by Commonwealth Edison are used for PM10 and $SO_2$ (Tom Hemminger, Commonwealth Edison, 1991, pers. commun.). Generic emission rates are used for other pollutants (California Energy Commission 1992). Avoided emissions are calculated by multiplying annual savings in electric energy from trees by the estimated power-plant emission rate for each pollutant (McPherson et al. 1993b) (Table 4).

The societal value of reducing air pollutants through tree planting is estimated using the cost of traditional air-pollution

Table 3.—Location reduction factors for energy, hydrologic, and other benefits, in percent

| Category | Tree location | | | | |
| --- | --- | --- | --- | --- | --- |
| | Park | Yard | Street | Highway | Housing |
| Shade | 30 | 60 | 50 | 30 | 50 |
| ET cooling | 50 | 90 | 80 | 50 | 80 |
| Wind | 50 | 90 | 80 | 50 | 80 |
| Hydrologic | 15 | 30 | 70 | 25 | 30 |
| Other benefits | | | | | |
| Species factor | 70 | 70 | 70 | 70 | 70 |
| Condition factor | 70 | 70 | 70 | 70 | 70 |
| Location factor | 70 | 75 | 75 | 65 | 65 |

Table 4.—Assumptions for estimating implied value of air quality improvement

| Item | PM10 | $O_3$ | $NO_2$ | $SO_2$ | CO |
|---|---|---|---|---|---|
| Deposition velocity (cm/sec) | 0.60 | 0.45 | 0.40 | 0.66 | 0.0006 |
| Control costs (dollars/ton) | 1,307 | 490 | 4,412 | 1,634 | 920 |
| Emission factors (lb/MWh) | 0.14 | 0.03 | 2.10 | 6.81 | 0.63 |

controls as proxies for the price society is willing to pay to reduce air pollutants. Due to the unavailability of data for Chicago regarding air-pollution control costs, 1990 estimates for the Northeastern United States are used for this analysis (California Energy Commission 1992). These values may not reflect the actual price Chicagoans are willing to pay to reduce various air pollutants. Deposition velocities, control costs, and emission factors for each pollutant are listed in Table 4.

## Carbon Dioxide Sequestered and Avoided

Carbon dioxide is a major greenhouse gas that influences atmospheric processes and climate. As part of the CUFCP, the potential of urban and community forests to directly store carbon in their biomass has been reported in this report (Nowak 1994c: Chapter 6). Other studies have analyzed the extent to which cooling energy savings attributed to urban forests reduce atmospheric carbon released by power plants as a byproduct of electric generation (Huang et al. 1987; Rowntree and Nowak 1991, Sampson et al. 1992; Nowak 1993). Generally, avoided carbon emissions are many times greater per tree than are amounts of carbon stored. This study uses an approach similar to that developed by Rowntree and Nowak (1991).

Sequestered carbon is calculated using biomass equations for a sugar maple (*Acer saccharum*) to represent hardwood biomass (Wenger 1984). Hardwood dry weight is estimated to be 56 percent of fresh weight and carbon storage is approximately 45 percent of total dry-weight biomass. Annual carbon sequestration for a 20-inch d.b.h. (45-foot tall) deciduous tree is estimated to be 100 lb (45 kg).

Avoided carbon emissions from power plants are calculated using energy analysis estimates of cooling energy saved and Commonwealth Edison's current fuel mix. A weighted average carbon emission rate of 0.11 lb (50 g) per kilowatt-hour was calculated. Estimated carbon emissions associated with natural gas consumed for space heating total 29.9 lb (13.6 kg) per million Btu (Larry Guzy, Peoples Gas, 1993, pers. commun.). The implied value of stored and avoided carbon is assumed to be $22 per ton (California Energy Commission 1992).

## Hydrologic Benefits

Rainfall intercepted and stored by the crowns of trees eventually evaporates. Findings from hydrologic simulations using different amounts of tree-canopy cover indicate that existing tree cover reduces urban stormwater runoff by 4 to 8 percent, and that modest increases in tree cover can further reduce runoff (Sanders 1986; Lormand 1988). Power plants use approximately 0.6 gal (2.3 l) of water to produce 1 kWh of electricity (McPherson 1991), so trees that provide energy savings through cooling also reduce water use associated with power production. Avoided water use at power plants is calculated by multiplying the rate of water use (0.6 gal) and kilowatt-hours of annual cooling energy saved. According to the Chicago Water Collection Division, the value of this water is estimated using a local retail water price of $0.00175 per gallon.

Most jurisdictions in the Chicago area require on-site retention-detention basins or other control devices to ensure that off-site flow does not exceed predevelopment rates. Costs for land acquisition, basin excavation, landscaping, and maintenance were approximately $0.02 per gallon of water retained (McPherson et al. 1993b). This price is used to establish a base implied value for rainfall interception and consequent avoided costs for stormwater control.

The amount of rainfall intercepted annually by trees is calculated as a linear function of tree size (Aston 1979). The value of tree-crown interception for retention-detention begins to accrue after the storage capacity of soil and other surfaces is filled and runoff commences. For example, storm events less than 0.1 inch seldom result in runoff. For this study, it is assumed that 80 percent of annual rainfall results in runoff. Interception equations for leafless and in-leaf periods (Hamilton and Rowe 1949) are used to estimate annual interception volumes for trees with different crown spreads.

In urban areas, land-cover characteristics dominate runoff processes and overland flow. Runoff from parking lots will exceed runoff from lawns under similar storm conditions. Thus, the potential effect on runoff of rainfall interception by trees can vary according to land cover characteristics associated with each planting location. To calculate net avoided runoff, land-cover reduction factors are incorporated and are assigned to each location based on the rational method for estimating runoff (Dunne and Leopold 1978) (Table 2).

## Other Benefits

There are many environmental and aesthetic benefits provided by trees in Chicago that should be included in any benefit-cost analysis. Environmental benefits from trees not accounted for thus far include noise abatement, soil conser-

vation, water-quality effects, increased human thermal comfort, and wildlife habitat. Although such benefits are more difficult to quantify than those described previously, they can be just as important.

Research shows that humans derive substantial pleasure from trees, whether it be feelings of relaxation, connection to nature, or religious joy (Dwyer et al. 1992). Trees provide important settings for recreation in and near cities. Research on the aesthetic quality of residential streets has shown that street trees have the single strongest positive influence on scenic quality.

Research comparing variations in sales prices over a large number of residential properties with different tree resources suggests that people are willing to pay 3 to 7 percent more for residential properties with ample tree resources versus few or no trees (Morales et al. 1983; Payne 1973). One of the most comprehensive studies of the influence of trees on residential property values was based on actual sales prices for 844 single-family homes in Athens, Georgia (Anderson and Cordell 1988). Each large front-yard tree was associated with about a 1-percent increase in sales price ($336). A value of 9 percent ($15,000) was determined in a U.S. Tax Court case for the loss of a large black oak on a property valued at $164,500 (Neely 1988).

Several approaches can be used to estimate the value of "other" benefits provided by trees. The hedonic pricing approach relies on differences in sales prices or property values of similar houses with good tree cover and no or little tree cover. The dollar difference should reflect the willingness of buyers to pay for the economic, social, and environmental benefits that trees provide. Some limitations to using this approach for this study include the difficulty associated with determining the value of individual trees on a property; the need to extrapolate results from studies done years ago in the east and south to Chicago; and the need to extrapolate results from trees on residential properties to trees in other locations (e.g., streets, parks, highways, public housing).

A second approach is to estimate the compensatory value of a tree using techniques developed by the Council of Landscape and Tree Appraisers and described by Neely (1992). Tree valuation is used by appraisers to calculate the replacement cost of a tree of similar size and kind as one that has been damaged or destroyed. The replacement value of smaller trees is estimated using local market prices for a transplantable tree of similar size and species. For larger trees, a basic value is calculated based on the local market price for the largest normally-available transplantable tree. This value is then adjusted downward to account for the species, condition, and location. A trunk adjustment factor is applied to trees larger than 30 inches d.b.h. based on the premise that a mature tree will not increase in value as rapidly as its trunk area will increase (Figure 1).

A good overview of the tree valuation method is provided by Miller (1988). The approach is used with street tree inventory data to estimate the asset value of street tree populations. The tree valuation was used in an economic analysis of the optimum pruning cycle for Milwaukee, Wisconsin by comparing the marginal cost of pruning to its marginal return (Miller and Sylvester 1981). Street tree inventory data regarding

–△– Trunk Diameter      –●– Trunk Area      –■– Adjusted Trunk Area
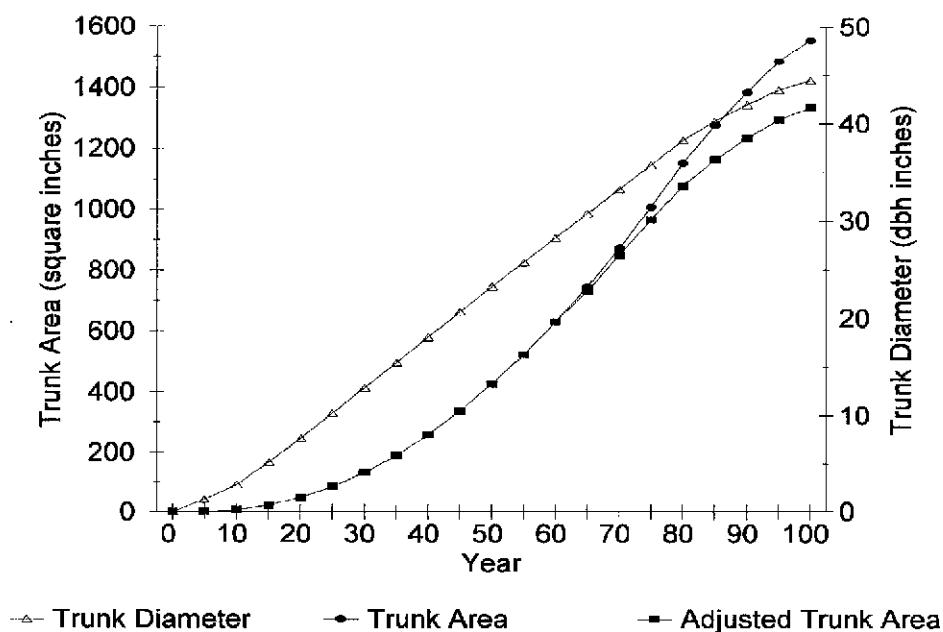
Figure 1. —Trunk area is adjusted for trees greater than 30 inches d.b.h. to more realistically estimate their replacement value. Estimated trunk diameter for a typical green ash used to calculate trunk area and tree replacement value is shown.

pruning intervals and tree condition were used with regression analysis to determine relations between pruning and condition class. Marginal costs were calculated as the loss in tree value associated with lower condition classes and extended pruning cycles. Thus, Miller and Sylvester (1981) applied the tree valuation formula to estimate the economic value of benefits forgone as tree condition deteriorates. This study adopts a similar approach to estimate the total value of benefits trees produce at a given time. Then the value of energy, air quality, carbon, and hydrologic benefits are subtracted from this total to calculate the remaining "other benefits". Tree replacement value (Neely 1988) is estimated as:

Replacement Value = Basic Value x Species Factor x
Condition Factor x Location Factor

where Basic Value = $27 x (0.789 x $d_2$) and d is tree d.b.h. in inches. Because in this analysis benefits begin accruing in 1992, basic value is calculated using $27 per square inch of trunk area, the value used in 1992 (Neely 1988). Currently, it costs about $33 to $35 per square inch of trunk area to purchase and install a typical 4-inch (10 cm) tree in the Chicago area (George Ware, Morton Arboretum, 1993, pers. commun.). Species and condition factors are assumed to be 70 percent for all trees, corresponding with species that are fairly well adapted to local growing conditions and in fair to good condition (Table 3). Locations factors range from 65 percent for highway and public housing trees to 75 percent for street trees based on the site context, functional contribution of trees, and likely placement (Table 3).

As described previously, annual tree-replacement value is calculated as the incremental value associated with the yearly increase in trunk diameter of each age class. To avoid double-counting the environmental benefits already discussed (e.g., energy and carbon savings, improvement in air quality, hydrologic benefits), these benefits are totaled and subtracted from the incremental tree replacement value each year. Theoretically, the amount remaining after the environmental benefits already accounted for are deducted represents the value of benefits such as aesthetic value, improved health, wildlife value, and social empowerment.

## Discount Rates

C-BAT was designed to estimate annual costs and benefits over a 30-year period. This is long enough to reflect benefits from maturing trees and still be within the planning horizon of policymakers. With a tree-planting and care program, benefits and costs are incurred at various points in time. Because decisionmakers have other uses for the dollars that they invest in the tree program as well as the ones they receive, it is important that the analysis reflect the cost of other foregone investment opportunities. This usually is done by discounting all benefits and costs to the beginning of the investment period using a rate of compound interest. The discount rate incorporates the time value of money and inflation. The former refers to the fact that a dollar received in the future is worth less than one received in the present since the present dollar can earn interest. Inflation is the anticipated escalation in prices over time. For studies such as this, selecting a discount rate is problematic because the cost of capital for a municipality is different than for a

resident or a nonprofit organization, all of whom are investing in the planting and care of trees. The net present value (NPV) of investments will be higher for decisionmakers with lower discount rates, but lower for those who face a higher cost of capital. At higher discount rates, NPV decrease several fold because most costs are incurred during the first five years when trees are planted, while most benefits accrue later as the trees mature and are discounted heavily. To assess how C-BAT findings change in response to different discount rates simulations were conducted using rates of 4, 7, and 10 percent. The NPV estimates (benefits minus costs) in this study can be interpreted as yield on the investment in excess of the cost of capital (discount or interest rate).

Investment in tree planting is evaluated using NPV and benefit-cost ratios. The former is the present value of benefits minus the present value of costs; the latter is the ratio of the present value of benefits and costs. If the benefit-cost ratio is greater than one, net benefits are produced. Higher ratios and NPV indicate greater returns relative to dollars invested.

## Model Limitations

The application of C-BAT yields results that must be interpreted with care because of the limitations associated with the available data and with C-BAT itself. There is considerable variability in the quality of information upon which C-BAT results are based. For instance, cost data for tree planting, pruning, and removal are thought to be quite reliable, but information on litigation/liability, infrastructure repair, and administration costs was difficult to obtain and is less reliable. Second, there is a high degree of uncertainty associated with some parameters used to model benefits. For example, a stronger empirical basis is needed to estimate benefits not explicitly accounted for, such as "other" benefits. Limitations of the tree valuation method include 1) the need to extrapolate value to large trees for which transplants of similar size are unavailable, 2) the lack of research-based guides for adjusting the basic value by species, condition, and location, and 3) the fact that the amount one demands as compensation for a damaged or destroyed tree may be greater than what one is willing to pay for the same tree prior to the casualty (Randall 1981).

Limited urban forest research makes it necessary to base some assumptions on professional observation and data from forest trees rather than on research results for urban trees. Carbon sequestration benefits may be understated if open-growing urban trees have relatively more biomass than forest trees.

C-BAT accounts for only a few of the many benefits and costs associated with trees. For example, some benefits and costs not explicitly considered in this study include effects of trees on human health and wildlife habitat, as well as costs of pick-up and disposal of tree litter.

This is pioneering research that awaits thorough testing and validation with field data. Results are first-order approximations and some error is to be expected. As our understanding of urban forestry increases better methods will be available to estimate benefits and costs.

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# Results and Discussion

## Growth, Mortality, and Leaf Area

Growth curves for the typical trees are shown in Figure 2. The green ash in park, yard, and public housing sites display similar growth rates. Growth rates for trees along highways and residential streets are slower because less favorable growing conditions are assumed.

Mortality rates reflect anticipated loss associated with growing conditions, care, and likely damage from cars, vandalism, pest/disease, and other impacts. Loss rates are projected to be greatest along residential streets (42 percent), where trees are exposed to a variety of human and environmental abuse (Table 5). A 39-percent loss rate is projected for trees planted in parks, on public housing sites, and along highways. About 18 percent of the trees planted in residential yards are expected to die. Of the 95,000 trees planted, 33,150 (35 percent) are projected to die, leaving 61,850 trees alive at the end of the 30-year analysis (Figure 3).

The total amount of leaf area varies according to tree numbers and size. Although twice as many trees are projected to be planted along residential streets than in yards, total leaf area is similar because yard trees are faster growing (i.e., larger trees) and have a lower mortality rate (Figure 4). Because relatively few trees are projected to be planted in highway and public housing locations, their projected total leaf area is small.

## Future Tree Cover

Patterns of growth and mortality that influence total leaf area have a similar impact on new tree cover (Table 5). Planting of 95,000 trees is projected to add approximately 1,204 acres (487 ha) of future tree cover 30 years after planting began. Yard trees account for 26 percent of all trees planted

and 36 percent of new tree cover. Together, park and street-tree plantings contribute 56 percent of total future tree cover; trees planted along highways and on public housing sites account for the remaining 6 percent.

To place the magnitude of future tree cover in perspective it was compared to the amounts of current tree cover and total land area of Chicago. Based on our analysis of aerial photographs, trees and shrubs cover about 18,608 acres (7,530 ha) or 11.1 percent of total land area in Chicago (McPherson et al. 1993a). The addition of 1,204 acres (487 ha) of new tree cover due to planting of 95,000 trees increases overall tree cover by about 1 percent, assuming no other change in land cover. This future tree cover amounts to 7 percent of existing tree cover, so it is not an insignificant contribution.

Another way to assess the relative impact of these proposed plantings is to project their effect on the current canopy-stocking levels. We found that about 32 percent of land in Chicago that is actively managed is Available Growing Space (AGS), meaning land that can be planted with trees because it is not covered with paving and buildings (McPherson et al. 1993a). The proportion of AGS occupied by trees is called the Canopy Stocking Level (CSL), and is about 25 percent in Chicago. By comparison, CSL for 12 other U.S. cities ranged from 19 to 65 percent (McPherson et al. 1993b). The relatively low CSL for Chicago implies that there is space available for new tree planting, though some of this space should not be planted with trees (e.g., prairie, playfields). The additional 1,204 acres (487 ha) of future tree cover would increase CSL from 25 percent to 28 percent.

## Net Present Values and Benefit-Cost Ratios

The NPV reflects the magnitude of investment in tree planting and care at each location, as well as the flow of benefits and costs over time. The projected NPVs were positive at all

Table 5.—C-BAT results

| Tree location | No. trees planted | Mortality rate (%)[a] | New tree cover[b] | NPV in $1,000[c] | Benefit /cost[d] | Per planted tree (dollars)[e] | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | PV benefit | PV cost | NPV |
| Park | 12,500 | 39 | 190 | 5,592 | 2.14 | 840 | 393 | 447 |
| Yard | 25,000 | 18 | 433 | 14,637 | 3.51 | 818 | 233 | 585 |
| Street | 50,000 | 42 | 489 | 15,160 | 2.81 | 471 | 168 | 303 |
| Highway | 5,000 | 39 | 58 | 1,606 | 2.32 | 564 | 243 | 321 |
| Housing | 2,500 | 39 | 34 | 1,155 | 3.52 | 645 | 184 | 461 |
| Total | 95,000 | 35 | 1,204 | 38,150 | 2.83 | 621 | 219 | 402 |

[a] Percentage of trees planted expected to die during 30-year planning period.
[b] Estimate of new tree cover in acres provided by plantings in 30 years (2022) assuming listed mortality and no replacement planting after 5 years.
[c] Net present values assuming 7-percent discount rate and 30-year analysis period.
[d] Discounted benefit-cost ratio assuming 7-percent discount rate and 30-year analysis period.
[e] Present value of benefits and costs per planted tree assuming 7-percent discount rate and 30-year analysis period.
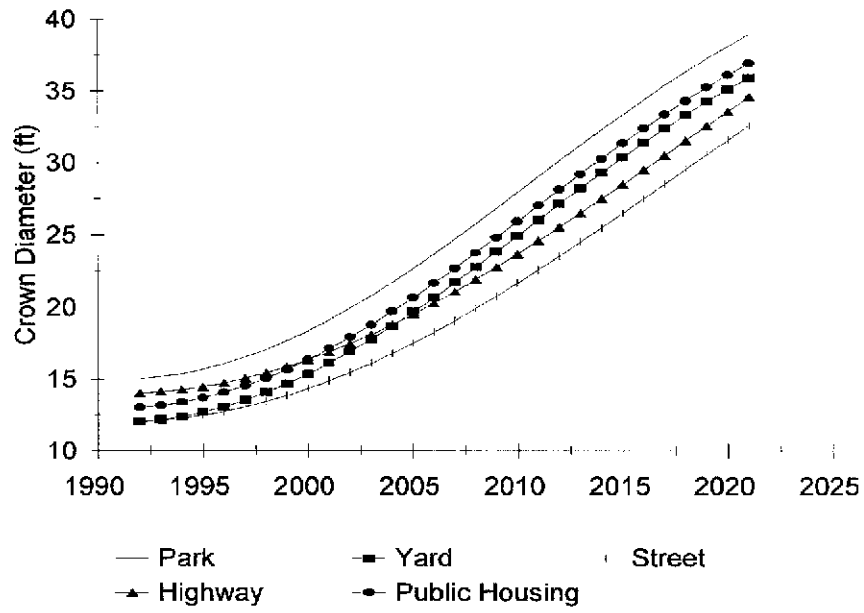
Figure 2. —Growth curves modeled for the typical green ash tree at each planting location.
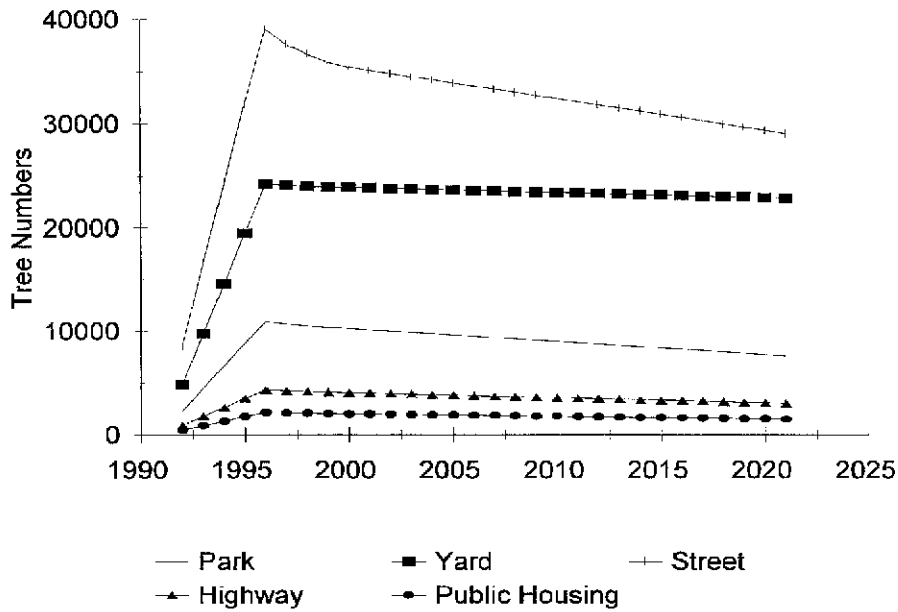


Figure 3. —Projected number of live trees at each location, assuming planting and replacement during the first 5 years only.
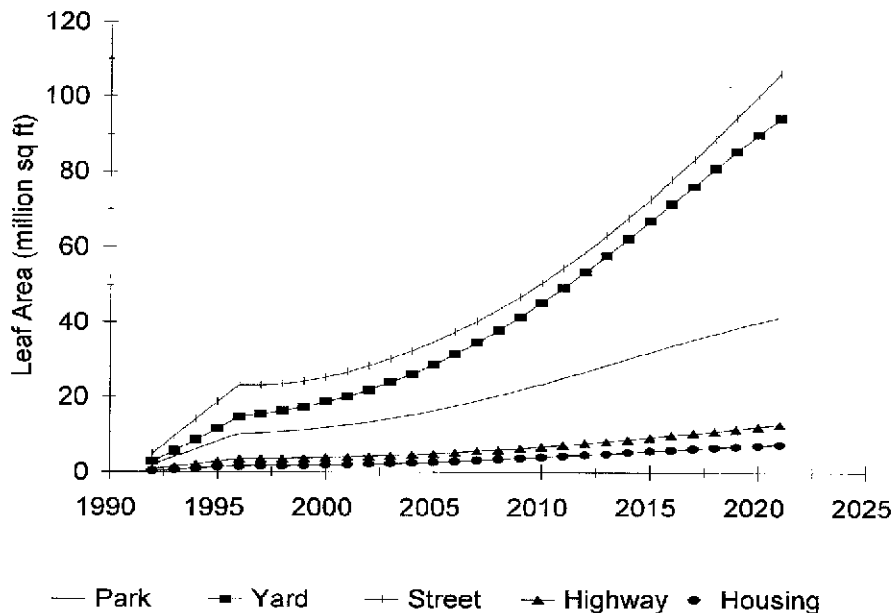
Figure 4. —Projected leaf-surface area for trees at each planting location.

discount rates, ranging from $638,153 at public housing sites with a 10 percent discount rate to $30.6 million for street trees with a 4 percent discount rate. At a 7 percent discount rate, the NPV of the entire planting (95,000 trees) is projected to be $38 million or about $402 per planted tree (Table 5). This means that on average the present value of the yield on investment in tree planting and care in excess of the cost of capital is $402 per tree. The NPV of street and yard trees is projected to be about $15 million each, while the NPV for park tree plantings is $5.6 million. The NPVs are lower for planting and care of trees along highways ($1.6 million) and at public housing sites ($1.2 million) because fewer trees are projected to be planted than in the other locations.

The discounted benefit-cost ratio (BCR), or the present value of benefits divided by costs, is greater than 1.0 at all discount rates. The BCRs range from 1.49 for park trees with a 10-percent discount rate, to 5.52 for residential yard trees with a 4-percent discount rate. At a 7-percent discount rate, the BCR for all locations is 2.83, meaning that $2.83 is returned for every $1 invested in tree planting and care in excess of the 7-percent cost of capital (Table 5). BCRs are projected to be greatest for residential plantings (3.5 for yard and public housing at 7-percent) and least for park trees (2.14), although actual BCRs will vary with the mix of species used and other factors influencing growth, mortality, and tree performance.

Although NPVs and BCRs vary considerably with discount rate, these results indicate that economic incentives for investing in tree planting and care exist, even for decisionmakers who face relatively high discount rates. While the rate of return on investment in tree planting and care is less at higher discount rates, benefits still exceed costs for

this 30 year analysis. Given this result, a 7 percent discount rate is assumed for findings that follow.

The estimated present value of total benefits and costs is $59 and $21 million, respectively (Tables 6 -7). Expenditures for planting alone are projected to account for more than 80 percent of all costs except for trees at public housing sites, where program administration costs are substantial. "Other" scenic, social, and ecological benefits represent 52 to 78 percent of total benefits. Energy savings, removal of atmospheric $CO_2$, and hydrologic benefits are the next most important benefits produced by the trees.

Heating savings associated with reductions in windspeed from the maturing trees are projected to account for about 70 percent of total energy savings (Table 6). This trend, noted in the previous section of this report, can be attributed to Chicago's relatively long heating season and the pervasiveness of space-heating devices compared to air conditioners. The present value of carbon emissions avoided due to heating and cooling energy savings is about 3 to 6 times the value of carbon sequestered by trees (Table 6). In several other studies, savings from avoided emissions were 4 to 15 times greater than savings from direct carbon uptake and storage in tree biomass (Huang et al. 1987; Nowak 1993; Sampson et al. 1992). Smaller avoided emissions for Chicago can be explained by several factors. First, 80 percent of Chicago's base-load electricity is generated by nuclear power, with relatively little emissions of $CO_2$. Second, Chicago has a short cooling season, so savings in air-conditioning energy are less than the national average or regions with warmer weather. Third, although heating savings are substantial in Chicago, natural gas is a relatively clean burning fuel, so

Table 6.—Projected present value of benefits for tree plantings in Chicago (30 year analysis, 7-percent discount rate, in thousands of dollars)

| Benefit category | Tree location | | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| | Park | Yard | Street | Highway | Housing | Total |
| Energy[a] | | | | | | |
| Shade | 233 | 984 | 1,184 | 91 | 75 | 2,567 |
| ET cooling | 340 | 1,296 | 1,676 | 135 | 105 | 3,552 |
| Wind reduction | 1,479 | 5,648 | 7,302 | 586 | 457 | 15,472 |
| Subtotal | 2,052 | 7,928 | 10,162 | 812 | 637 | 21,591 |
| | | | | | | |
| Air quality[b] | | | | | | |
| PM10 | 8 | 11 | 11 | 2 | 1 | 33 |
| Ozone | 1 | 2 | 1 | 0 | 0 | 4 |
| Nitrogen dioxide | 8 | 19 | 18 | 2 | 2 | 49 |
| Sulfur dioxide | 8 | 23 | 21 | 2 | 2 | 56 |
| Carbon monoxide | 1 | 1 | 1 | 0 | 0 | 3 |
| Subtotal | 26 | 56 | 52 | 6 | 5 | 145 |
| | | | | | | |
| Carbon dioxide[c] | | | | | | |
| Sequestered | 37 | 65 | 82 | 12 | 5 | 201 |
| Avoided | 92 | 359 | 465 | 37 | 27 | 980 |
| Subtotal | 129 | 424 | 547 | 49 | 32 | 1,181 |
| | | | | | | |
| Hydrologic[d] | | | | | | |
| Runoff avoided | 46 | 170 | 494 | 24 | 15 | 749 |
| Saved at power plant | 6 | 26 | 32 | 3 | 2 | 69 |
| Subtotal | 52 | 196 | 526 | 27 | 17 | 818 |
| | | | | | | |
| Other benefits[e] | 8,242 | 11,854 | 12,262 | 1,926 | 923 | 35,207 |
| | | | | | | |
| Total | 10,501 | 20,458 | 23,549 | 2,820 | 1,614 | 58,942 |

[a] Net heating and cooling savings estimated using Chicago weather data and utility prices of $0.12 per kWh and $5 per MBtu. Heating costs due to winter shade from trees are included in this analysis.

[b] Implied values calculated using traditional costs of pollution control (see Table 4).

[c] Implied values calculated using traditional costs of control ($0.011/lb) and carbon emission rates of 0.11 lb/kWh and 29.9 lb per MBtu.

[d] Implied values calculated using typical retention/detention basin costs for stormwater runoff control ($0.02/gal) and potable water cost of ($0.00175/gal) for avoided power plant water consumption.

[e] Based on tree replacement costs (Neely 1988).

carbon savings are not great. Thus, care must be taken in comparing results from Chicago with other communities. Savings in air-conditioning energy and associated removal of atmospheric $CO_2$ could be higher in communities served by utilities more reliant on coal, oil, and gas than Commonwealth Edison, or in cities with longer cooling seasons.

## Present Values of Costs and Benefits Per Planted Tree

Differences in return on investment can be understood by examining the present value of costs and benefits per planted tree at different planting locations (Figures 5-6). Despite the fact that trees of similar size and wholesale price are projected for planting in all locations, the present value of planting costs varies markedly, ranging from $109 per tree at public housing sites where volunteer assistance kept costs down to $341 in parks where costs for initial irrigation added to planting expenditures. Participation by residents of public housing in tree

planting and care can reduce initial tree loss to neglect vandalism. Similarly, initial watering of park trees can increase survival rates by reducing tree loss to drought.

The present value of pruning costs is only $12 per planted street tree even though trees are assumed to be pruned more frequently along streets than at other locations (every 6 years). In fact, the present value of total costs is only $168 per tree for street trees (Figure 5). Cost-effective planting and care of street trees is important because they account for about one-third of Chicago's overall tree cover (McPherson et al. 1993a).

The present value of removal costs is projected to be highest for trees planted in parks and public housing sites ($16 to $22 per tree). Costs for infrastructure repair, pest and disease control, and liability/litigation are relatively small. The present value of program administration costs for tree plantings by Openlands and trained volunteers is $35 per planted tree. A similar finding was noted for other U.S. cities (McPherson

Table 7.—Projected present value of costs for tree plantings in Chicago (30 year analysis, 7-percent discount rate, in thousands of dollars)

| Cost category | Tree location | | | | | |
|---|---|---|---|---|---|---|
| | Park | Yard | Street | Highway | Housing | Total |
| Planting[a] | 4,258 | 5,484 | 7,107 | 1,097 | 272 | 18,218 |
| Pruning[b] | 346 | 192 | 585 | 75 | 57 | 1,255 |
| Removal[c] | | | | | | |
| Tree | 221 | 105 | 547 | 18 | 36 | 927 |
| Stump | 27 | 15 | 90 | 9 | 4 | 145 |
| Subtotal | 248 | 120 | 637 | 27 | 40 | 1,072 |
| Tree waste disposal[d] | 31 | 0 | 0 | 0 | 0 | 31 |
| Inspection[e] | 3 | 0 | 13 | 0 | 1 | 17 |
| Infrastructure repair[f] | | | | | | |
| Sewer/water | 3 | 14 | 8 | 0 | 1 | 26 |
| Sidewalk/curb | 5 | 7 | 27 | 1 | 1 | 41 |
| Subtotal | 8 | 21 | 35 | 1 | 2 | 67 |
| Liability/litigation[g] | 0 | 6 | 11 | 1 | 0 | 18 |
| Program administration[h] | 15 | 0 | 0 | 13 | 87 | 115 |
| Total | 4,909 | 5,823 | 8,388 | 1,214 | 459 | 20,793 |

[a] Reported cost of trees, site preparation, planting, and initial watering (see Table 2).

[b] Reported cost of standard Class II pruning. Pruning frequency varied by location (see Table 2).

[c] Reported cost of tree and stump removal. Frequency of removals varied by location (see Table 2).

[d] Tree waste disposal fee $40/ton. Value of wood waste recycled as compost and mulch assumed to offset recycling costs where no net cost shown.

[e] Reported labor and material costs for systematic tree inspection (see Table 2).

[f] Cost of infrastructure repair due to damage from tree roots assumed to vary by location (see Table 2).

[g] Cost of litigation/liability as reported or based on data from other cities (McPherson et al. 1993) when unavailable.

[h] Salaries of administrative personnel and other program administration expenditures. Administrative costs were incorporated in other reported costs for residential street trees.
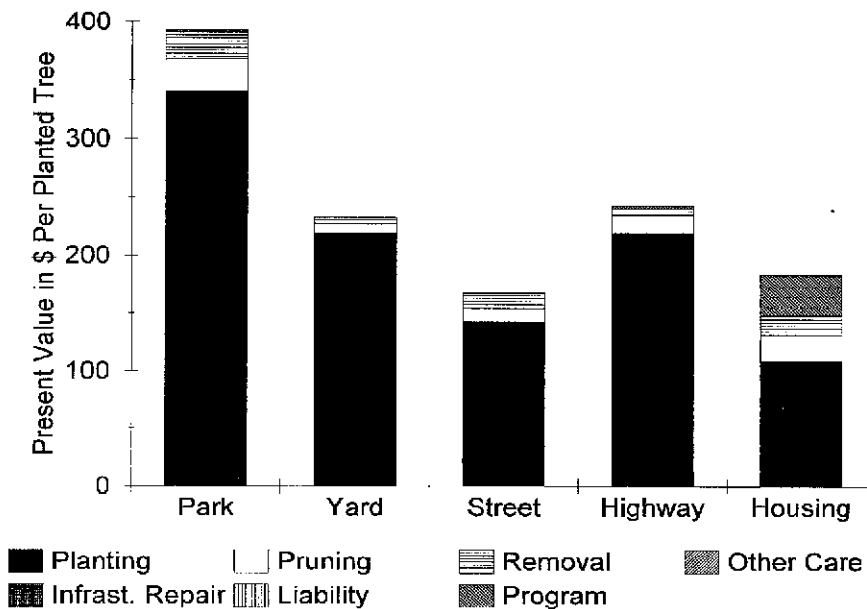


Figure 5. —Present value of costs per tree planted at each location, assuming a 30-year analysis period and 7-percent discount rate.
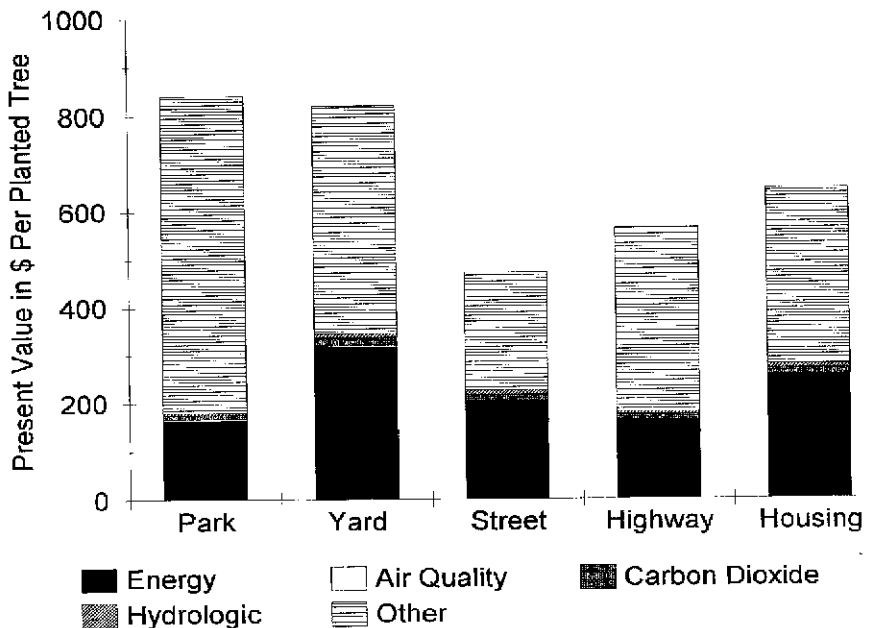
Figure 6. —Present value of benefits per tree planted at each location, assuming a 30-year analysis period and 7-percent discount rate.

et al. 1993b). Generally, nonprofit tree groups have higher administrative costs than municipal programs using in-house or contracted services because of their small size and amount of funds spent organizing and training volunteers. These additional expenditures somewhat offset savings associated with reduced labor costs for planting and initial tree care compared to municipal programs.

The projected present value of benefits per planted tree is $471 and $564 for street and highway plantings, respectively, $645 for public housing sites, and more than $800 for trees planted in parks and residential yards (Figure 6). Lower benefits for street and highway trees can be attributed to their slower growth (Figure 2), smaller total leaf area (Figure 3), and relatively smaller energy and other benefits due to locational factors.

The amount of annual benefits the typical tree produces depends on tree size as well as relations between location and functional performance. Larger trees can produce more benefits than smaller trees because they have more leaf-surface area. Because yard trees exert more influence on building energy use than highway trees, they produce greater energy savings per unit leaf area. To illustrate how these factors influence benefits, nondiscounted annual benefits are estimated for the typical tree at year 30 in each typical location (Table 8). Estimated savings in annual air-conditioning energy from the 36-foot tall (14-inches d.b.h.) yard tree are 201 kWh (0.7 GJ) ($24 nominal) compared to 102 kWh (0.4 GJ) ($12 nominal) for a 34-foot tall (13-inches d.b.h.) tree along a highway. Differences in benefits from the uptake of air pollutants by trees, including carbon sequestered, are assumed to be solely due to differences in tree size, because little is known about spatial variations in pollution

concentrations that influence rates of vegetation uptake. However, location-related differences in cooling energy savings translate into differences in avoided emissions and water consumed in the process of electric power generation. For instance, trees are projected to intercept more particulate matter and absorb more $O_3$ and $NO_2$ directly than in avoided power-plant emissions. But energy savings from the same trees result in greater avoided emissions of $SO_2$, CO, and $CO_2$ than is gained through direct absorption and sequestration. Street trees are projected to provide the greatest annual reductions in avoided stormwater runoff, 327 gallons (12.4 kl) for the 32-foot tall tree (12-inches d.b.h.) compared to 104 gallons (3.9 kl) avoided by a park tree of larger size. More runoff is avoided by street trees than by trees at other sites because street tree canopies intercept rainfall over mostly paved surfaces. In the absence of street trees, rainfall on paving begins to runoff quickly. Trees in yards and parks provide less reduction in avoided runoff because in their absence, more rainfall infiltrates into soil and vegetated areas; thus, less total runoff is avoided. Assumed differences in economic, social, aesthetic, and psychological values attached to trees in different locations are reflected in the projected value of "other" benefits (Table 8).

## Discounted Payback Periods

The discounted payback period is the number of years before the benefit-cost ratio exceeds 1.0 and net benefits begin to accrue. Assuming a 7 percent discount rate, projected payback periods range from 9 years for trees planted and maintained at public housing sites to 15 years for plantings in parks and along highways (Figure 7). Yard and street trees are projected to have 13- and 14-year discounted payback periods, respectively. As expected, payback periods are

Table 8.—Projected annual benefits produced 30 years after planting by the typical green ash tree at typical locations

| Benefit category | Tree location | | | | |
| --- | --- | --- | --- | --- | --- |
| | Park | Yard | Street | Highway | Housing |
| Tree size (height in feet) | 39 | 36 | 32 | 34 | 37 |
| d.b.h. (inches) | 16 | 14 | 12 | 13 | 14.5 |
| Energy | | | | | |
|   Cooling (kWh) | 116 | 201 | 152 | 102 | 179 |
|   Heating (MBtu) | 5.1 | 8.3 | 6.5 | 4.5 | 7.7 |
| PM10 (lb) | | | | | |
|   Direct uptake | 2.19 | 1.8 | 1.41 | 1.67 | 1.93 |
|   Avoided emissions | 0.02 | 0.30 | 0.02 | 0.01 | 0.02 |
| Ozone (lb) | | | | | |
|   Direct uptake | 0.79 | 0.65 | 0.51 | 0.60 | 0.70 |
|   Avoided emissions | 0 | 0.01 | 0.01 | 0 | 0.01 |
| Nitogen dioxide (lb) | | | | | |
|   Direct uptake | 0.55 | 0.45 | 0.36 | 0.42 | 0.48 |
|   Avoided emissions | 0.15 | 0.26 | 0.19 | 0.13 | 0.23 |
| Sulphur dioxide (lb) | | | | | |
|   Direct uptake | 0.51 | 0.42 | 0.33 | 0.39 | 0.45 |
|   Avoided emissions | 0.79 | 1.37 | 1.03 | 0.69 | 1.22 |
| Carbon monoxide (lb) | | | | | |
|   Direct uptake | 0.04 | 0.03 | 0.03 | 0.03 | 0.04 |
|   Avoided emissions | 0.08 | 0.13 | 0.10 | 0.07 | 0.12 |
| Carbon dioxide (lb) | | | | | |
|   Direct uptake | 112 | 94 | 77 | 87 | 49 |
|   Avoided emissions | 166 | 271 | 212 | 145 | 241 |
| Hydrology (gal) | | | | | |
|   Runoff avoided | 104 | 177 | 327 | 132 | 187 |
|   Water saved | 69 | 120 | 91 | 61 | 102 |
| Other benefits (dollars) | 196 | 234 | 248 | 231 | 190 |
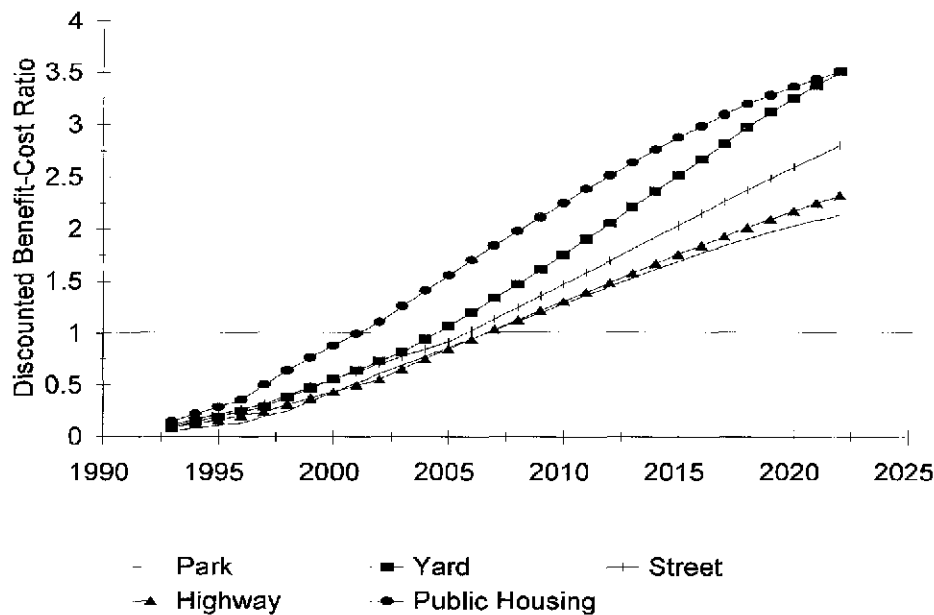


Figure 7. —Discounted payback periods depict the number of years before the benefit-cost ratio exceeds 1.0. This analysis assumes a 30-year planning period and 7-percent discount rate.

slightly longer at the 10 percent discount rate (11 to 18 years), and shorter at most locations with a 4-percent discount rate (9 to 13 years).

Early payback at public housing sites can be attributed to several factors. Trees are projected to add leaf area at a relatively rapid rate due to low initial mortality and fast growth compared to trees at other locations. These trees are relatively inexpensive to plant and establish due to participation by residents and volunteers. Thus, the payback period is shortened because upfront costs, which are heavily discounted compared to costs incurred in the future, are low.

# Conclusions

Are trees worth it? Do their benefits exceed their costs? If so, by how much? Our 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-percent discount rate, 95,000 trees planted), the projected NPV of the simulated tree planting is $38 million or $402 per planted tree. A benefit-cost ratio of 2.83 indicates that the value of projected benefits is nearly three times the value of projected costs.

In what locations do trees provide the greatest net benefits? Benefit-cost ratios are projected to be positive for plantings at park, yard, street, highway, and public housing locations at discount rates ranging from 4 to 10 percent. Assuming a 7-percent discount rate, BCRs are largest for trees in residential yard and public housing (3.5) sites. The following traits are associated with trees in these locations: relatively inexpensive to establish, low mortality rates, vigorous growth, and large energy saving. 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 stormwater runoff, remove atmospheric $CO_2$, 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 receive. C-BAT findings suggest that discounted payback periods for trees in Chicago can range from 9 to 18 years. Shorter payback periods are obtained at lower discount rates, while higher rates lengthen the payback periods. These payback periods compare favorably with those for similar plantings in other U.S. cities (McPherson et al. 1993b).

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. These concepts are not new and many currently are being applied in Chicago. Most of the following recommendations also have application in communities outside Chicago as well.

1. Select the right tree for each location. Given that planting and establishment costs represent a large fraction of total tree expenditures, investing in trees that are well suited to their sites makes economic sense. Matching tree to site should take advantage of local knowledge of the tolerances of various tree species. Species that have proven to be well adapted should be selected in most cases, though limited testing of new introductions increases species diversity and adds new horticultural knowledge (Richards 1993). When selecting a tree an important first question is: will this tree survive the first 5 years after transplanting? A second question is: what are the long-term maintenance requirements of this tree and do they match the level of maintenance likely to be delivered? Fast starters that have short life spans or high maintenance requirements are unlikely to maximize net benefits in the long term. A third question is: what functional benefits does a tree produce and will this species provide them? For example, if summer shade and winter sunlight are desired benefits, then a "solar friendly" species should be given high priority (McPherson 1994: Chapter 7, this report).

2. Weigh the desirability of controlling initial planting costs with the need to provide growing environments suitable for healthy, long-lived trees. Because the costs of initial investments in a project are high, ways to cut up-front costs should be considered. Some strategies include the use of trained volunteers, smaller tree sizes, and follow-up care to increase survival rates. When unamended growing conditions are likely to be favorable, such as yard or garden settings, it may be cost-effective to use smaller, inexpensive stock that reduces planting costs. However, in highly urbanized settings, money may be well spent creating growing environments to improve the long-term performance of trees. Frequent replacement of small trees in restricted growing space may be less economical than investing initially in environments conducive to the culture of long-lived, vigorous shade trees.

3. 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 to 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 long-term tree care plan should include frequent visits to each tree during the first 10 years after planting to develop a sound branching structure and correct other problems, and less frequent but regular pruning, inspection, and treatment as needed. Mature trees in Chicago provide substantial benefits today. Maintenance that extends the life of these trees will pay dividends in the short term, just as routine maintenance of transplants will pay dividends in the future.

Clearly, a healthy urban forest can produce long-term benefits that all Chicagoans can share. This study has developed

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initial estimates of the value of some of these benefits, as well as the costs. To improve the health and increase the productivity of Chicago's urban forest will require increased support from agencies and local residents. Information from this chapter could be part of a public education program aimed at making more residents aware of the value their trees add to the environment in which they live.

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## Chapter 9

# Sustaining Chicago's Urban Forest: Policy Opportunities and Continuing Research

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## Abstract

Chicago's trees are a community resource that provide a myriad of benefits. Obtaining and sustaining higher levels of net benefits from Chicago's urban forest will require more active participation by residents, businesses, utilities, and governments. Opportunities for policies and programs that forge new links between city residents and city trees are outlined. They address issues such as economic development, environmental planning, public housing, energy conservation, and management of the region's air, water, and land resources.

Although this report marks completion of the 3-year Chicago Urban Forest Climate Project, scientists will continue to study many aspects of Chicago's urban environment. Ongoing research that measures and models the effects of trees on urban climate, air quality, and carbon flux is summarized. A book that will document results of this research is planned for publication in 1996.

## Introduction

Research findings presented in this report describe relations between the structure of Chicago's urban forest and environmental and ecological processes that influence hydroclimate, carbon flux, energy use, and air quality. The value that Chicagoans' place on tree-related services is estimated by accounting for annual benefits and costs associated with their planting and long-term care. Strategies are presented that can maximize return on investment.

Chicago's trees are a community resource that provide a myriad of benefits. Obtaining and sustaining higher levels of net benefits from Chicago's urban forest will require more active participation by residents, businesses, utilities, and governments. Whether they know it or not, each of these entities has a vested interest in Chicago's urban forest and stands to gain from the increased benefits it can produce. Policies and programs that could expand the current role of these participants in the planning and management of Chicago's future urban forest are described in the following section.

## Policy and Program Opportunities

### Green Infrastructure and Development

The 1909 Plan of Chicago envisioned a continuous greenbelt of forest preserves, parks, and boulevards around the city. As this "green infrastructure" developed, it added value to nearby properties, provided accessible recreational opportunities, improved local environments, guided growth, and contributed to Chicago's unique character as a "City in a Garden." Today, Chicagoans enjoy many of the benefits that this greenspace provides. As Chicago evolves into the 21st century, the green infrastructure can continue to play a prominent role. Urban forest planning and management can address issues such as job training, conservation education, neighborhood revitalization, mitigation of heat islands, energy conservation, stormwater management and water quality, biological diversity, wildlife habitat, and outdoor recreation.

A comprehensive set of urban forest planning principles could position greenspace once again as a value-adding magnet for economic development. Through planning, greenspaces created as a part of development can be linked and connected to Chicago's historic network of greenbelts and the region's system of greenways. The design of Chicago's new green infrastructure can integrate values that residents demand of greenspace with the most recent advances in urban forest science. In this way, Chicagoans can redefine the greenspace legacy they have inherited to fit the social, economic, and environmental needs of current and future generations.

### Partnerships for Tree Planting and Care at Public Housing Sites

CUFCP research results suggest great potential net benefits from tree planting and care at public housing sites. Relatively large energy savings could accrue to persons in low-income areas who now spend larger than average percentages of their income to heat and cool their homes. Because residents of public housing incur a disproportionate health risk due to exposure to air pollution, tree plantings designed to improve air quality could provide substantial health benefits. Also, local residents who participate in the planting and care of trees can strengthen bonds with both neighbors and nature. Seasonal job training in arboriculture and full-time employment opportunities could result from a substantial commitment to the restoration of urban forests in areas with

the greatest need for increased tree cover. Finally, business opportunities for local entrepreneurs might be increased in a more serene and attractive retail environment associated with a healthy urban forest.

Potential partners for shade tree programs in public housing sites include the Chicago Housing Authority, Chamber of Commerce, Openlands, Commonwealth Edison, People's Gas, Center for Neighborhood Technology, and other local, state, and federal organizations that manage public housing, energy, water, and air resources.

### Urban Forest Stewardship Program

Chicago's street and park trees account for more than one-third of the city's tree cover. The health, welfare, and productivity of these public trees is important to the health, welfare, and productivity of all city residents. The responsibility for stewardship of street and park trees rests with Chicago's Bureau of Forestry and the Chicago Park District. To increase and sustain benefits from public trees, these organizations require adequate funding for tree care operations. Other partners can assist with an urban forest stewardship effort. For example, urban greenspace influences the quantity and quality of stormwater runoff. Thus, there are opportunities for water resource agencies to expand their role from management of local restoration sites to stewardship of the urban-forest canopy. Stewardship programs supported by organizations responsible for managing water, air, and energy resources could provide financial assistance for professional care of existing trees and funds to develop and distribute educational materials for use by residents and design professionals.

### Yard-Tree Planting Program

Electric utilities are beginning to factor the external costs of supplying power into their resource planning process. External costs are costs for reclaiming land, cleaning air, and mitigating other impacts of power production that are not fully reflected in the price of electricity. As generating stations come due for replacement, more utilities are evaluating the potential of shade trees to cool urban heat islands and reduce the demand for air conditioning. Utilities such as Potomac Electric Power Company, Tucson Electric Power, and the Sacramento Municipal Utility District have initiated shade-tree programs because the value of energy saved exceeds the cost of generating new electricity. Each of these programs is a joint effort between the utility and a local nonprofit tree group. The utility provides funding to the group, which implements the yard-tree planting and care program. Urban foresters are employed and trained to ensure that trees are selected and planted where they will provide the greatest energy savings. To save money and promote inter-actions at the neighborhood level, each planting usually involves residents in the same block or neighborhood. Workshops and educational materials are used to train residents in proper planting and tree-care practices.

Initial economic analyses described by McPherson (Chapter 8, this report) suggest that the present value of benefits produced by yard trees in Chicago can be 3 1/2 times their cost. Trees provide benefits other than energy savings that should interest utilities, such as removal of air pollutants and atmospheric carbon dioxide (Chapters 5 and 6, this report). Such economic incentives can provide new opportunities for local utilities to take a more active role in the planting and care of Chicago's urban forest.

In Chicago and surrounding communities steps have been taken to make the most of funds available for urban forestry. Partnerships like Gateway Green bring together municipal foresters, representatives of highway departments and non-profit tree groups, and professional arborists to create and share resources in new ways. Volunteer-based groups like TreeKeepers work with local residents to ensure that trees receive the care they need to survive after planting. The Chicago Bureau of Forestry has invested in a training program and now employs more than 100 certified arborists, each more knowledgeable than ever about tree care. The Chicago Park District is systematically inventorying trees and developing urban-forest management plans for its historic parks. However, the continued support of all Chicagoans is needed to forge new links between city residents and city trees. A public education program that informs residents about the benefits of a healthy and productive urban forest is one way to strengthen this connection.

## Continuing Research

The CUFCP has created an extensive database on urban forest structure and function. Although completion of the 3-year CUFCP is marked by this report, scientists will continue to study many aspects of Chicago's urban environment. A book that will document results of CUFCP work is planned for publication in 1996. Also, methods and tools developed as part of the CUFCP are being improved and disseminated to address urban-forest planning and management issues in other U.S. cities. A brief description of on-going research in Chicago follows.

### Modeling the Effect of Urban Trees on Ozone Concentrations

This cooperative research with the Lake Michigan Air Directors Consortium is investigating the effect of increasing or decreasing the amount of urban trees in Cook and DuPage Counties on concentrations of ozone in the Chicago area. This research will incorporate data on emissions of volatile organic compounds by trees, as well as information on ozone deposition and modifications in air temperature due to trees.

### Emissions of Volatile Organic Compounds by Vegetation

This research is estimating the amount of isoprene, monoterpenes, and other volatile organic compounds emitted by vegetation in the Chicago area in 1991 and comparing these emissions with anthropogenic emissions in the same area. Results will be used to help quantify the overall effect of urban trees on ozone and test the applicability of the U.S. Environmental Protection Agency's Biogenic Emission Inventory System in two heavily urbanized counties. Many

organizations use the Biogenic Emission Inventory System to estimate emissions of non-methane hydrocarbons as part of state implementation plans.

## Measuring and Modeling the Effect of Urban Trees on Microclimate

Research continues to analyze microclimatic data collected at 39 sites to better understand tree influences on climate as a function of area-wide tree and building attributes, nearby tree and building characteristics, and general weather conditions. Validated mathematical models will predict how different building and tree configurations affect air temperature and wind speed in Chicago. Input for the models will consist of hourly weather data from an airport and estimates of characteristics of tree and building structure. The models will be applied to evaluate further how trees influence energy use in houses, air quality, and human comfort outdoors.

## Modeling the Effect of Urban Trees on Local Scale Hydroclimate

This study continues to investigate relations between observed fluxes, in particular latent heat flux (energy going into evaporation) and sensible heat flux (energy going into warming the air) with tree-cover density. A geographic information system, which has been developed, will provide a basis for interpreting the representativeness of flux measurements and for objectively determining model input for surface parameters. Numerical boundary layer models will be used to predict the effects of different tree-planting scenarios on local scale energy and water exchanges.

## Landscape Carbon Budgets and Planning Guidelines

This study quantifies landscape-related carbon storage and annual carbon fluxes for two residential blocks in Chicago. Landscape planting and management guidelines based on increased rates of carbon removal due to direct sequestration by trees and reduction of indirect emissions associated with energy savings for residential heating and cooling will be presented.

## Use of Airborne Videography to Describe Urban Forest Cover in Oak Park, Illinois

Computer image processing technologies provide new tools for assessing urban forest structure and health. This study compares data on land cover from two types of airborne videography in terms of accuracy, cost, and compatibility with geographic information systems. Information on forest cover obtained from black and white and color infrared photographs also are being compared. Potential uses and limitations associated with each type of imagery will be outlined.

# Appendix A

**Supplemental Tables for Chapter 2**

Table 1. —Average shading coefficients (percentage of
sunlight intercepted by foliated tree canopies) used in
regression model for leaf-surface area of individual urban
trees (derived from McPherson 1984)

| Common name | Shading coefficient |
| --- | --- |
| American elm | 0.87 |
| Amur maple | 0.91 |
| Ash (average) | 0.83 |
| Beech | 0.88 |
| Birch | 0.82 |
| Catalpa | 0.76 |
| Cottonwood | 0.85 |
| Crabapple | 0.85 |
| Elm (average) | 0.86 |
| Ginkgo | 0.81 |
| Golden-rain tree | 0.81 |
| Green ash | 0.83 |
| Hackberry | 0.88 |
| Hawthorn | 0.84 |
| Honeylocust | 0.67 |
| Horsechestnut | 0.88 |
| Kentucky coffeetree | 0.86 |
| Linden | 0.88 |
| Maple (average) | 0.86 |
| Norway maple | 0.88 |
| Oak (average) | 0.79 |
| Pear | 0.80 |
| Pin oak | 0.78 |
| Poplar (average) | 0.78 |
| Red maple | 0.83 |
| Red oak | 0.81 |
| Russian olive | 0.87 |
| Serviceberry | 0.77 |
| Shagbark hickory | 0.77 |
| Siberian elm | 0.85 |
| Silver maple | 0.83 |
| Sugar maple | 0.84 |
| Sycamore | 0.86 |
| Tuliptree | 0.90 |
| Walnut/hickory | 0.84 |
| White oak | 0.75 |

## Table 2. —Scientific names of tree species or genera

| Common name | Scientific name | Common name | Scientific name |
|---|---|---|---|
| Ailanthus | *Ailanthus altissima* | Magnolia | *Magnolia spp.* |
| Alder | *Alnus spp.* | Maple (other)[c] | *Acer spp.* |
| American elm | *Ulmus americana* | Mountain ash | *Sorbus spp.* |
| Amur maple | *Acer ginnala* | Mulberry | *Morus spp.* |
| Apple | *Malus pumila* | Norway maple | *Acer platanoides* |
| Arborvitae | *Thuja occidentalis* | Norway spruce | *Picea abies* |
| Ash (other)[a] | *Fraxinus spp.* | Oak (other)[d] | *Quercus spp.* |
| Austrian pine | *Pinus nigra* | Other[e] | |
| Basswood | *Tilia americana* | Pear | *Pyrus spp.* |
| Beech | *Fagus grandifolia* | Pin oak | *Quercus palustris* |
| Black locust | *Robinia pseudoacacia* | Poplar (other)[f] | *Populus spp.* |
| Blue spruce | *Picea pungens* | Prunus spp.[g] | *Prunus spp.* (including *Amygdalus persica*) |
| Boxelder | *Acer negundo* | Redbud | *Cercis canadensis* |
| Buckthorn | *Rhamnus spp.* | Red maple | *Acer rubrum* |
| Bur oak | *Quercus macrocarpa* | Red/black oak | *Quercus rubra/Q. velutina* |
| Catalpa | *Catalpa speciosa* | Red pine | *Pinus resinosa* |
| Chinese elm | *Ulmus parvifolia* | Red/black spruce | *Picea rubens/P. mariana* |
| Cottonwood | *Populus deltoides* | River birch | *Betula nigra* |
| Crabapple | *Malus spp.* | Russian olive | *Elaeagnus angustifolia* |
| Cypress/cedar | *Cupressocyparis spp./ Chamaecyparus spp.* | Sassafras | *Sassafras albidum* |
| Dogwood | *Cornus spp.* | Scotch pine | *Pinus sylvestris* |
| Elm (other)[b] | *Ulmus spp.* | Serviceberry | *Amelanchier spp.* |
| Euonymus | *Euonymus spp.* | Shagbark hickory | *Carya ovata* |
| Fir | *Abies spp.* | Siberian elm | *Ulmus pumila* |
| Ginkgo | *Ginkgo biloba* | Silver maple | *Acer saccharinum* |
| Green/white ash | *Fraxinus pennsylvanica/ F. americana* | Slippery elm | *Ulmus rubra* |
| Golden-rain tree | *Koelreuteria paniculata* | Smoketree | *Cotinus spp.* |
| Hackberry | *Celtis occidentalis* | Spruce (other)[h] | *Picea spp.* |
| Hawthorn | *Crataegus spp.* | Sugar maple | *Acer saccharum* |
| Hemlock | *Tsuga canadensis* | Sumac | *Rhus spp.* |
| Hickory | *Carya spp.* | Swamp white oak | *Quercus bicolor* |
| Honeylocust | *Gleditsia triacanthos* | Sycamore | *Platanus spp.* |
| Honeysuckle | *Lonicera spp.* | Tuliptree | *Liriodendron tulipifera* |
| Horsechestnut | *Aesculus spp.* | Viburnum | *Viburnum spp.* |
| Ironwood | *Ostrya virginiana* | Walnut | *Juglans spp.* |
| Jack pine | *Pinus banksiana* | White birch | *Betula papyrifera* |
| Juniper | *Juniperus spp.* | White oak | *Quercus alba* |
| Kentucky coffeetree | *Gymnocladus dioica* | White pine | *Pinus strobus* |
| Larch | *Larix spp.* | White poplar | *Populus alba* |
| Lilac | *Syringa spp.* | White spruce | *Picea glauca* |
| Linden | *Tilia spp.* (exclusive of *T. americana*) | Willow | *Salix spp.* |
| Lombardi poplar | *Populus nigra italica* | Yew | *Taxus spp.* |

[a] Exclusive of *Fraxinus pennsylvanica* and *F. americana.*
[b] Exclusive of *Ulmus americana, U. parvifolia, U. pumila,* and *U. rubra.*
[c] Exclusive of *Acer ginnala, A. negundo, A. platanoides, A. rubrum, A. saccharum,* and *A. saccharinum.*
[d] Exclusive of *Quercus macrocarpa, Q. rubra, Q, velutina, Q. bicolor,* and *Q. alba.*
[e] Includes 12 minor individual species (sample size = 1) and unknown species that are not included in other species-identification categories.
[f] Exclusive of *Populus deltoides, P. alba,* and *P. nigra italica.*
[g] Cherries, plums, peaches.
[h] Exclusive of *Picea abies, P. rubens, P. mariana,* and *P. glauca.*

Table 3. —Tree composition in Chicago based on number and percentage of trees, and species dominance based on percentage of total leaf-surface area

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| Cottonwood | 535,900 | 303,100 | 13.0 | 1 | 15.8 | 1 |
| Green/white ash | 495,500 | 132,100 | 12.0 | 2 | 12.9 | 2 |
| American elm | 297,100 | 167,200 | 7.2 | 3 | 4.3 | 6 |
| Prunus spp. | 268,200 | 103,100 | 6.5 | 4 | 2.4 | 11 |
| Hawthorn | 259,500 | 105,500 | 6.3 | 5 | 1.9 | 17 |
| Buckthorn | 232,100 | 101,100 | 5.6 | 6 | 0.9 | 27 |
| Honeylocust | 189,000 | 43,800 | 4.6 | 7 | 3.4 | 8 |
| Boxelder | 178,900 | 86,700 | 4.3 | 8 | 2.0 | 15 |
| Mulberry | 166,600 | 49,600 | 4.0 | 9 | 2.3 | 13 |
| Silver maple | 124,700 | 26,800 | 3.0 | 10 | 7.2 | 3 |
| Norway maple | 122,600 | 30,900 | 3.0 | 11 | 6.7 | 5 |
| Yew | 112,000 | 87,700 | 2.7 | 12 | 1.6 | 20 |
| Ash (other) | 107,500 | 58,100 | 2.6 | 13 | 1.5 | 21 |
| Ailanthus | 89,200 | 29,900 | 2.2 | 14 | 4.2 | 7 |
| Crabapple | 77,700 | 28,500 | 1.9 | 15 | 1.9 | 18 |
| Elm (other) | 64,900 | 49,000 | 1.6 | 16 | 1.0 | 23 |
| Hackberry | 62,100 | 33,200 | 1.5 | 17 | 2.3 | 12 |
| Chinese elm | 60,000 | 30,000 | 1.5 | 18 | 0.9 | 26 |
| Blue spruce | 58,900 | 25,200 | 1.4 | 19 | 1.6 | 19 |
| White oak | 49,600 | 29,700 | 1.2 | 20 | 7.0 | 4 |
| Swamp white oak | 47,500 | 34,100 | 1.2 | 21 | 2.3 | 14 |
| Siberian elm | 45,000 | 27,500 | 1.1 | 22 | 0.7 | 29 |
| Walnut | 41,600 | 34,700 | 1.0 | 23 | 1.3 | 22 |
| Honeysuckle | 38,700 | 25,300 | 0.9 | 24 | 0.5 | 32 |
| Hickory | 30,100 | 10,300 | 0.7 | 25 | 0.3 | 33 |
| Norway spruce | 29,200 | 17,900 | 0.7 | 26 | 0.7 | 28 |
| Red/black oak | 29,000 | 26,000 | 0.7 | 27 | 2.5 | 9 |
| Basswood | 26,800 | 13,600 | 0.6 | 28 | 1.9 | 16 |
| Arborvitae | 25,300 | 12,200 | 0.6 | 29 | 0.1 | 44 |
| Shagbark hickory | 20,700 | 14,500 | 0.5 | 30 | 0.1 | 43 |
| Linden | 18,600 | 8,900 | 0.5 | 31 | 2.5 | 10 |
| Lilac | 17,800 | 8,900 | 0.4 | 32 | 0.1 | 42 |
| Sugar maple | 17,700 | 9,600 | 0.4 | 33 | 0.9 | 25 |
| Pear | 14,800 | 10,500 | 0.4 | 34 | 0.2 | 40 |
| White pine | 14,300 | 8,200 | 0.3 | 35 | 0.5 | 31 |
| Other | 13,900 | 7,700 | 0.3 | 36 | 0.0 | 50 |
| Juniper | 13,100 | 10,200 | 0.3 | 37 | 0.0 | 47 |
| Catalpa | 11,600 | 8,200 | 0.3 | 38 | 0.3 | 36 |
| White spruce | 11,000 | 7,900 | 0.3 | 39 | 0.3 | 35 |
| Austrian pine | 10,600 | 7,600 | 0.3 | 40 | 0.0 | 46 |

Table 3.—continued

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| White birch | 9,600 | 9,600 | 0.2 | 41 | 0.5 | 30 |
| Golden-rain tree | 8,700 | 8,700 | 0.2 | 42 | 0.2 | 37 |
| Poplar (other) | 8,700 | 8,700 | 0.2 | 43 | 0.2 | 39 |
| Red maple | 8,700 | 8,700 | 0.2 | 43 | 0.0 | 52 |
| Horsechestnut | 8,200 | 6,200 | 0.2 | 45 | 0.2 | 38 |
| Willow | 7,800 | 7,800 | 0.2 | 46 | 0.1 | 45 |
| Cypress /cedar | 6,700 | 6,700 | 0.2 | 47 | 0.3 | 34 |
| Bur oak | 6,500 | 6,500 | 0.2 | 48 | 1.0 | 24 |
| Black locust | 5,200 | 5,200 | 0.1 | 49 | 0.2 | 41 |
| Dogwood | 5,200 | 3,600 | 0.1 | 49 | 0.0 | 54 |
| Euonymus | 5,200 | 5,200 | 0.1 | 49 | 0.0 | 49 |
| Sumac | 4,500 | 4,500 | 0.1 | 52 | 0.0 | 57 |
| Apple | 3,800 | 3,800 | 0.1 | 53 | 0.0 | 53 |
| Spruce (other) | 2,600 | 2,600 | 0.1 | 54 | 0.0 | 55 |
| Vibumum | 2,600 | 2,600 | 0.1 | 54 | 0.0 | 48 |
| Red pine | 2,000 | 2,000 | 0.0 | 56 | 0.0 | 51 |
| Fir | 1,500 | 1,500 | 0.0 | 57 | 0.0 | 56 |
| White poplar | 1,300 | 1,300 | 0.0 | 58 | 0.0 | 58 |

Table 4. —Tree composition in suburban Cook County based on number and percentage of trees, and species dominance based on percentage of total leaf-surface area

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| Buckthorn | 4,601,600 | 1,430,800 | 14.5 | 1 | 2.9 | 12 |
| Green/white ash | 3,181,900 | 745,300 | 10.0 | 2 | 9.6 | 3 |
| *Prunus* spp. | 2,619,300 | 660,100 | 8.2 | 3 | 4.0 | 9 |
| American elm | 2,126,400 | 741,700 | 6.7 | 4 | 9.8 | 2 |
| Boxelder | 1,757,800 | 447,200 | 5.5 | 5 | 4.6 | 6 |
| Hawthorn | 1,715,600 | 440,100 | 5.4 | 6 | 3.6 | 10 |
| Alder | 1,337,200 | 1,130,400 | 4.2 | 7 | 0.5 | 33 |
| Silver maple | 1,220,200 | 287,900 | 3.8 | 8 | 10.9 | 1 |
| Red/black oak | 1,044,100 | 328,200 | 3.3 | 9 | 5.2 | 4 |
| Poplar (other) | 841,400 | 527,800 | 2.6 | 10 | 1.3 | 21 |
| Black locust | 831,000 | 618,200 | 2.6 | 11 | 0.4 | 38 |
| Slippery elm | 732,900 | 582,800 | 2.3 | 12 | 1.2 | 23 |
| Cottonwood | 715,700 | 352,600 | 2.3 | 13 | 3.0 | 11 |
| Sugar maple | 590,400 | 507,600 | 1.9 | 14 | 1.4 | 20 |
| White oak | 540,100 | 236,200 | 1.7 | 15 | 4.5 | 7 |
| Crabapple | 490,800 | 100,300 | 1.5 | 16 | 1.8 | 15 |
| Honeylocust | 430,400 | 81,200 | 1.4 | 17 | 1.7 | 16 |
| Mulberry | 414,500 | 132,200 | 1.3 | 18 | 1.2 | 22 |
| Bur oak | 408,000 | 211,400 | 1.3 | 19 | 1.6 | 18 |
| Norway maple | 407,900 | 110,700 | 1.3 | 20 | 4.3 | 8 |
| Basswood | 395,300 | 302,400 | 1.2 | 21 | 0.6 | 31 |
| Juniper | 366,700 | 135,700 | 1.2 | 22 | 0.2 | 50 |
| Arborvitae | 335,200 | 148,800 | 1.1 | 23 | 0.3 | 41 |
| Shagbark hickory | 323,200 | 245,700 | 1.0 | 24 | 0.8 | 26 |
| Blue spruce | 321,100 | 85,500 | 1.0 | 25 | 0.8 | 27 |
| Willow | 317,400 | 99,800 | 1.0 | 26 | 5.0 | 5 |
| Ash (other) | 290,600 | 113,100 | 0.9 | 27 | 0.2 | 48 |
| Hickory | 281,200 | 139,300 | 0.9 | 28 | 0.3 | 42 |
| Other | 271,000 | 120,600 | 0.9 | 29 | 1.5 | 19 |
| Elm (other) | 262,400 | 119,600 | 0.8 | 30 | 0.5 | 34 |
| Siberian elm | 216,600 | 76,100 | 0.7 | 31 | 1.6 | 17 |
| Apple | 146,200 | 59,800 | 0.5 | 32 | 0.5 | 35 |
| Maple (other) | 140,400 | 118,700 | 0.4 | 33 | 0.2 | 47 |
| Norway spruce | 138,500 | 42,400 | 0.4 | 34 | 2.7 | 13 |
| Lilac | 137,300 | 57,500 | 0.4 | 35 | 0.1 | 52 |
| Dogwood | 127,500 | 69,100 | 0.4 | 36 | 0.1 | 60 |
| River birch | 124,300 | 91,900 | 0.4 | 37 | 0.4 | 40 |
| Swamp white oak | 123,100 | 55,100 | 0.4 | 38 | 2.5 | 14 |
| Scotch pine | 109,700 | 42,600 | 0.3 | 39 | 0.4 | 37 |
| Red maple | 106,700 | 67,600 | 0.3 | 40 | 0.6 | 32 |

Table 4. —continued

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| Linden | 99,300 | 44,200 | 0.3 | 41 | 0.7 | 29 |
| White birch | 92,400 | 28,200 | 0.3 | 42 | 0.4 | 36 |
| Yew | 90,200 | 42,200 | 0.3 | 43 | 0.1 | 58 |
| Pin oak | 84,100 | 34,000 | 0.3 | 44 | 0.9 | 25 |
| Red pine | 76,300 | 34,800 | 0.2 | 45 | 0.9 | 24 |
| Pear | 64,200 | 32,300 | 0.2 | 46 | 0.2 | 44 |
| Ironwood | 63,300 | 48,500 | 0.2 | 47 | 0.2 | 49 |
| White spruce | 62,500 | 27,500 | 0.2 | 48 | 0.1 | 57 |
| Hackberry | 56,400 | 30,000 | 0.2 | 49 | 0.8 | 28 |
| Sycamore | 54,300 | 40,300 | 0.2 | 50 | 0.1 | 55 |
| Redbud | 52,700 | 31,100 | 0.2 | 51 | 0.2 | 46 |
| Honeysuckle | 48,500 | 29,900 | 0.2 | 52 | 0.1 | 61 |
| Magnolia | 47,900 | 18,600 | 0.2 | 53 | 0.1 | 51 |
| Amur maple | 40,400 | 26,500 | 0.1 | 54 | 0.1 | 54 |
| Sassafras | 35,200 | 28,300 | 0.1 | 55 | 0.1 | 53 |
| Walnut | 32,500 | 17,300 | 0.1 | 56 | 0.4 | 39 |
| Austrian pine | 29,900 | 14,900 | 0.1 | 57 | 0.1 | 56 |
| Catalpa | 27,100 | 14,100 | 0.1 | 58 | 0.6 | 30 |
| Spruce (other) | 21,800 | 15,400 | 0.1 | 59 | 0.0 | 64 |
| Russian olive | 19,700 | 13,000 | 0.1 | 60 | 0.1 | 59 |
| Smoketree | 17,300 | 11,100 | 0.1 | 61 | 0.0 | 69 |
| Larch | 16,400 | 10,400 | 0.1 | 62 | 0.0 | 67 |
| White poplar | 14,800 | 10,400 | 0.0 | 63 | 0.0 | 62 |
| White pine | 14,500 | 10,800 | 0.0 | 64 | 0.2 | 45 |
| Fir | 13,600 | 10,500 | 0.0 | 65 | 0.0 | 63 |
| Lombardi poplar | 11,600 | 11,600 | 0.0 | 66 | 0.0 | 72 |
| Cypress/cedar | 9,000 | 9,000 | 0.0 | 67 | 0.0 | 68 |
| Kentucky coffeetree | 9,000 | 9,000 | 0.0 | 67 | 0.0 | 74 |
| Oak (other) | 9,000 | 9,000 | 0.0 | 67 | 0.0 | 83 |
| Sumac | 9,000 | 9,000 | 0.0 | 67 | 0.0 | 70 |
| Viburnum | 9,000 | 9,000 | 0.0 | 67 | 0.0 | 71 |
| Ginkgo | 7,400 | 5,200 | 0.0 | 72 | 0.0 | 73 |
| Tuliptree | 7,400 | 5,200 | 0.0 | 72 | 0.0 | 66 |
| Euonymus | 6,600 | 6,600 | 0.0 | 74 | 0.0 | 65 |
| Serviceberry | 5,700 | 5,700 | 0.0 | 75 | 0.0 | 75 |
| Horsechestnut | 5,500 | 5,500 | 0.0 | 76 | 0.3 | 43 |

Table 5. —Tree composition in DuPage County based on number and percentage of trees, and species dominance based on percentage of total leaf-surface area

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| Willow | 1,819,400 | 1,754,000 | 12.2 | 1 | 2.3 | 15 |
| Boxelder | 1,630,900 | 454,500 | 10.9 | 2 | 6.2 | 3 |
| Buckthorn | 1,619,400 | 572,600 | 10.9 | 3 | 3.7 | 8 |
| Prunus spp. | 1,253,100 | 333,100 | 8.4 | 4 | 4.3 | 7 |
| Green/white ash | 950,200 | 381,400 | 6.4 | 5 | 5.2 | 5 |
| Cottonwood | 658,600 | 442,500 | 4.4 | 6 | 3.4 | 10 |
| Hawthorn | 650,900 | 175,000 | 4.4 | 7 | 1.2 | 22 |
| Shagbark hickory | 520,700 | 295,800 | 3.5 | 8 | 2.6 | 13 |
| American elm | 458,200 | 168,300 | 3.1 | 9 | 4.5 | 6 |
| Mulberry | 299,300 | 88,300 | 2.0 | 10 | 2.5 | 14 |
| Red/black oak | 299,100 | 131,100 | 2.0 | 11 | 1.9 | 16 |
| Blue spruce | 295,700 | 92,900 | 2.0 | 12 | 1.9 | 17 |
| Silver maple | 286,800 | 47,900 | 1.9 | 13 | 9.4 | 2 |
| Bur oak | 275,700 | 109,700 | 1.9 | 14 | 5.7 | 4 |
| Basswood | 243,500 | 144,400 | 1.6 | 15 | 1.3 | 20 |
| Black locust | 236,900 | 157,300 | 1.6 | 16 | 0.9 | 25 |
| Jack pine | 234,300 | 169,800 | 1.6 | 17 | 0.2 | 39 |
| White oak | 218,200 | 66,900 | 1.5 | 18 | 17.3 | 1 |
| Crabapple | 211,200 | 28,900 | 1.4 | 19 | 1.6 | 19 |
| Walnut | 190,100 | 121,100 | 1.3 | 20 | 3.4 | 9 |
| Arborvitae | 162,800 | 63,500 | 1.1 | 21 | 0.3 | 37 |
| Norway maple | 161,700 | 31,100 | 1.1 | 22 | 3.1 | 11 |
| Sumac | 136,300 | 86,500 | 0.9 | 23 | 0.1 | 59 |
| Honeylocust | 133,700 | 28,900 | 0.9 | 24 | 0.9 | 27 |
| Pin oak | 112,200 | 41,600 | 0.8 | 25 | 2.8 | 12 |
| Elm (other) | 108,500 | 58,800 | 0.7 | 26 | 0.5 | 31 |
| Slippery elm | 108,200 | 79,200 | 0.7 | 27 | 0.7 | 30 |
| Austrian pine | 107,800 | 47,300 | 0.7 | 28 | 0.4 | 32 |
| Other | 102,200 | 59,100 | 0.7 | 29 | 0.1 | 57 |
| Honeysuckle | 98,800 | 54,500 | 0.7 | 30 | 1.7 | 18 |
| Norway spruce | 97,700 | 32,400 | 0.7 | 31 | 0.7 | 29 |
| Sugar maple | 74,400 | 22,300 | 0.5 | 32 | 0.8 | 28 |
| Hackberry | 71,400 | 56,000 | 0.5 | 33 | 0.1 | 50 |
| Siberian elm | 71,300 | 29,200 | 0.5 | 34 | 1.2 | 23 |
| Magnolia | 59,300 | 19,600 | 0.4 | 35 | 0.2 | 38 |
| Apple | 56,200 | 16,100 | 0.4 | 36 | 0.4 | 33 |
| Chinese elm | 49,400 | 29,900 | 0.3 | 37 | 0.2 | 42 |
| Juniper | 48,300 | 16,500 | 0.3 | 38 | 0.1 | 60 |
| White pine | 48,000 | 16,400 | 0.3 | 39 | 0.9 | 26 |
| Red pine | 46,000 | 24,900 | 0.3 | 40 | 0.2 | 45 |

Table 5. —continued

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| Scotch pine | 45,200 | 15,200 | 0.3 | 41 | 0.1 | 46 |
| Red maple | 41,200 | 17,000 | 0.3 | 42 | 1.2 | 21 |
| Linden | 40,200 | 17,900 | 0.3 | 43 | 0.3 | 34 |
| White birch | 40,200 | 16,300 | 0.3 | 43 | 0.2 | 43 |
| Pear | 39,300 | 13,000 | 0.3 | 45 | 0.1 | 58 |
| White spruce | 39,100 | 19,900 | 0.3 | 46 | 0.1 | 48 |
| Hickory | 36,900 | 21,200 | 0.2 | 47 | 0.1 | 56 |
| Yew | 35,600 | 17,200 | 0.2 | 48 | 0.0 | 61 |
| Poplar (other) | 35,600 | 16,700 | 0.2 | 48 | 0.9 | 24 |
| Viburnum | 34,000 | 18,700 | 0.2 | 50 | 0.0 | 69 |
| Dogwood | 33,000 | 11,400 | 0.2 | 51 | 0.1 | 53 |
| Red spruce | 31,000 | 29,200 | 0.2 | 52 | 0.1 | 49 |
| Amur maple | 26,700 | 14,500 | 0.2 | 53 | 0.1 | 55 |
| Redbud | 23,300 | 7,100 | 0.2 | 54 | 0.1 | 54 |
| River birch | 21,100 | 7,800 | 0.1 | 55 | 0.3 | 36 |
| Russian olive | 19,900 | 16,600 | 0.1 | 56 | 0.2 | 40 |
| Lilac | 18,500 | 8,100 | 0.1 | 57 | 0.0 | 66 |
| Fir | 16,000 | 8,900 | 0.1 | 58 | 0.0 | 63 |
| Euonymus | 14,300 | 11,400 | 0.1 | 59 | 0.0 | 64 |
| Maple (other) | 12,600 | 6,800 | 0.1 | 60 | 0.1 | 47 |
| Ash (other) | 11,800 | 8,300 | 0.1 | 61 | 0.0 | 67 |
| Tuliptree | 10,300 | 9,700 | 0.1 | 62 | 0.0 | 73 |
| Hemlock | 10,100 | 6,200 | 0.1 | 63 | 0.0 | 65 |
| Horsechestnut | 9,100 | 5,900 | 0.1 | 64 | 0.2 | 41 |
| Catalpa | 7,400 | 4,700 | 0.0 | 65 | 0.1 | 51 |
| Oak (other) | 5,800 | 4,800 | 0.0 | 66 | 0.0 | 68 |
| White poplar | 5,100 | 3,700 | 0.0 | 67 | 0.2 | 44 |
| Mountain ash | 5,000 | 3,500 | 0.0 | 68 | 0.0 | 62 |
| Kentucky coffeetree | 4,400 | 3,400 | 0.0 | 69 | 0.1 | 52 |
| Sycamore | 3,500 | 2,100 | 0.0 | 70 | 0.3 | 35 |
| Alder | 3,500 | 3,500 | 0.0 | 70 | 0.0 | 72 |
| Beech | 3,400 | 2,900 | 0.0 | 72 | 0.0 | 71 |
| Serviceberry | 2,700 | 2,700 | 0.0 | 73 | 0.0 | 75 |
| Spruce (other) | 1,200 | 1,200 | 0.0 | 74 | 0.0 | 77 |
| Swamp white oak | 1,100 | 1,100 | 0.0 | 75 | 0.0 | 76 |
| Ginkgo | 900 | 900 | 0.0 | 76 | 0.0 | 70 |
| Smoketree | 500 | 500 | 0.0 | 77 | 0.0 | 74 |
| Ailanthus | 500 | 500 | 0.0 | 77 | 0.0 | 78 |

Table 6. —Tree composition in study area based on number and percentage of trees, and species dominance based on percentage of total leaf-surface area

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| Buckthorn | 6,453,100 | 1,544,400 | 12.7 | 1 | 2.9 | 11 |
| Green/white ash | 4,627,500 | 847,600 | 9.1 | 2 | 8.7 | 2 |
| *Prunus* spp. | 4,140,600 | 746,500 | 8.1 | 3 | 3.9 | 9 |
| Boxelder | 3,567,600 | 643,500 | 7.0 | 4 | 4.8 | 5 |
| American elm | 2,881,700 | 778,700 | 5.7 | 5 | 7.6 | 4 |
| Hawthorn | 2,626,000 | 485,300 | 5.2 | 6 | 2.7 | 13 |
| Willow | 2,144,600 | 1,756,800 | 4.2 | 7 | 3.6 | 10 |
| Cottonwood | 1,910,200 | 641,900 | 3.8 | 8 | 4.6 | 6 |
| Silver maple | 1,631,600 | 293,100 | 3.2 | 9 | 10.0 | 1 |
| Red/black oak | 1,372,200 | 354,400 | 2.7 | 10 | 3.9 | 8 |
| Alder | 1,340,700 | 1,130,400 | 2.6 | 11 | 0.3 | 41 |
| Black locust | 1,073,000 | 637,900 | 2.1 | 12 | 0.5 | 35 |
| Poplar (other) | 885,600 | 528,200 | 1.7 | 13 | 1.0 | 25 |
| Mulberry | 880,300 | 166,500 | 1.7 | 14 | 1.7 | 17 |
| Shagbark hickory | 864,600 | 384,800 | 1.7 | 15 | 1.2 | 22 |
| Slippery elm | 841,100 | 588,200 | 1.7 | 16 | 0.9 | 28 |
| White oak | 807,800 | 247,300 | 1.6 | 17 | 8.5 | 3 |
| Crabapple | 779,700 | 108,200 | 1.5 | 18 | 1.8 | 15 |
| Honeylocust | 753,100 | 96,700 | 1.5 | 19 | 1.7 | 18 |
| Norway maple | 692,300 | 119,000 | 1.4 | 20 | 4.2 | 7 |
| Bur oak | 690,200 | 238,300 | 1.4 | 21 | 2.7 | 12 |
| Sugar maple | 682,500 | 508,200 | 1.3 | 22 | 1.2 | 23 |
| Blue spruce | 675,800 | 128,700 | 1.3 | 23 | 1.2 | 24 |
| Basswood | 665,600 | 335,400 | 1.3 | 24 | 1.0 | 26 |
| Arborvitae | 523,300 | 162,200 | 1.0 | 25 | 0.3 | 45 |
| Elm (other) | 435,800 | 142,000 | 0.9 | 26 | 0.6 | 34 |
| Juniper | 428,200 | 137,100 | 0.8 | 27 | 0.1 | 58 |
| Ash (other) | 409,900 | 127,500 | 0.8 | 28 | 0.3 | 44 |
| Other | 387,100 | 134,500 | 0.8 | 29 | 0.9 | 27 |
| Hickory | 348,300 | 141,300 | 0.7 | 30 | 0.2 | 48 |
| Siberian elm | 332,800 | 86,100 | 0.7 | 31 | 1.4 | 20 |
| Norway spruce | 265,400 | 56,300 | 0.5 | 32 | 1.9 | 14 |
| Walnut | 264,100 | 127,100 | 0.5 | 33 | 1.4 | 19 |
| Yew | 237,800 | 98,800 | 0.5 | 34 | 0.3 | 47 |
| Jack pine | 234,300 | 169,800 | 0.5 | 35 | 0.1 | 65 |
| Apple | 206,300 | 62,000 | 0.4 | 36 | 0.4 | 39 |
| Pin oak | 196,300 | 53,700 | 0.4 | 37 | 1.4 | 21 |
| Hackberry | 189,900 | 71,700 | 0.4 | 38 | 0.8 | 30 |
| Honeysuckle | 186,100 | 67,100 | 0.4 | 39 | 0.6 | 33 |
| Lilac | 173,700 | 58,700 | 0.3 | 40 | 0.1 | 59 |
| Swamp white oak | 171,700 | 64,800 | 0.3 | 41 | 1.8 | 16 |

Table 6. —continued

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| Dogwood | 165,700 | 70,100 | 0.3 | 42 | 0.1 | 64 |
| Linden | 158,100 | 48,500 | 0.3 | 43 | 0.6 | 29 |
| Red maple | 156,500 | 70,300 | 0.3 | 44 | 0.7 | 31 |
| Scotch pine | 154,900 | 45,300 | 0.3 | 45 | 0.3 | 43 |
| Maple (other) | 152,900 | 118,800 | 0.3 | 46 | 0.1 | 55 |
| Sumac | 149,900 | 87,100 | 0.3 | 47 | 0.0 | 72 |
| Austrian pine | 148,300 | 50,200 | 0.3 | 48 | 0.2 | 49 |
| River birch | 145,400 | 92,200 | 0.3 | 49 | 0.3 | 42 |
| White birch | 142,200 | 33,900 | 0.3 | 50 | 0.4 | 40 |
| Red pine | 124,300 | 42,800 | 0.2 | 51 | 0.6 | 32 |
| Pear | 118,200 | 36,300 | 0.2 | 52 | 0.2 | 50 |
| White spruce | 112,500 | 34,900 | 0.2 | 53 | 0.1 | 56 |
| Chinese elm | 109,400 | 42,400 | 0.2 | 54 | 0.2 | 51 |
| Magnolia | 107,200 | 27,000 | 0.2 | 55 | 0.2 | 53 |
| Ailanthus | 89,800 | 29,900 | 0.2 | 56 | 0.5 | 36 |
| White pine | 76,800 | 21,300 | 0.2 | 57 | 0.5 | 37 |
| Redbud | 76,000 | 31,900 | 0.1 | 58 | 0.2 | 54 |
| Amur maple | 67,100 | 30,200 | 0.1 | 59 | 0.1 | 61 |
| Ironwood | 63,300 | 48,500 | 0.1 | 60 | 0.1 | 60 |
| Sycamore | 57,800 | 40,300 | 0.1 | 61 | 0.2 | 52 |
| Catalpa | 46,100 | 17,000 | 0.1 | 62 | 0.4 | 38 |
| Viburnum | 45,600 | 21,000 | 0.1 | 63 | 0.0 | 76 |
| Russian olive | 39,600 | 21,100 | 0.1 | 64 | 0.1 | 57 |
| Sassafras | 35,200 | 28,300 | 0.1 | 65 | 0.1 | 63 |
| Fir | 31,000 | 13,900 | 0.1 | 65 | 0.0 | 69 |
| Red spruce | 31,000 | 29,200 | 0.1 | 65 | 0.0 | 67 |
| Euonymus | 26,000 | 14,100 | 0.1 | 68 | 0.0 | 71 |
| Spruce (other) | 25,600 | 15,700 | 0.1 | 69 | 0.0 | 73 |
| Horsechestnut | 22,700 | 10,100 | 0.0 | 70 | 0.3 | 46 |
| White poplar | 21,300 | 11,100 | 0.0 | 71 | 0.1 | 62 |
| Smoketree | 17,800 | 11,100 | 0.0 | 72 | 0.0 | 78 |
| Tuliptree | 17,700 | 11,000 | 0.0 | 73 | 0.0 | 74 |
| Larch | 16,400 | 10,400 | 0.0 | 74 | 0.0 | 79 |
| Cypress/cedar | 15,800 | 11,300 | 0.0 | 75 | 0.0 | 66 |
| Oak (other) | 14,800 | 10,200 | 0.0 | 76 | 0.0 | 81 |
| Kentucky coffeetree | 13,500 | 9,700 | 0.0 | 77 | 0.0 | 68 |
| Lombardi poplar | 11,600 | 11,600 | 0.0 | 78 | 0.0 | 84 |
| Hemlock | 10,100 | 6,200 | 0.0 | 79 | 0.0 | 77 |
| Golden raintree | 8,700 | 8,700 | 0.0 | 80 | 0.0 | 70 |
| Serviceberry | 8,400 | 6,300 | 0.0 | 81 | 0.0 | 83 |
| Ginkgo | 8,300 | 5,300 | 0.0 | 82 | 0.0 | 80 |
| Mountain ash | 5,000 | 3,500 | 0.0 | 83 | 0.0 | 75 |
| Beech | 3,400 | 2,900 | 0.0 | 84 | 0.0 | 82 |

Table 7. —Tree composition on institutional lands dominated by buildings in Chicago, DuPage County and entire study area (no trees were sampled for this land use in suburban Cook County) based on number and percentage of trees, and species dominance based on total leaf-surface area in each sector

| Species | Tree population | | | | Species dominance | |
| | Number | SE | Percent | Rank | Percent | Rank |
|---|---|---|---|---|---|---|
| CHICAGO | | | | | | |
| Green/white ash | 45,600 | 45,600 | 62.5 | 1 | 36.8 | 2 |
| Honeylocust | 18,200 | 18,200 | 25.0 | 2 | 24.5 | 3 |
| Hawthorn | 9,100 | 9,100 | 12.5 | 3 | 38.6 | 1 |
| DUPAGE COUNTY | | | | | | |
| White oak | 14,300 | 14,300 | 25.0 | 1 | 60.0 | 1 |
| Cottonwood | 14,300 | 14,300 | 25.0 | 1 | 35.4 | 2 |
| Boxelder | 14,300 | 14,300 | 25.0 | 1 | 4.5 | 3 |
| Other | 14,300 | 14,300 | 25.0 | 1 | 0.0 | 4 |
| STUDY AREA | | | | | | |
| Green/white ash | 45,600 | 45,600 | 35.0 | 1 | 8.5 | 4 |
| Honeylocust | 18,200 | 18,200 | 14.0 | 2 | 5.6 | 5 |
| White oak | 14,300 | 14,300 | 11.0 | 3 | 46.3 | 1 |
| Cottonwood | 14,300 | 14,300 | 11.0 | 3 | 27.3 | 2 |
| Boxelder | 14,300 | 14,300 | 11.0 | 3 | 3.5 | 6 |
| Other | 14,300 | 14,300 | 11.0 | 3 | 0.0 | 7 |
| Hawthorn | 9,100 | 9,100 | 7.0 | 7 | 8.9 | 3 |

Table 8. —Tree composition on transportational lands in Chicago, DuPage County and entire study area (no trees were sampled on transportational lands in suburban Cook County) based on number and percentage of trees, and species dominance based on total leaf-surface area in each sector

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| **CHICAGO** | | | | | | |
| Yew | 86,700 | 86,700 | 38.5 | 1 | 25.2 | 2 |
| Green/white ash | 86,700 | 86,700 | 38.5 | 1 | 61.7 | 1 |
| Chinese elm | 26,000 | 26,000 | 11.5 | 3 | 5.5 | 3 |
| Honeylocust | 17,300 | 11,800 | 7.7 | 4 | 2.1 | 5 |
| Silver maple | 8,700 | 8,700 | 3.8 | 5 | 5.5 | 4 |
| **DUPAGE COUNTY** | | | | | | |
| Sumac | 13,900 | 13,900 | 50.0 | 1 | 1.1 | 2 |
| White oak | 6,900 | 6,900 | 25.0 | 2 | 98.1 | 1 |
| Buckthorn | 6,900 | 6,900 | 25.0 | 2 | 0.8 | 3 |
| **STUDY AREA** | | | | | | |
| Yew | 86,700 | 86,700 | 34.2 | 1 | 17.1 | 3 |
| Green/white ash | 86,700 | 86,700 | 34.2 | 1 | 41.9 | 1 |
| Chinese elm | 26,000 | 26,000 | 10.3 | 3 | 3.8 | 4 |
| Honeylocust | 17,300 | 11,800 | 6.8 | 4 | 1.4 | 6 |
| Sumac | 13,900 | 13,900 | 5.5 | 5 | 0.4 | 7 |
| Silver maple | 8,700 | 8,700 | 3.4 | 6 | 3.7 | 5 |
| Buckthorn | 6,900 | 6,900 | 2.7 | 7 | 0.2 | 8 |
| White oak | 6,900 | 6,900 | 2.7 | 8 | 31.4 | 2 |

Table 9. —Tree species composition on agricultural lands in DuPage County (no trees were sampled on agricultural lands in other sectors of the study area) based on number and percentage of trees, and species dominance based on total leaf-surface area

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| *Prunus* spp. | 138,200 | 138,200 | 31.3 | 1 | 11.5 | 3 |
| Mulberry | 110,600 | 75,400 | 25.0 | 2 | 33.7 | 2 |
| Other | 55,300 | 55,300 | 12.5 | 3 | 2.9 | 6 |
| Hackberry | 55,300 | 55,300 | 12.5 | 3 | 7.4 | 4 |
| Chinese elm | 27,600 | 27,600 | 6.3 | 5 | 5.2 | 5 |
| Boxelder | 27,600 | 27,600 | 6.3 | 5 | 2.6 | 7 |
| Silver maple | 27,600 | 27,600 | 6.3 | 5 | 36.8 | 1 |

Table 10. —Tree composition on multifamily residential lands in Chicago, suburban Cook County, DuPage County, and entire study area based on number and percentage of trees, and species dominance based on percent of total leaf-surface area in each sector

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| **CHICAGO** | | | | | | |
| Boxelder | 68,700 | 68,700 | 34.5 | 1 | 23.3 | 3 |
| Cottonwood | 34,400 | 34,400 | 17.2 | 2 | 34.9 | 1 |
| Green/white ash | 34,400 | 34,400 | 17.2 | 2 | 7.7 | 5 |
| Honeylocust | 20,600 | 20,600 | 10.3 | 4 | 8.5 | 4 |
| Crabapple | 20,600 | 20,600 | 10.3 | 4 | 25.0 | 2 |
| Norway maple | 20,600 | 20,600 | 10.3 | 4 | 0.7 | 6 |
| **SUBURBAN COOK COUNTY** | | | | | | |
| Honeylocust | 64,500 | 33,400 | 27.8 | 1 | 20.5 | 2 |
| Boxelder | 51,600 | 51,600 | 22.2 | 2 | 10.4 | 5 |
| Lilac | 25,800 | 25,800 | 11.1 | 3 | 11.5 | 4 |
| Blue spruce | 12,900 | 12,900 | 5.6 | 4 | 2.7 | 8 |
| Norway maple | 12,900 | 12,900 | 5.6 | 4 | 25.4 | 1 |
| Red/black oak | 12,900 | 12,900 | 5.6 | 4 | 2.2 | 9 |
| Hawthorn | 12,900 | 12,900 | 5.6 | 4 | 14.3 | 3 |
| Siberian elm | 12,900 | 12,900 | 5.6 | 4 | 6.0 | 7 |
| Crabapple | 12,900 | 12,900 | 5.6 | 4 | 6.4 | 6 |
| Mulberry | 12,900 | 12,900 | 5.6 | 4 | 0.6 | 10 |
| **DUPAGE COUNTY** | | | | | | |
| Blue spruce | 29,600 | 24,600 | 19.4 | 1 | 8.6 | 3 |
| Crabapple | 24,600 | 11,200 | 16.1 | 2 | 33.4 | 1 |
| Red pine | 14,800 | 14,800 | 9.7 | 3 | 7.6 | 4 |
| Honeylocust | 9,900 | 9,900 | 6.5 | 4 | 4.3 | 6 |
| Green/white ash | 9,900 | 6,600 | 6.5 | 4 | 25.8 | 2 |
| White pine | 9,900 | 9,900 | 6.5 | 4 | 1.2 | 10 |
| Austrian pine | 9,900 | 6,600 | 6.5 | 4 | 2.2 | 8 |
| Scotch pine | 4,900 | 4,900 | 3.2 | 8 | 0.4 | 16 |
| Jack pine | 4,900 | 4,900 | 3.2 | 8 | 4.0 | 7 |
| Norway spruce | 4,900 | 4,900 | 3.2 | 8 | 1.1 | 13 |
| Boxelder | 4,900 | 4,900 | 3.2 | 8 | 1.3 | 9 |
| Hemlock | 4,900 | 4,900 | 3.2 | 8 | 0.6 | 15 |
| Buckthorn | 4,900 | 4,900 | 3.2 | 8 | 1.1 | 12 |
| Maple (other) | 4,900 | 4,900 | 3.2 | 8 | 6.7 | 5 |
| Norway maple | 4,900 | 4,900 | 3.2 | 8 | 1.1 | 11 |
| Arborvitae | 4,900 | 4,900 | 3.2 | 8 | 0.6 | 14 |
| **STUDY AREA** | | | | | | |
| Boxelder | 125,300 | 86,100 | 21.4 | 1 | 14.0 | 3 |
| Honeylocust | 95,000 | 40,500 | 16.3 | 2 | 12.1 | 4 |
| Crabapple | 58,200 | 26,800 | 10.0 | 3 | 19.8 | 1 |
| Green/white ash | 44,200 | 35,000 | 7.6 | 4 | 8.6 | 6 |
| Blue spruce | 42,500 | 27,800 | 7.3 | 5 | 2.8 | 9 |
| Norway maple | 38,500 | 24,800 | 6.6 | 6 | 9.9 | 5 |
| Cottonwood | 34,400 | 34,400 | 5.9 | 7 | 14.8 | 2 |
| Lilac | 25,800 | 25,800 | 4.4 | 8 | 4.2 | 8 |
| Red pine | 14,800 | 14,800 | 2.5 | 9 | 1.6 | 11 |
| Hawthorn | 12,900 | 12,900 | 2.2 | 10 | 5.3 | 7 |
| Siberian elm | 12,900 | 12,900 | 2.2 | 10 | 2.2 | 10 |
| Mulberry | 12,900 | 12,900 | 2.2 | 10 | 0.2 | 19 |
| Red/black oak | 12,900 | 12,900 | 2.2 | 10 | 0.8 | 13 |
| White pine | 9,900 | 9,900 | 1.7 | 14 | 0.3 | 16 |
| Austrian pine | 9,900 | 6,600 | 1.7 | 14 | 0.5 | 15 |
| Norway spruce | 4,900 | 4,900 | 0.8 | 16 | 0.2 | 18 |
| Arborvitae | 4,900 | 4,900 | 0.8 | 16 | 0.1 | 20 |
| Scotch pine | 4,900 | 4,900 | 0.8 | 16 | 0.1 | 22 |
| Maple (other) | 4,900 | 4,900 | 0.8 | 16 | 1.4 | 12 |
| Hemlock | 4,900 | 4,900 | 0.8 | 16 | 0.1 | 21 |
| Buckthorn | 4,900 | 4,900 | 0.8 | 16 | 0.2 | 17 |
| Jack pine | 4,900 | 4,900 | 0.8 | 16 | 0.8 | 14 |

Table 11. —Tree composition on commercial/industrial lands in Chicago, suburban Cook County, DuPage County, and entire study area based on number and percentage of trees, and species dominance based on percent of total leaf-surface area in each sector

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| CHICAGO | | | | | | |
| Cottonwood | 16,700 | 16,700 | 50.0 | 1 | 84.1 | 1 |
| Ailanthus | 16,700 | 16,700 | 50.0 | 1 | 15.9 | 2 |
| SUBURBAN COOK COUNTY | | | | | | |
| Green/white ash | 634,900 | 549,200 | 62.2 | 1 | 77.3 | 1 |
| Poplar (other) | 109,500 | 109,500 | 10.7 | 2 | 0.4 | 5 |
| Boxelder | 109,500 | 109,500 | 10.7 | 2 | 11.7 | 2 |
| Other | 109,500 | 109,500 | 10.7 | 2 | 8.1 | 3 |
| *Prunus* spp. | 57,600 | 57,600 | 5.6 | 5 | 2.5 | 4 |
| DUPAGE COUNTY | | | | | | |
| Russian olive | 16,300 | 16,300 | 20.0 | 1 | 20.2 | 3 |
| Siberian elm | 16,300 | 16,300 | 20.0 | 1 | 30.4 | 2 |
| Norway maple | 16,300 | 16,300 | 20.0 | 1 | 41.0 | 1 |
| Green/white ash | 16,300 | 16,300 | 20.0 | 1 | 5.6 | 4 |
| Magnolia | 16,300 | 16,300 | 20.0 | 1 | 2.7 | 5 |
| STUDY AREA | | | | | | |
| Green/white ash | 651,200 | 549,400 | 57.3 | 1 | 47.9 | 1 |
| Boxelder | 109,500 | 109,500 | 9.6 | 2 | 6.9 | 5 |
| Poplar (other) | 109,500 | 109,500 | 9.6 | 2 | 0.2 | 11 |
| Other | 109,500 | 109,500 | 9.6 | 2 | 4.8 | 6 |
| *Prunus* spp. | 57,600 | 57,600 | 5.1 | 5 | 1.5 | 8 |
| Ailanthus | 16,700 | 16,700 | 1.5 | 6 | 0.7 | 10 |
| Cottonwood | 16,700 | 16,700 | 1.5 | 6 | 3.8 | 7 |
| Russian olive | 16,300 | 16,300 | 1.4 | 8 | 7.3 | 4 |
| Siberian elm | 16,300 | 16,300 | 1.4 | 8 | 11.0 | 3 |
| Norway maple | 16,300 | 16,300 | 1.4 | 8 | 14.8 | 2 |
| Magnolia | 16,300 | 16,300 | 1.4 | 8 | 1.0 | 9 |

Table 12. —Tree composition on vacant lands in Chicago, suburban Cook County, DuPage County, and entire study area based on top 20 species in number and percentage of trees, and species dominance based on percent of total leaf-surface area in each sector

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| CHICAGO | | | | | | |
| Cottonwood | 178,300 | 96,800 | 36.1 | 1 | 68.3 | 1 |
| Ash (other) | 52,000 | 52,000 | 10.5 | 2 | 1.3 | 5 |
| Elm (other) | 47,700 | 47,700 | 9.7 | 3 | 7.6 | 3 |
| Walnut | 41,600 | 34,700 | 8.4 | 4 | 12.9 | 2 |
| Mulberry | 39,000 | 34,500 | 7.9 | 5 | 1.1 | 6 |
| American elm | 21,700 | 21,700 | 4.4 | 6 | 1.0 | 8 |
| Buckthorn | 17,300 | 13,300 | 3.5 | 7 | 0.5 | 14 |
| Green/white ash | 17,300 | 13,300 | 3.5 | 7 | 0.8 | 10 |
| Ailanthus | 17,300 | 13,300 | 3.5 | 7 | 0.6 | 13 |
| Chinese elm | 13,000 | 9,300 | 2.6 | 10 | 0.7 | 11 |
| Hawthorn | 13,000 | 13,000 | 2.6 | 10 | 0.5 | 15 |
| Poplar (other) | 8,700 | 8,700 | 1.8 | 12 | 1.9 | 4 |
| Siberian elm | 8,700 | 5,800 | 1.8 | 12 | 1.0 | 7 |
| Red maple | 8,700 | 8,700 | 1.8 | 12 | 0.2 | 16 |
| Honeylocust | 4,900 | 4,900 | 1.0 | 15 | 0.9 | 9 |
| Silver maple | 4,300 | 4,300 | 0.9 | 16 | 0.6 | 12 |
| SUBURBAN COOK COUNTY | | | | | | |
| Poplar (other) | 670,400 | 514,700 | 17.4 | 1 | 23.3 | 1 |
| Black locust | 606,600 | 606,600 | 15.7 | 2 | 1.7 | 11 |
| Cottonwood | 399,100 | 334,500 | 10.3 | 3 | 20.4 | 2 |
| *Prunus* spp. | 367,100 | 317,600 | 9.5 | 4 | 3.5 | 7 |
| Green/white ash | 335,200 | 208,600 | 8.7 | 5 | 3.3 | 8 |
| Boxelder | 271,400 | 155,400 | 7.0 | 6 | 12.6 | 4 |
| American elm | 239,400 | 208,200 | 6.2 | 7 | 7.1 | 5 |
| Buckthorn | 207,500 | 90,000 | 5.4 | 8 | 2.2 | 9 |
| Silver maple | 191,500 | 191,500 | 5.0 | 9 | 5.7 | 6 |
| Willow | 143,700 | 87,900 | 3.7 | 10 | 16.0 | 3 |
| Ash (other) | 127,700 | 96,500 | 3.3 | 11 | 1.7 | 10 |
| Red/black oak | 95,800 | 69,800 | 2.5 | 12 | 0.8 | 13 |
| Dogwood | 79,800 | 64,900 | 2.1 | 13 | 0.9 | 12 |
| White oak | 63,800 | 63,800 | 1.7 | 14 | 0.5 | 14 |
| Pin oak | 31,900 | 21,900 | 0.8 | 15 | 0.2 | 15 |
| Siberian elm | 16,000 | 16,000 | 0.4 | 16 | 0.0 | 16 |
| Other | 16,000 | 16,000 | 0.4 | 16 | 0.0 | 17 |
| DUPAGE COUNTY | | | | | | |
| Willow | 1,767,900 | 1,753,900 | 27.4 | 1 | 5.6 | 10 |
| Boxelder | 956,00 | 366,700 | 14.8 | 2 | 19.3 | 1 |
| Green/white ash | 602,400 | 377,300 | 9.3 | 3 | 10.0 | 2 |
| Buckthorn | 602,400 | 377,300 | 9.3 | 4 | 8.5 | 3 |
| Cottonwood | 406,00 | 392,100 | 6.3 | 5 | 6.7 | 7 |
| Shagbark hickory | 406,00 | 291,000 | 6.3 | 5 | 5.8 | 8 |
| *Prunus* spp. | 340,450 | 188,300 | 5.3 | 7 | 4.0 | 11 |
| Red/black oak | 157,100 | 107,100 | 2.4 | 8 | 5.7 | 9 |
| Basswood | 157,100 | 130,300 | 2.4 | 8 | 6.8 | 6 |
| Black locust | 144,100 | 144,100 | 2.2 | 10 | 1.3 | 14 |
| American elm | 131,000 | 117,700 | 2.0 | 11 | 7.0 | 4 |
| Bur oak | 117,900 | 91,500 | 1.8 | 12 | 6.8 | 5 |
| Walnut | 117,900 | 117,900 | 1.8 | 12 | 3.8 | 12 |
| Hawthorn | 104,800 | 60,200 | 1.6 | 14 | 0.8 | 18 |
| Slippery elm | 91,700 | 78,700 | 1.4 | 15 | 1.8 | 13 |

Table 12. —continued

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| Elm (other) | 78,600 | 56,900 | 1.2 | 16 | 0.6 | 21 |
| Honeysuckle | 65,500 | 53,100 | 1.0 | 17 | 0.7 | 20 |
| Sumac | 39,300 | 39,300 | 0.6 | 18 | 0.1 | 24 |
| Austrian pine | 39,300 | 39,300 | 0.6 | 18 | 1.1 | 16 |
| Pin oak | 26,200 | 26,200 | 0.4 | 20 | 1.3 | 15 |
| Mulberry | 13,100 | 13,100 | 0.2 | 24 | 0.7 | 19 |
| Linden | 13,100 | 13,100 | 0.2 | 24 | 0.9 | 17 |
| STUDY AREA | | | | | | |
| Willow | 1,911,500 | 1,756,100 | 17.7 | 1 | 8.2 | 3 |
| Boxelder | 1,227,300 | 398,200 | 11.4 | 2 | 14.3 | 2 |
| Cottonwood | 983,300 | 524,500 | 9.1 | 3 | 20.3 | 1 |
| Green/white ash | 954,900 | 431,400 | 8.8 | 4 | 6.4 | 5 |
| Buckthorn | 827,200 | 388,100 | 7.7 | 5 | 5.2 | 7 |
| Black locust | 750,600 | 623,400 | 7.0 | 6 | 1.2 | 16 |
| Prunus spp. | 707,600 | 369,300 | 6.6 | 7 | 3.2 | 12 |
| Poplar (other) | 679,100 | 514,800 | 6.3 | 8 | 7.9 | 4 |
| Shagbark hickory | 406,000 | 291,000 | 3.8 | 9 | 3.1 | 13 |
| American elm | 392,100 | 240,100 | 3.6 | 10 | 6.2 | 6 |
| Red/black oak | 252,900 | 127,800 | 2.3 | 11 | 3.3 | 11 |
| Silver maple | 209.000 | 192,000 | 1.9 | 12 | 2.1 | 14 |
| Ash (other) | 179,700 | 109,600 | 1.7 | 13 | 0.7 | 18 |
| Walnut | 159,400 | 122,900 | 1.5 | 14 | 3.9 | 8 |
| Basswood | 157,100 | 130,300 | 1.5 | 15 | 3.5 | 10 |
| Elm (other) | 126,200 | 74,200 | 1.2 | 16 | 1.4 | 15 |
| Bur oak | 117,900 | 91,500 | 1.1 | 17 | 3.6 | 9 |
| Hawthorn | 117,800 | 61,600 | 1.1 | 18 | 0.5 | 22 |
| Slippery elm | 91,700 | 78,700 | 0.8 | 19 | 1.0 | 17 |
| Dogwood | 79,800 | 64,900 | 0.7 | 20 | 0.3 | 25 |
| Pin oak | 58,100 | 34,200 | 0.5 | 23 | 0.7 | 19 |
| Austrian pine | 39,300 | 39,300 | 0.4 | 26 | 0.6 | 20 |

Table 13. —Tree composition on residential lands in Chicago, suburban Cook County, DuPage County, and entire study area based on top 20 species in number and percentage of trees, and species dominance based on percent of total leaf-surface area in each sector

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| **CHICAGO** | | | | | | |
| Green/white ash | 116,100 | 43,600 | 9.2 | 1 | 11.8 | 2 |
| Mulberry | 112,000 | 34,400 | 8.9 | 2 | 2.8 | 12 |
| Honeylocust | 108,400 | 29,800 | 8.6 | 3 | 4.6 | 7 |
| Norway maple | 96,800 | 22,800 | 7.7 | 4 | 12.7 | 1 |
| Silver maple | 78,000 | 18,400 | 6.2 | 5 | 8.0 | 5 |
| *Prunus* spp. | 76,700 | 25,700 | 6.1 | 6 | 1.6 | 15 |
| Blue spruce | 58,900 | 25,200 | 4.7 | 7 | 3.2 | 10 |
| Ailanthus | 55,200 | 20,900 | 4.4 | 8 | 8.4 | 4 |
| American elm | 45,200 | 23,900 | 3.6 | 9 | 1.5 | 17 |
| Swamp white oak | 42,300 | 33,900 | 3.4 | 10 | 3.6 | 9 |
| Honeysuckle | 38,700 | 25,300 | 3.1 | 11 | 1.0 | 22 |
| Ash (other) | 34,800 | 21,300 | 2.8 | 12 | 2.7 | 13 |
| Crabapple | 33,800 | 15,000 | 2.7 | 13 | 0.9 | 23 |
| Norway spruce | 29,200 | 17,900 | 2.3 | 14 | 1.5 | 16 |
| Boxelder | 27,300 | 14,400 | 2.2 | 15 | 0.4 | 29 |
| Yew | 25,400 | 12,900 | 2.0 | 16 | 0.3 | 34 |
| Arborvitae | 25,300 | 12,200 | 2.0 | 17 | 0.2 | 35 |
| Chinese elm | 18,400 | 11,500 | 1.5 | 18 | 1.1 | 19 |
| Lilac | 17,800 | 8,900 | 1.4 | 19 | 0.3 | 33 |
| Pear | 14,800 | 10,500 | 1.2 | 20 | 0.4 | 31 |
| Cottonwood | 14,100 | 11,600 | 1.1 | 22 | 8.5 | 3 |
| Sugar maple | 12,500 | 8,900 | 1.0 | 24 | 1.5 | 18 |
| Linden | 10,800 | 7,800 | 0.9 | 27 | 4.5 | 8 |
| White oak | 10,800 | 7,800 | 0.9 | 27 | 7.4 | 6 |
| White birch | 9,600 | 9,600 | 0.8 | 31 | 1.0 | 20 |
| Basswood | 8,700 | 8,700 | 0.7 | 33 | 3.0 | 11 |
| Bur oak | 6,500 | 6,500 | 0.5 | 38 | 2.0 | 14 |
| **SUBURBAN COOK COUNTY** | | | | | | |
| Silver maple | 603,300 | 124,800 | 9.0 | 1 | 18.1 | 1 |
| Green/white ash | 474,500 | 117,700 | 7.1 | 2 | 9.4 | 2 |
| Crabapple | 423,600 | 93,600 | 6.3 | 3 | 3.3 | 10 |
| Buckthorn | 394,900 | 118,700 | 5.9 | 4 | 0.7 | 25 |
| *Prunus* spp. | 357,800 | 70,900 | 5.3 | 5 | 3.2 | 11 |
| Juniper | 357,700 | 135,400 | 5.3 | 6 | 0.3 | 40 |
| Mulberry | 347,300 | 127,200 | 5.2 | 7 | 2.2 | 15 |
| Arborvitae | 326,200 | 148,500 | 4.9 | 8 | 0.7 | 27 |
| Blue spruce | 299,200 | 84,000 | 4.5 | 9 | 1.5 | 17 |
| Norway maple | 295,500 | 73,000 | 4.4 | 10 | 5.8 | 4 |
| American elm | 285,800 | 115,900 | 4.3 | 11 | 6.6 | 3 |
| Honeylocust | 239,200 | 51,900 | 3.6 | 12 | 2.8 | 13 |
| Siberian elm | 169,600 | 71,100 | 2.5 | 13 | 3.3 | 9 |
| Boxelder | 149,100 | 55,600 | 2.2 | 14 | 2.2 | 14 |
| Apple | 146,200 | 59,800 | 2.2 | 15 | 1.1 | 21 |
| Norway spruce | 129,400 | 41,400 | 1.9 | 16 | 4.9 | 6 |
| White oak | 114,300 | 114,300 | 1.7 | 17 | 4.1 | 8 |
| Lilac | 111,500 | 51,400 | 1.7 | 18 | 0.1 | 48 |
| Red maple | 106,700 | 67,600 | 1.6 | 19 | 1.2 | 20 |
| Willow | 101,400 | 31,000 | 1.5 | 20 | 5.6 | 5 |
| Sugar maple | 65,600 | 31,100 | 1.0 | 24 | 1.4 | 18 |
| Other | 46,000 | 19,100 | 0.7 | 31 | 3.1 | 12 |
| Hackberry | 29,300 | 22,200 | 0.4 | 38 | 1.6 | 16 |
| Swamp white oak | 23,600 | 20,500 | 0.4 | 40 | 4.7 | 7 |
| Catalpa | 18,100 | 10,800 | 0.3 | 44 | 1.3 | 19 |

Table 13. —continued

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| **DUPAGE COUNTY** | | | | | | |
| Buckthorn | 655,600 | 398,800 | 14.5 | 1 | 3.0 | 9 |
| Blue spruce | 266,200 | 89,600 | 5.9 | 2 | 3.3 | 8 |
| Silver maple | 246,000 | 36,900 | 5.4 | 3 | 16.3 | 1 |
| Green/white ash | 242,300 | 37,400 | 5.3 | 4 | 4.7 | 5 |
| *Prunus* spp. | 207,500 | 43,100 | 4.6 | 5 | 2.8 | 11 |
| Crabapple | 162,000 | 23,200 | 3.6 | 6 | 2.2 | 14 |
| Arborvitae | 142,700 | 62,400 | 3.2 | 7 | 0.4 | 39 |
| Norway maple | 133,000 | 25,500 | 2.9 | 8 | 4.1 | 6 |
| Red/black oak | 130,600 | 75,400 | 2.9 | 9 | 1.9 | 16 |
| White oak | 128,900 | 58,300 | 2.8 | 10 | 12.8 | 2 |
| Mulberry | 118,900 | 37,400 | 2.6 | 11 | 1.1 | 26 |
| Hawthorn | 115,300 | 40,000 | 2.5 | 12 | 0.7 | 29 |
| American elm | 108,100 | 33,400 | 2.4 | 13 | 3.8 | 7 |
| Bur oak | 105,000 | 43,200 | 2.3 | 14 | 5.8 | 3 |
| Shagbark hickory | 103,400 | 52,400 | 2.3 | 15 | 2.2 | 15 |
| Honeylocust | 101,200 | 22,000 | 2.2 | 16 | 1.3 | 23 |
| Boxelder | 95,200 | 23,800 | 2.1 | 17 | 1.5 | 22 |
| Black locust | 92,800 | 63,200 | 2.0 | 18 | 1.3 | 25 |
| Norway spruce | 92,800 | 32,000 | 2.0 | 19 | 1.3 | 24 |
| Pin oak | 82,200 | 32,100 | 1.8 | 20 | 4.8 | 4 |
| Siberian elm | 51,200 | 23,900 | 1.1 | 23 | 1.5 | 20 |
| Willow | 47,800 | 12,500 | 1.1 | 25 | 2.6 | 12 |
| Red maple | 41,200 | 17,000 | 0.9 | 28 | 2.3 | 13 |
| White pine | 38,200 | 13,100 | 0.8 | 32 | 1.6 | 18 |
| Poplar (other) | 31,800 | 16,200 | 0.7 | 37 | 1.6 | 17 |
| Cottonwood | 30,400 | 13,100 | 0.7 | 40 | 1.5 | 19 |
| **STUDY AREA** | | | | | | |
| Buckthorn | 1,050,400 | 416,100 | 8.4 | 1 | 1.4 | 21 |
| Silver maple | 927,400 | 131,400 | 7.4 | 2 | 16.3 | 1 |
| Green/white ash | 832,900 | 131,000 | 6.7 | 3 | 8.1 | 2 |
| *Prunus* spp. | 642,000 | 86,900 | 5.1 | 4 | 2.9 | 9 |
| Blue spruce | 624,300 | 125,400 | 5.0 | 5 | 2.3 | 14 |
| Crabapple | 619,400 | 97,600 | 5.0 | 6 | 2.7 | 10 |
| Mulberry | 578,200 | 137,000 | 4.6 | 7 | 1.9 | 15 |
| Norway maple | 525,300 | 80,600 | 4.2 | 8 | 6.1 | 4 |
| Arborvitae | 494,300 | 161,600 | 4.0 | 9 | 0.5 | 37 |
| Honeylocust | 448,800 | 63,800 | 3.6 | 10 | 2.5 | 12 |
| American elm | 439,000 | 123,000 | 3.5 | 11 | 5.1 | 5 |
| Juniper | 419,100 | 136,800 | 3.4 | 12 | 0.2 | 51 |
| Boxelder | 271,600 | 62,200 | 2.2 | 13 | 1.8 | 16 |
| White oak | 254,000 | 128,600 | 2.0 | 14 | 7.3 | 3 |
| Norway spruce | 251,400 | 55,300 | 2.0 | 15 | 3.3 | 7 |
| Siberian elm | 231,200 | 75,300 | 1.8 | 16 | 2.4 | 13 |
| Apple | 206,300 | 62,000 | 1.7 | 17 | 0.8 | 31 |
| Hawthorn | 169,300 | 45,600 | 1.4 | 18 | 0.4 | 41 |
| Red/black oak | 161,700 | 78,700 | 1.3 | 19 | 1.1 | 23 |
| Yew | 151,200 | 47,300 | 1.2 | 20 | 0.2 | 56 |
| Willow | 149,200 | 33,400 | 1.2 | 21 | 4.0 | 6 |
| Red maple | 147,900 | 69,700 | 1.2 | 22 | 1.4 | 20 |
| Bur oak | 121,300 | 44,800 | 1.0 | 26 | 2.5 | 11 |
| Pin oak | 107,200 | 36,000 | 0.9 | 32 | 1.7 | 18 |
| Swamp white oak | 67,000 | 39,600 | 0.5 | 40 | 3.0 | 8 |
| Other | 59,000 | 19,900 | 0.5 | 42 | 1.8 | 17 |
| Cottonwood | 44,500 | 17,500 | 0.4 | 50 | 1.5 | 19 |

Table 14. —Tree composition on institutional lands dominated by vegetation in Chicago, suburban Cook County, DuPage County, and entire study area based on top 20 species in number and percentage of trees, and species dominance based on percent of total leaf-surface area in each sector

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| CHICAGO | | | | | | |
| Cottonwood | 292,300 | 284,500 | 15.8 | 1 | 9.2 | 5 |
| American elm | 230,300 | 164,000 | 12.5 | 2 | 11.9 | 1 |
| Hawthorn | 230,300 | 104,100 | 12.5 | 2 | 4.8 | 9 |
| Buckthorn | 214,700 | 100,200 | 11.6 | 4 | 2.8 | 11 |
| Green/white ash | 195,400 | 67,700 | 10.6 | 5 | 9.6 | 4 |
| Prunus spp. | 191,400 | 99,900 | 10.4 | 6 | 5.5 | 8 |
| Boxelder | 82,800 | 50,800 | 4.5 | 7 | 2.5 | 12 |
| Hackberry | 62,100 | 33,200 | 3.4 | 8 | 8.0 | 7 |
| White oak | 38,800 | 28,700 | 2.1 | 9 | 11.6 | 2 |
| Silver maple | 33,600 | 16,900 | 1.8 | 10 | 10.0 | 3 |
| Red/black oak | 28,500 | 26,000 | 1.5 | 11 | 8.6 | 6 |
| Siberian elm | 25,900 | 25,900 | 1.4 | 12 | 1.1 | 16 |
| Crabapple | 23,300 | 12,700 | 1.3 | 13 | 0.9 | 18 |
| Shagbark hickory | 20,700 | 14,500 | 1.1 | 14 | 0.5 | 24 |
| Ash (other) | 20,700 | 15,000 | 1.1 | 14 | 0.2 | 26 |
| Hickory | 20,700 | 8,600 | 1.1 | 14 | 0.7 | 21 |
| Honeylocust | 19,400 | 10,500 | 1.1 | 17 | 0.8 | 19 |
| Basswood | 18,100 | 10,500 | 1.0 | 18 | 1.5 | 15 |
| Mulberry | 15,500 | 9,500 | 0.8 | 19 | 2.8 | 10 |
| Other | 12,900 | 7,600 | 0.7 | 20 | 0.1 | 31 |
| Linden | 7,800 | 4,400 | 0.4 | 22 | 1.0 | 17 |
| Norway maple | 5,200 | 3,600 | 0.3 | 24 | 1.6 | 14 |
| Sugar maple | 5,200 | 3,600 | 0.3 | 24 | 0.7 | 20 |
| Swamp white oak | 5,200 | 3,600 | 0.3 | 24 | 1.8 | 13 |
| SUBURBAN COOK COUNTY | | | | | | |
| Buckthorn | 3,999,200 | 1,423,000 | 20.0 | 1 | 5.3 | 7 |
| Prunus spp. | 1,836,800 | 571,400 | 9.2 | 2 | 4.9 | 8 |
| Green/white ash | 1,737,200 | 443,300 | 8.7 | 3 | 9.6 | 3 |
| Hawthorn | 1,655,700 | 439,400 | 8.3 | 4 | 7.2 | 4 |
| American elm | 1,601,200 | 702,400 | 8.0 | 5 | 13.7 | 1 |
| Alder | 1,330,100 | 1,130,400 | 6.7 | 6 | 1.1 | 20 |
| Boxelder | 1,176,300 | 397,600 | 5.9 | 7 | 6.0 | 5 |
| Red/black oak | 904,800 | 319,600 | 4.5 | 8 | 10.0 | 2 |
| Slippery elm | 732,900 | 582,800 | 3.7 | 9 | 2.5 | 14 |
| Sugar maple | 524,800 | 506,600 | 2.6 | 10 | 1.7 | 16 |
| Silver maple | 425,300 | 175,100 | 2.1 | 11 | 4.5 | 9 |
| Bur oak | 398,100 | 211,200 | 2.0 | 12 | 2.6 | 13 |
| Basswood | 380,000 | 302,300 | 1.9 | 13 | 1.0 | 21 |
| White oak | 361,900 | 196,600 | 1.8 | 14 | 5.4 | 6 |
| Cottonwood | 316,700 | 111,500 | 1.6 | 15 | 4.4 | 10 |
| Shagbark hickory | 316,700 | 245,600 | 1.6 | 15 | 1.7 | 17 |
| Hickory | 271,400 | 138,900 | 1.4 | 17 | 0.6 | 25 |
| Elm (other) | 262,400 | 119,600 | 1.3 | 18 | 1.1 | 19 |
| Black locust | 190,000 | 117,100 | 1.0 | 19 | 0.3 | 33 |
| Ash (other) | 162,900 | 59,000 | 0.8 | 20 | 0.2 | 36 |
| Norway maple | 99,500 | 82,200 | 0.5 | 24 | 2.9 | 12 |
| Willow | 72,400 | 35,500 | 0.4 | 27 | 3.4 | 11 |
| Pin oak | 27,100 | 20,100 | 0.1 | 36 | 1.7 | 15 |
| Red pine | 27,100 | 27,100 | 0.1 | 36 | 1.6 | 18 |

Table 14. —continued

| Species | Tree population | | | | Species dominance | |
|---|---|---|---|---|---|---|
| | Number | SE | Percent | Rank | Percent | Rank |
| **DUPAGE COUNTY** | | | | | | |
| *Prunus* spp. | 566,900 | 233,500 | 17.9 | 1 | 8.1 | 4 |
| Boxelder | 532,900 | 265,600 | 16.8 | 2 | 9.8 | 2 |
| Hawthorn | 430,900 | 159,400 | 13.6 | 3 | 2.9 | 11 |
| Buckthorn | 349,600 | 162,500 | 11.1 | 4 | 3.1 | 10 |
| Jack pine | 226,800 | 169,700 | 7.2 | 5 | 0.8 | 15 |
| American elm | 219,200 | 115,600 | 6.9 | 6 | 5.7 | 6 |
| Cottonwood | 207,900 | 204,100 | 6.6 | 7 | 4.1 | 8 |
| Sumac | 83,200 | 75,900 | 2.6 | 8 | 0.1 | 23 |
| Green/white ash | 79,400 | 36,900 | 2.5 | 9 | 3.3 | 9 |
| White oak | 68,000 | 28,700 | 2.2 | 10 | 34.1 | 1 |
| Basswood | 60,500 | 60,500 | 1.9 | 11 | 0.6 | 16 |
| Mulberry | 56,700 | 23,300 | 1.8 | 12 | 5.6 | 7 |
| Bur oak | 52,900 | 42,200 | 1.7 | 13 | 6.1 | 5 |
| Walnut | 26,500 | 17,100 | 0.8 | 14 | 8.4 | 3 |
| Sugar maple | 26,500 | 12,200 | 0.8 | 14 | 0.9 | 14 |
| Crabapple | 24,600 | 13,000 | 0.8 | 16 | 0.5 | 17 |
| Honeylocust | 22,700 | 15,900 | 0.7 | 17 | 0.4 | 18 |
| Arborvitae | 15,100 | 10,600 | 0.5 | 18 | 0.2 | 19 |
| Scotch pine | 12,700 | 9,600 | 0.4 | 19 | 0.1 | 28 |
| Viburnum | 11,300 | 11,300 | 0.4 | 20 | 0.0 | 31 |
| Shagbark hickory | 11,300 | 8,400 | 0.4 | 20 | 2.2 | 12 |
| Norway maple | 7,600 | 5,300 | 0.2 | 25 | 1.7 | 13 |
| Siberian elm | 3,800 | 3,800 | 0.1 | 29 | 0.2 | 20 |
| **STUDY AREA** | | | | | | |
| Buckthorn | 4,563,500 | 1,435,700 | 18.3 | 1 | 4.7 | 9 |
| *Prunus* spp. | 2,595,100 | 625,300 | 10.4 | 2 | 5.6 | 7 |
| Hawthorn | 2,316,800 | 478,900 | 9.3 | 3 | 6.2 | 6 |
| American elm | 2,050,600 | 730,500 | 8.2 | 4 | 12.0 | 1 |
| Green/white ash | 2,012,000 | 450,000 | 8.1 | 5 | 8.4 | 3 |
| Boxelder | 1,791,900 | 480,900 | 7.2 | 6 | 6.4 | 5 |
| Alder | 1,330,100 | 1,130,400 | 5.3 | 7 | 0.8 | 23 |
| Red/black oak | 944,600 | 320,800 | 3.8 | 8 | 8.0 | 4 |
| Cottonwood | 816,900 | 367,400 | 3.3 | 9 | 4.8 | 8 |
| Slippery elm | 740,500 | 582,900 | 3.0 | 10 | 1.8 | 14 |
| Sugar maple | 556,400 | 506,800 | 2.2 | 11 | 1.5 | 18 |
| White oak | 468,800 | 200,700 | 1.9 | 12 | 11.4 | 2 |
| Silver maple | 458,900 | 175,900 | 1.8 | 13 | 4.2 | 10 |
| Basswood | 458,600 | 308,400 | 1.8 | 14 | 0.9 | 21 |
| Bur oak | 451,000 | 215,400 | 1.8 | 15 | 3.0 | 11 |
| Shagbark hickory | 348,700 | 246,200 | 1.4 | 16 | 1.7 | 16 |
| Hickory | 292,100 | 139,200 | 1.2 | 17 | 0.5 | 29 |
| Elm (other) | 272,700 | 120,100 | 1.1 | 18 | 0.8 | 22 |
| Jack pine | 226,800 | 169,700 | 0.9 | 19 | 0.1 | 40 |
| Black locust | 195,200 | 117,300 | 0.8 | 20 | 0.3 | 31 |
| Mulberry | 126,500 | 41,900 | 0.5 | 24 | 1.6 | 17 |
| Norway maple | 112,300 | 82,400 | 0.4 | 26 | 2.6 | 12 |
| Willow | 83,900 | 36,500 | 0.3 | 32 | 2.5 | 13 |
| Walnut | 35,500 | 19,400 | 0.1 | 40 | 1.7 | 15 |
| Pin oak | 30,900 | 20,500 | 0.1 | 41 | 1.3 | 19 |
| Red pine | 27,100 | 27,100 | 0.1 | 43 | 1.1 | 20 |

Table 15. —Distribution of tree diameters in Chicago, suburban Cook County, DuPage County, and entire study area, by land use

| Land use | 0-7 cm Percent[a] | SE | 8-15 cm Percent[a] | SE | 16-30 cm Percent[a] | SE | 31-46 cm Percent[a] | SE | 47-61 cm Percent[a] | SE | 62-76 cm Percent[a] | SE | 77+ cm Percent[a] | SE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CHICAGO** | | | | | | | | | | | | | | |
| Agriculture | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Commercial/indust. | 50.0 | 0.0 | 50.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (bldg.) | 0.0 | 0.0 | 62.5 | 23.6 | 25.0 | 28.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 12.5 | 4.7 |
| Institutional (veg.) | 55.2 | 9.7 | 24.8 | 3.3 | 12.6 | 3.2 | 3.6 | 1.1 | 2.0 | 0.9 | 1.1 | 0.5 | 0.7 | 0.4 |
| Multiresidential | 55.2 | 12.4 | 17.2 | 7.2 | 0.0 | 0.0 | 17.2 | 7.2 | 0.0 | 0.0 | 0.0 | 0.0 | 10.3 | 12.8 |
| Residential | 22.8 | 3.0 | 20.0 | 2.7 | 26.8 | 2.8 | 15.5 | 2.1 | 7.9 | 1.8 | 4.4 | 1.1 | 2.6 | 1.2 |
| Transportation | 7.7 | 8.9 | 0.0 | 0.0 | 80.8 | 19.7 | 7.7 | 7.5 | 0.0 | 0.0 | 0.0 | 0.0 | 3.8 | 4.4 |
| Vacant | 51.8 | 9.2 | 22.0 | 3.6 | 10.2 | 3.1 | 12.4 | 3.9 | 1.8 | 0.9 | 0.9 | 0.9 | 1.0 | 1.2 |
| Overall | 41.3 | 4.6 | 22.2 | 1.8 | 19.9 | 2.1 | 9.1 | 1.1 | 3.5 | 0.7 | 1.9 | 0.4 | 2.1 | 0.8 |
| **SUBURBAN COOK COUNTY** | | | | | | | | | | | | | | |
| Agriculture | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Commercial/indust. | 75.1 | 13.5 | 24.9 | 13.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (bldg.) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (veg.) | 64.1 | 3.2 | 20.2 | 1.6 | 11.0 | 1.6 | 2.8 | 0.6 | 1.4 | 0.3 | 0.3 | 0.1 | 0.3 | 0.1 |
| Multiresidential | 27.8 | 11.5 | 22.2 | 10.9 | 44.4 | 10.4 | 5.6 | 5.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Residential | 28.2 | 2.8 | 24.9 | 1.8 | 22.5 | 2.2 | 14.2 | 1.7 | 5.7 | 0.8 | 2.7 | 0.7 | 1.8 | 0.5 |
| Transportation | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Vacant | 80.2 | 4.7 | 10.7 | 2.1 | 5.8 | 2.1 | 2.5 | 1.4 | 0.4 | 0.4 | 0.0 | 0.0 | 0.4 | 0.4 |
| Overall | 58.5 | 2.2 | 20.2 | 1.2 | 12.7 | 1.2 | 5.1 | 0.6 | 2.2 | 0.3 | 0.7 | 0.2 | 0.6 | 0.2 |
| **DUPAGE COUNTY** | | | | | | | | | | | | | | |
| Agriculture | 75.0 | 9.1 | 25.0 | 9.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Commercial/indust. | 40.0 | 22.8 | 0.0 | 0.0 | 40.0 | 22.8 | 20.0 | 18.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (bldg.) | 0.0 | 0.0 | 25.0 | 17.1 | 25.0 | 17.1 | 0.0 | 0.0 | 25.0 | 26.1 | 25.0 | 26.1 | 0.0 | 0.0 |
| Institutional (veg.) | 52.2 | 3.7 | 26.2 | 1.6 | 15.0 | 3.4 | 2.9 | 0.8 | 2.0 | 0.7 | 1.6 | 0.6 | 0.1 | 0.1 |
| Multiresidential | 22.6 | 9.4 | 41.9 | 11.1 | 35.5 | 9.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Residential | 34.6 | 5.3 | 24.3 | 1.8 | 22.1 | 2.9 | 10.0 | 1.3 | 5.1 | 1.0 | 2.6 | 0.5 | 1.2 | 0.4 |
| Transportation | 75.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 25.0 | 0.0 | 0.0 | 0.0 |
| Vacant | 69.5 | 11.3 | 18.5 | 6.8 | 10.2 | 4.6 | 1.2 | 0.7 | 0.6 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| Overall | 54.5 | 5.2 | 22.2 | 3.0 | 15.0 | 2.3 | 4.3 | 0.5 | 2.4 | 0.4 | 1.3 | 0.2 | 0.4 | 0.1 |
| **STUDY AREA** | | | | | | | | | | | | | | |
| Agriculture | 75.0 | 4.3 | 25.0 | 4.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Commercial/indust. | 71.8 | 8.7 | 23.9 | 7.9 | 2.9 | 3.6 | 1.4 | 2.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (bldg.) | 0.0 | 0.0 | 46.0 | 6.2 | 25.0 | 7.0 | 0.0 | 0.0 | 11.0 | 5.5 | 11.0 | 5.5 | 7.0 | 1.0 |
| Institutional (veg.) | 61.9 | 2.6 | 21.3 | 1.2 | 11.6 | 1.4 | 2.9 | 0.5 | 1.6 | 0.3 | 0.5 | 0.1 | 0.3 | 0.1 |
| Multiresidential | 35.8 | 7.3 | 25.7 | 5.5 | 26.9 | 4.0 | 8.1 | 3.9 | 0.0 | 0.0 | 0.0 | 0.0 | 3.5 | 6.1 |
| Residential | 30.0 | 2.2 | 24.2 | 1.2 | 22.8 | 1.5 | 12.8 | 1.1 | 5.7 | 0.6 | 2.8 | 0.5 | 1.7 | 0.4 |
| Transportation | 15.1 | 2.9 | 0.0 | 0.0 | 71.9 | 6.4 | 6.8 | 2.4 | 0.0 | 0.0 | 2.7 | 0.0 | 3.4 | 1.4 |
| Vacant | 72.5 | 4.9 | 15.9 | 2.7 | 8.6 | 2.0 | 2.2 | 0.9 | 0.6 | 0.3 | 0.0 | 0.1 | 0.2 | 0.3 |
| Overall | 56.0 | 2.1 | 20.9 | 1.2 | 13.9 | 1.0 | 5.2 | 0.4 | 2.3 | 0.2 | 1.0 | 0.1 | 0.7 | 0.1 |

[a] Percentage of land-use population in sector

Table 16. —Distribution of tree condition in Chicago, suburban Cook County, DuPage County, and entire study area, by land use

| Land use | | Excellent | | Good | | Moderate | | Poor | | Dying | | Dead | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE |
| **CHICAGO** | | | | | | | | | | | | | |
| Agriculture | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Commercial/indust. | | 0.0 | 0.0 | 100.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (bldg.) | | 25.0 | 9.4 | 62.5 | 14.2 | 12.5 | 4.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (veg.) | | 2.1 | 0.9 | 43.3 | 6.4 | 32.8 | 4.0 | 10.7 | 2.5 | 2.1 | 0.5 | 9.0 | 1.4 |
| Multiresidential | | 27.6 | 6.2 | 44.8 | 6.4 | 27.6 | 10.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Residential | | 18.4 | 2.9 | 52.9 | 4.3 | 23.0 | 3.9 | 5.4 | 1.3 | 0.0 | 0.0 | 0.3 | 0.2 |
| Transportation | | 0.0 | 0.0 | 88.5 | 11.3 | 3.8 | 4.4 | 7.7 | 7.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| Vacant | | 8.8 | 5.3 | 50.7 | 10.8 | 20.3 | 7.3 | 8.8 | 3.0 | 3.5 | 0.9 | 7.9 | 6.3 |
| | Overall | 9.4 | 1.2 | 50.5 | 3.5 | 25.9 | 2.4 | 7.9 | 1.3 | 1.4 | 0.2 | 5.0 | 1.0 |
| **SUBURBAN COOK COUNTY** | | | | | | | | | | | | | |
| Agriculture | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Commercial/indust. | | 14.2 | 15.5 | 64.3 | 11.6 | 21.4 | 3.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (bldg.) | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (veg.) | | 4.6 | 1.0 | 52.9 | 3.4 | 19.7 | 1.7 | 6.7 | 1.1 | 3.4 | 0.7 | 12.7 | 1.8 |
| Multiresidential | | 11.1 | 10.7 | 88.9 | 10.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Residential | | 23.4 | 3.3 | 56.9 | 3.6 | 15.5 | 2.6 | 3.5 | 0.8 | 0.2 | 0.2 | 0.5 | 0.3 |
| Transportation | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Vacant | | 8.3 | 3.3 | 66.5 | 5.6 | 12.0 | 4.1 | 1.7 | 0.7 | 0.4 | 0.4 | 11.2 | 2.6 |
| | Overall | 9.4 | 1.1 | 56.0 | 2.4 | 17.8 | 1.3 | 5.2 | 0.7 | 2.2 | 0.5 | 9.4 | 1.2 |
| **DUPAGE COUNTY** | | | | | | | | | | | | | |
| Agriculture | | 12.5 | 13.7 | 68.8 | 6.9 | 18.8 | 6.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Commercial/indust. | | 40.0 | 22.8 | 60.0 | 22.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (bldg.) | | 0.0 | 0.0 | 50.0 | 19.8 | 0.0 | 0.0 | 25.0 | 26.1 | 0.0 | 0.0 | 25.0 | 17.1 |
| Institutional (veg.) | | 10.5 | 2.8 | 36.7 | 3.8 | 19.5 | 2.1 | 14.5 | 2.7 | 4.3 | 1.6 | 14.5 | 1.8 |
| Multiresidential | | 38.7 | 13.0 | 45.2 | 12.4 | 12.9 | 6.7 | 3.2 | 2.9 | 0.0 | 0.0 | 0.0 | 0.0 |
| Residential | | 23.4 | 3.1 | 51.6 | 4.2 | 15.2 | 2.3 | 5.0 | 1.1 | 1.5 | 0.6 | 3.3 | 1.3 |
| Transportation | | 0.0 | 0.0 | 100.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Vacant | | 10.0 | 3.0 | 61.0 | 9.6 | 13.4 | 5.1 | 7.5 | 3.6 | 2.4 | 1.2 | 5.7 | 2.7 |
| | Overall | 14.6 | 1.8 | 53.1 | 4.4 | 15.3 | 2.4 | 8.0 | 1.7 | 2.4 | 0.6 | 6.6 | 1.3 |
| **STUDY AREA** | | | | | | | | | | | | | |
| Agriculture | | 12.5 | 6.5 | 68.8 | 3.2 | 18.8 | 3.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Commercial/indust. | | 15.6 | 9.7 | 65.1 | 7.7 | 19.3 | 2.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Institutional (bldg.) | | 14.0 | 2.0 | 57.0 | 5.1 | 7.0 | 1.0 | 11.0 | 5.5 | 0.0 | 0.0 | 11.0 | 3.6 |
| Institutional (veg.) | | 5.2 | 0.9 | 50.1 | 2.5 | 20.6 | 1.3 | 8.0 | 0.9 | 3.4 | 0.6 | 12.6 | 1.3 |
| Multiresidential | | 23.9 | 5.3 | 62.4 | 5.3 | 12.8 | 5.1 | 0.8 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| Residential | | 22.9 | 2.1 | 54.6 | 2.4 | 16.2 | 1.7 | 4.2 | 0.6 | 0.7 | 0.2 | 1.5 | 0.4 |
| Transportation | | 0.0 | 0.0 | 89.7 | 3.7 | 3.4 | 1.4 | 6.8 | 2.4 | 0.0 | 0.0 | 0.0 | 0.0 |
| Vacant | | 9.3 | 2.2 | 62.5 | 4.7 | 13.2 | 3.0 | 5.5 | 1.4 | 1.8 | 0.5 | 7.7 | 1.8 |
| | Overall | 10.9 | 0.9 | 54.7 | 2.0 | 17.7 | 1.1 | 6.2 | 0.7 | 2.2 | 0.3 | 8.3 | 0.8 |

[a] Percentage of land-use population in sector

Table 17. —Distribution of ground-surface materials in Chicago, suburban Cook County, DuPage County, and entire study area, by land use

| Surface type | Chicago | | Cook County | | DuPage County | | Study Area | |
|---|---|---|---|---|---|---|---|---|
| | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE |
| **INSTITUTIONAL (vegetation)** | | | | | | | | |
| Grass (maintained) | 46.6 | 5.8 | 32.1 | 4.7 | 41.8 | 6.1 | 35.9 | 3.4 |
| Herbaceous | 11.9 | 3.5 | 15.8 | 2.8 | 12.0 | 2.9 | 14.5 | 2.0 |
| Shrub | 3.7 | 1.5 | 15.4 | 2.9 | 14.4 | 3.5 | 13.7 | 2.1 |
| Duff | 6.1 | 2.8 | 10.9 | 2.7 | 3.9 | 1.8 | 8.9 | 1.9 |
| Soil | 10.5 | 3.4 | 7.7 | 2.0 | 3.3 | 1.4 | 7.1 | 1.4 |
| Grass (unmaintained) | 0.4 | 0.4 | 6.3 | 1.9 | 12.2 | 3.7 | 6.8 | 1.5 |
| Tar | 14.6 | 3.9 | 1.4 | 0.7 | 5.8 | 2.4 | 4.0 | 0.8 |
| Water | 1.5 | 1.3 | 4.0 | 1.8 | 4.2 | 2.5 | 3.7 | 1.3 |
| Rock | 0.6 | 0.6 | 2.3 | 1.4 | 1.7 | 0.7 | 2.0 | 1.0 |
| Building | 0.5 | 0.4 | 1.3 | 1.1 | 0.4 | 0.4 | 1.0 | 0.8 |
| Other structure | 1.7 | 0.8 | 1.0 | 0.5 | 0.1 | 0.1 | 0.9 | 0.3 |
| Cement | 1.4 | 0.6 | 0.8 | 0.5 | 0.0 | 0.0 | 0.7 | 0.3 |
| Other impervious | 0.0 | 0.0 | 0.9 | 0.4 | 0.2 | 0.2 | 0.6 | 0.3 |
| Wood | 0.5 | 0.3 | 0.1 | 0.1 | 0.0 | 0.0 | 0.2 | 0.1 |
| All surfaces | 100.0 | | 100.0 | | 100.0 | | 100.0 | |
| | | | | | | | | |
| **AGRICULTURAL** | | | | | | | | |
| Herbaceous | 0.0 | 0.0 | 60.6 | 12.5 | 76.3 | 9.6 | 67.8 | 8.0 |
| Soil | 100 | 0.0 | 37.8 | 11.7 | 2.7 | 1.6 | 21.4 | 6.2 |
| Grass (unmaintained) | 0.0 | 0.0 | 1.1 | 1.1 | 10.7 | 6.8 | 5.7 | 3.3 |
| Grass (maintained) | 0.0 | 0.0 | 0.6 | 0.6 | 7.3 | 5.2 | 3.8 | 2.5 |
| Tar | 0.0 | 0.0 | 0.0 | 0.0 | 2.0 | 2.0 | 0.9 | 0.9 |
| Rock | 0.0 | 0.0 | 0.0 | 0.0 | 0.6 | 0.6 | 0.3 | 0.3 |
| Duff | 0.0 | 0.0 | 0.0 | 0.0 | 0.3 | 0.3 | 0.2 | 0.2 |
| Shrub | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 |
| Building | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Cement | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Other impervious | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Other structure | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Water | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Wood | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| All surfaces | 100.0 | | 100.0 | | 100.0 | | 100.0 | |
| | | | | | | | | |
| **INSTITUTIONAL (building)** | | | | | | | | |
| Grass (maintained) | 17.3 | 8.0 | 59.7 | 13.7 | 40.2 | 24.4 | 46.5 | 9.6 |
| Tar | 51.6 | 14.8 | 15.2 | 8.1 | 3.0 | 3.0 | 20.4 | 5.7 |
| Building | 20.6 | 13.6 | 19.4 | 13.0 | 16.0 | 16.0 | 19.0 | 8.7 |
| Grass (unmaintained) | 0.0 | 0.0 | 0.0 | 0.0 | 20.0 | 20.0 | 4.2 | 4.2 |
| Cement | 4.8 | 2.7 | 2.6 | 1.3 | 0.6 | 0.6 | 2.6 | 1.0 |
| Herbaceous | 0.0 | 0.0 | 0.0 | 0.0 | 10.0 | 10.0 | 2.1 | 2.1 |
| Rock | 3.1 | 3.1 | 1.0 | 1.0 | 2.0 | 2.0 | 1.7 | 1.0 |
| Soil | 0.6 | 0.6 | 0.3 | 0.2 | 6.0 | 6.0 | 1.6 | 1.3 |
| Other structure | 0.9 | 0.6 | 1.7 | 1.2 | 0.2 | 0.2 | 1.2 | 0.7 |
| Duff | 0.0 | 0.0 | 0.0 | 0.0 | 2.0 | 2.0 | 0.4 | 0.4 |
| Shrub | 0.5 | 0.5 | 0.1 | 0.1 | 0.0 | 0.0 | 0.2 | 0.1 |
| Other impervious | 0.6 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 |
| Water | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Wood | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| All surfaces | 100.0 | | 100.0 | | 100.0 | | 100.0 | |

Table 17.—continued

| Surface type | Chicago Percent[a] | SE | Cook County Percent[a] | SE | DuPage County Percent[a] | SE | Study Area Percent[a] | SE |
|---|---|---|---|---|---|---|---|---|
| **COMMERCIAL/INDUSTRIAL** | | | | | | | | |
| Tar | 35.1 | 8.9 | 27.6 | 8.8 | 35.3 | 9.9 | 30.8 | 5.8 |
| Grass (maintained) | 1.0 | 0.7 | 22.7 | 7.7 | 14.7 | 5.8 | 15.8 | 4.6 |
| Building | 11.5 | 6.0 | 12.1 | 6.2 | 23.7 | 9.9 | 13.7 | 4.2 |
| Other impervious | 21.0 | 8.1 | 5.6 | 5.6 | 0.0 | 0.0 | 8.7 | 3.9 |
| Rock | 9.6 | 5.0 | 5.3 | 3.2 | 0.6 | 0.3 | 5.7 | 2.3 |
| Cement | 7.9 | 2.7 | 3.9 | 1.5 | 7.1 | 3.4 | 5.4 | 1.2 |
| Other structure | 2.6 | 1.2 | 6.8 | 5.1 | 0.5 | 0.4 | 4.7 | 3.0 |
| Soil | 1.7 | 1.2 | 2.9 | 2.8 | 15.7 | 10.4 | 4.6 | 2.3 |
| Water | 0.7 | 0.7 | 5.6 | 5.6 | 0.0 | 0.0 | 3.4 | 3.2 |
| Herbaceous | 4.4 | 2.4 | 3.1 | 2.8 | 0.8 | 0.8 | 3.1 | 1.7 |
| Shrub | 0.0 | 0.0 | 4.6 | 2.8 | 1.5 | 0.5 | 2.9 | 1.6 |
| Grass (unmaintained) | 3.8 | 2.7 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 0.7 |
| Wood | 0.7 | 0.7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 |
| Duff | 0.0 | 0.0 | 0.0 | 0.0 | 0.2 | 0.2 | 0.0 | 0.0 |
| All surfaces | 100.0 | | 100.0 | | 100.0 | | 100.0 | |
| | | | | | | | | |
| **MULTIRESIDENTIAL** | | | | | | | | |
| Building | 42.0 | 14.2 | 15.6 | 10.8 | 26.1 | 10.6 | 30.1 | 8.0 |
| Grass (maintained) | 19.3 | 9.3 | 29.3 | 8.9 | 39.7 | 9.5 | 26.4 | 5.7 |
| Tar | 6.7 | 6.7 | 44.9 | 10.7 | 16.1 | 8.4 | 21.5 | 5.1 |
| Cement | 15.1 | 7.1 | 3.1 | 1.8 | 2.4 | 0.7 | 8.7 | 3.5 |
| Shrub | 7.9 | 4.2 | 3.1 | 1.3 | 4.2 | 1.6 | 5.6 | 2.1 |
| Other impervious | 4.9 | 4.9 | 0.0 | 0.0 | 0.0 | 0.0 | 2.3 | 2.3 |
| Soil | 1.4 | 1.4 | 2.9 | 1.3 | 0.4 | 0.3 | 1.7 | 0.8 |
| Duff | 2.4 | 2.1 | 0.2 | 0.2 | 1.1 | 0.9 | 1.4 | 1.0 |
| Water | 0.0 | 0.0 | 0.0 | 0.0 | 7.7 | 4.3 | 1.4 | 0.8 |
| Rock | 0.0 | 0.0 | 0.3 | 0.3 | 1.2 | 0.5 | 0.3 | 0.1 |
| Herbaceous | 0.3 | 0.3 | 0.0 | 0.0 | 0.8 | 0.6 | 0.3 | 0.2 |
| Other structure | 0.0 | 0.0 | 0.6 | 0.4 | 0.4 | 0.2 | 0.3 | 0.1 |
| Grass (unmaintained) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Wood | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| All surfaces | 100.0 | | 100.0 | | 100.0 | | 100.0 | |
| | | | | | | | | |
| **TRANSPORTATION** | | | | | | | | |
| Tar | 42.7 | 12.1 | 23.5 | 12.3 | 37.2 | 10.1 | 31.4 | 7.9 |
| Grass (maintained) | 12.4 | 6.6 | 28.5 | 14.6 | 14.4 | 5.8 | 21.5 | 8.3 |
| Cement | 15.3 | 7.8 | 15.1 | 9.8 | 12.2 | 8.1 | 14.8 | 6.1 |
| Rock | 20.0 | 9.0 | 11.0 | 7.4 | 1.4 | 0.6 | 12.7 | 5.0 |
| Grass (unmaintained) | 3.6 | 3.6 | 11.1 | 8.2 | 22.8 | 8.7 | 10.1 | 4.8 |
| Soil | 0.9 | 0.7 | 10.3 | 7.3 | 0.4 | 0.4 | 6.0 | 4.0 |
| Herbaceous | 2.3 | 1.9 | 0.0 | 0.0 | 5.6 | 3.8 | 1.4 | 0.8 |
| Other structure | 1.9 | 1.6 | 0.5 | 0.5 | 0.2 | 0.2 | 0.9 | 0.6 |
| Shrub | 0.3 | 0.3 | 0.0 | 0.0 | 3.8 | 2.8 | 0.6 | 0.4 |
| Other impervious | 0.6 | 0.4 | 0.0 | 0.0 | 2.0 | 1.6 | 0.5 | 0.2 |
| Water | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.0 | 0.0 |
| Building | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Duff | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Wood | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| All surfaces | 100.0 | | 100.0 | | 100.0 | | 100.0 | |

Table 17. —continued

| Surface type | Chicago | | Cook County | | DuPage County | | Study Area | |
|---|---|---|---|---|---|---|---|---|
| | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE | Percent[a] | SE |
| VACANT | | | | | | | | |
| Herbaceous | 4.9 | 3.3 | 41.0 | 8.0 | 25.7 | 6.1 | 32.4 | 4.9 |
| Grass (unmaintained) | 32.8 | 11.4 | 25.0 | 6.5 | 31.7 | 10.3 | 28.1 | 5.3 |
| Shrub | 8.2 | 5.4 | 14.7 | 3.9 | 20.9 | 5.3 | 16.4 | 2.9 |
| Grass (maintained) | 13.6 | 8.3 | 9.7 | 6.4 | 3.9 | 2.7 | 8.0 | 3.7 |
| Soil | 14.8 | 6.7 | 5.7 | 3.1 | 8.3 | 5.6 | 7.5 | 2.7 |
| Duff | 8.6 | 6.9 | 0.6 | 0.5 | 4.3 | 2.3 | 2.7 | 1.1 |
| Water | 0.0 | 0.0 | 1.6 | 1.1 | 1.7 | 1.4 | 1.5 | 0.8 |
| Rock | 4.1 | 3.6 | 1.6 | 1.1 | 0.5 | 0.5 | 1.4 | 0.7 |
| Tar | 3.6 | 3.6 | 0.0 | 0.0 | 3.0 | 2.7 | 1.4 | 1.0 |
| Cement | 8.3 | 4.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.4 |
| Wood | 0.9 | 0.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 |
| Other structure | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Other impervious | 0.1 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Building | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| All surfaces | 100.0 | | 100.0 | | 100.0 | | 100.0 | |
| | | | | | | | | |
| RESIDENTIAL | | | | | | | | |
| Grass (maintained) | 29.0 | 1.4 | 42.0 | 2.1 | 52.3 | 1.7 | 42.4 | 1.3 |
| Building | 21.6 | 0.7 | 14.4 | 0.8 | 10.4 | 0.5 | 14.6 | 0.5 |
| Tar | 11.3 | 0.7 | 14.2 | 1.5 | 12.4 | 1.0 | 13.2 | 0.9 |
| Cement | 17.0 | 0.7 | 10.3 | 1.0 | 6.1 | 0.7 | 10.4 | 0.6 |
| Other structure | 7.9 | 0.5 | 5.3 | 0.5 | 4.4 | 0.5 | 5.5 | 0.3 |
| Shrub | 2.4 | 0.3 | 4.9 | 0.4 | 6.2 | 0.9 | 4.8 | 0.3 |
| Soil | 5.7 | 0.7 | 2.7 | 0.6 | 1.7 | 0.2 | 3.0 | 0.3 |
| Herbaceous | 2.3 | 0.3 | 2.4 | 0.5 | 2.5 | 0.4 | 2.4 | 0.3 |
| Rock | 1.2 | 0.2 | 2.2 | 0.4 | 1.9 | 0.3 | 1.9 | 0.2 |
| Other impervious | 0.7 | 0.2 | 0.8 | 0.3 | 0.5 | 7.1 | 0.7 | 1.9 |
| Duff | 0.4 | 0.2 | 0.3 | 0.1 | 0.9 | 0.2 | 0.5 | 0.1 |
| Water | 0.0 | 0.0 | 0.4 | 0.3 | 0.4 | 0.3 | 0.3 | 0.2 |
| Grass (unmaintained) | 0.5 | 0.3 | 0.2 | 0.1 | 0.3 | 0.3 | 0.2 | 0.1 |
| Wood | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 | 0.0 | 0.2 | 0.0 |
| All surfaces | 100.0 | | 100.0 | | 100.0 | | 100.0 | |

[a] Percentage of land-use population in sector.

# Appendix B

**Trees for Energy-Efficient Landscapes in Chicago**

Trees for energy-efficient landscapes in the Chicago area .

| Tree species | | Solar friendly | Form | Growth rate | Longevity |
|---|---|---|---|---|---|
| **Small (< 20 feet)** | | | | | |
| Dogwood, Corneliancherry | *Cornus mas* | NA | R | S | I |
| Filbert, European | *Corylus avellana* | NA | S | M | I |
| Hawthorn | *Crataegus spp.* | | | | |
|   Cockspur | *C. crus-galli* | Y | L | M | I |
|   Dotted | *C. punctata* | Y | L | M | L |
|   Downy | *C. mollis* | N | L | M | L |
|   Lavelle | *C. x lavallei* | N | R | M | I |
|   Vaughn | *C. 'Vaughn'* | NA | L | M | I |
|   Washington | *C. phaenopyrum* | N | V | M | I |
|   Winter King | *C. viridis 'Winter King'* | N | L | M | I |
| Lilac, Japanese Tree | *Syringa reticulata* | Y | R | S | I |
| Maple, Amur | *Acer ginnala* | Varies | R | M | I |
| Redbud | *Cercis canadensis* | Y | B | M | I |
| Smoketree, Common | *Cotinus coggygria* | Y | S | M | I |
| Willow, French Pussy | *Salix caprea* | NA | S | R | S |
| Crabapples | *Malus spp.* | Varies | Varies | M | I |
| **Medium (20-40 feet)** | | | | | |
| Alder | *Alnus spp.* | | | | |
|   European Black | *A. glutinosa* | N | O | R | I |
|   White | *A. incana* | NA | O | R | I |
| Catalpa | *Catalpa spp.* | | | | |
|   Chinese | *C. ovata* | NA | R | M | L |
|   Northern or Western | *C. speciosa* | NA | O | R | I |
|   Southern | *C. bignonioides* | NA | R | M | I |
| Corktree, Amur | *Phellodendron amurense* | Y | R | M | L |
| Elm, Lacebark | *Ulmus parviflora* | N | R | M | I |
| Linden, Littleleaf | *Tilia cordata* | Varies | P | M | I |
| Maple | *Acer spp.* | | | | |
|   Hedge | *A. campestre* | Varies | B | M | I |
|   Miyabe | *A. miyabei* | NA | R | M | L |
|   Tartarian | *A. tataricum* | NA | R | M | L |
| Osage-orange | *Maclura pomifera* | NA | R | M | L |
| Pagodatree, Japanese | *Sophora japonica* | Y | R | M | L |
| Poplar, Quaking Aspen | *Populus tremuloides* | Y | O | M | I |
| Yellowwood | *Cladrastis lutea* | Y | R | M | I |
| **Large (>40 feet)** | | | | | |
| Ash | *Fraxinus spp.* | | | | |
|   Green | *F. pennsylvanica* | Y | O | R | L |
|   White | *F. americana* | Y | O | M | L |
| Birch | *Betula nigra* | N | O | R | I |
| Coffeetree, Kentucky | *Gymnocladus dioica* | Y | R | M | L |
| Elm | *Ulmus spp.* | | | | |
|   English | *U. carpinifolia* | N | P | R | L |
|   Regal | *U. 'regal'* | NA | P | M | L |
| Ginkgo | *Ginkgo biloba* | Y | O | M | L |
| Hackberry, Common | *Celtis occidentalis* | Y | V | R | L |
| Honeylocust, Thornless | *Gleditsia triacanthos v. inermis* | Y | R | R | I |
| Horsechestnut, Common | *Aesculus hippocastanum* | N | R | M | L |
| Larch | *Larix spp.* | | | | |
|   European | *L. decidua* | Y | P | R | L |
|   Japanese | *L. kaempferi* | NA | P | R | L |
| Linden | *Tilia spp.* | | | | |
|   American (Basswood) | *T. americana* | N | O | M | L |
|   Bigleaf | *T. platyphyllos* | N | O | M | I |

Trees for energy-efficient landscapes in the Chicago area (continued).

| Tree species | | Solar friendly | Form | Growth rate | Longevity |
|---|---|---|---|---|---|
| **Large (>40 feet)** | | | | | |
| Maple | *Acer spp.* | | | | |
| Balck | *A. nigrum* | Y | O | M | L |
| Norway | *A. platanoides* | Y | R | M | L |
| Oak | *Quercus spp.* | | | | |
| Bur | *Q. macrocarpa* | N | B | M | L |
| English | *Q. robur* | N | R | M | L |
| Pin or Swamp | *Q. palustris* | N | P | R | L |
| Red | *Q. rubra* | N | R | M | L |
| Sawtooth | *Q. acutissima* | NA | P | M | L |
| Shingle | *Q. imbricaria* | NA | P | M | L |
| Southern Red | *Q. flacata* | NA | O | M | L |
| Swamp White | *Q. bicolor* | NA | R | M | L |
| White | *Q. alba* | N | R | M | L |
| Willow | *Q. phellos* | N | P | R | L |
| Persimmon, Common | *Diospyros virginiana* | Y | O | M | L |
| Redwood, Dawn | *Metasequoia glyptostroboides* | Y | P | R | L |
| Sourgum (Black Tupelo) | *Nyssa sylvatica* | Y | P | M | L |
| Sycamore | *Platanus occidentalis* | N | O | R | L |
| **Medium Evergreens (<40 feet)** | | | | | |
| Arbovitae | *Thuja spp.* | | | | |
| Oriental | *T. orientalis* | N | P | S | I |
| White Cedar | *T. occidentalis* | N | P | M | I |
| Juniper | *Juniperus spp.* | | | | |
| Chinese | *J. chinensis* | N | P | M | I |
| Eastern Redcedar | *J. virginiana* | N | P | M | L |
| Rocky Mountain | *J. scopulorum* | N | P | M | I |
| **Large Evergreens (>40 feet)** | | | | | |
| Pine | *Pinus spp.* | | | | |
| Austrian or Black | *P. nigra* | N | P | M | I |
| Red | *P. resinosa* | N | P | M | I |
| White | *P. strobus* | N | P | M | L |
| Spruce, Colorado | *Picea pungens* | N | P | M | L |

Legend

| Solar friendly | Form | | Growth rate | Longevity |
|---|---|---|---|---|
| Y=Yes | R=Rounded | L=Layered | S=Slow (<10"/year) | S=Short (<25 years) |
| N=No | P=Pyramidal | W=Weeping | M=Moderate (10-20"/year) | I=Intermediate (25-50 years) |
| NA=Data not available | V=Vase shaped | O=Oval | R=Rapid (>20"/year) | L=Long (>50 years) |
| Varies=with cultivar | B=Broad | S=Shrubby | | |

# Appendix C

**Standard Reports for Brick Base Case Buildings**

Chicago, Illinois          Tree Shade Only

Nat. Gas   ($/therm):   0.5
Electricity  ($/kWh):   0.12

1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing East)

| Source Energy Use (kBtu/ sq ft) | Tree Height and Distance from Building | | | | | % Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
| **East Tree** | | | | | | **East Tree** | | | |
| Total Heating Use | 82.50 | 82.88 | 82.99 | 83.06 | 82.96 | -0.46 | -0.59 | -0.68 | -0.56 |
| Total Cooling Use | 9.29 | 9.04 | 8.82 | 8.47 | 8.66 | 2.68 | 5.03 | 8.88 | 6.75 |
| Total Energy Use | 91.79 | 91.92 | 91.81 | 91.53 | 91.63 | -0.14 | -0.02 | 0.29 | 0.18 |
| Peak Cool (kW) | 4.49 | 4.49 | 4.49 | 4.49 | 4.49 | 0.01 | 0.01 | 0.02 | 0.02 |
| **South Tree** | | | | | | **South Tree** | | | |
| Total Heating Use | 82.50 | 82.99 | 83.22 | 83.70 | 83.23 | -0.59 | -0.86 | -1.45 | -0.88 |
| Total Cooling Use | 9.29 | 9.25 | 9.24 | 9.01 | 9.24 | 0.47 | 0.51 | 3.06 | 0.49 |
| Total Energy Use | 91.79 | 92.24 | 92.46 | 92.71 | 92.48 | -0.48 | -0.72 | -1 | -0.75 |
| Peak Cool (kW) | 4.49 | 4.49 | 4.49 | 4.49 | 4.49 | 0 | 0 | 0 | 0 |
| **West Tree** | | | | | | **West Tree** | | | |
| Total Heating Use | 82.50 | 82.62 | 82.66 | 82.78 | 82.67 | -0.14 | -0.19 | -0.34 | -0.2 |
| Total Cooling Use | 9.29 | 9.10 | 8.93 | 8.57 | 8.81 | 2.05 | 3.84 | 7.75 | 5.21 |
| Total Energy Use | 91.79 | 91.72 | 91.60 | 91.35 | 91.47 | 0.08 | 0.21 | 0.48 | 0.35 |
| Peak Cool (kW) | 4.49 | 4.38 | 4.29 | 4.02 | 4.21 | 2.47 | 4.45 | 10.4 | 6.17 |

| Annual Energy Use | Tree Height and Distance from Building | | | | | $ Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
| **East Tree** | | | | | | **East Tree** | | | |
| Heating (kBtu) | 170101 | 170878 | 171107 | 171256 | 171051 | -4 | -5 | -6 | -5 |
| Cooling (kWh) | 1928 | 1876 | 1831 | 1757 | 1798 | 6 | 12 | 21 | 16 |
| | | | | | | Total  2 | 7 | 15 | 11 |
| **South Tree** | | | | | | **South Tree** | | | |
| Heating (kBtu) | 170101 | 171106 | 171569 | 172574 | 171605 | -5 | -7 | -12 | -8 |
| Cooling (kWh) | 1928 | 1919 | 1918 | 1869 | 1919 | 1 | 1 | 7 | 1 |
| | | | | | | Total  -4 | -6 | -5 | -7 |
| **West Tree** | | | | | | **West Tree** | | | |
| Heating (kBtu) | 170101 | 170341 | 170430 | 170676 | 170439 | -1 | -2 | -3 | -2 |
| Cooling (kWh) | 1928 | 1889 | 1854 | 1779 | 1828 | 5 | 9 | 18 | 12 |
| | | | | | | Total  4 | 7 | 15 | 10 |

| Annual Hours of Use | Tree Height and Distance from Building | | | | | % Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
| **East Tree** | | | | | | **East Tree** | | | |
| Heating (hrs) | 4310 | 4331 | 4348 | 4355 | 4349 | -0.49 | -0.88 | -1.04 | -0.9 |
| Cooling (hrs) | 987 | 971 | 951 | 927 | 941 | 1.62 | 3.65 | 6.08 | 4.66 |
| **South Tree** | | | | | | **South Tree** | | | |
| Heating (hrs) | 4310 | 4335 | 4356 | 4394 | 4360 | -0.58 | -1.07 | -1.95 | -1.16 |
| Cooling (hrs) | 987 | 986 | 985 | 974 | 985 | 0.1 | 0.2 | 1.32 | 0.2 |
| **West Tree** | | | | | | **West Tree** | | | |
| Heating (hrs) | 4310 | 4317 | 4321 | 4330 | 4323 | -0.16 | -0.26 | -0.46 | -0.3 |
| Cooling (hrs) | 987 | 984 | 980 | 979 | 980 | 0.3 | 0.71 | 0.81 | 0.71 |

## Annual Heating and Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



▨ 24-ft tall, 12-ft away ▧ 36-ft tall, 22-ft away ▢ 50-ft tall, 22-ft away ▨ 50-ft tall, 34-ft away
1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing East)

# Annual Heating and Cooling Savings From Base Case
## Due to Shade from A Large Deciduous Tree - 22 ft Away



Heating    Cooling    Total Savings

1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing East)

# Annual Percentage Cooling Savings From Base Case
## Due to Shade from One Deciduous Tree



24-ft tall, 12-ft away    36-ft tall, 22-ft away
50-ft tall, 22-ft away    50-ft tall, 34-ft away

1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing East)

# Percentage Peak Cooling Savings From Base Case
## Due to Shade from One Deciduous Tree



24-ft tall, 12-ft away    36-ft tall, 22-ft away
50-ft tall, 22-ft away    50-ft tall, 34-ft away

1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing East)

**Energy Analysis**

| | | | | | | | Nat. Gas | ($/therm): | 0.5 |
| | | | | | | | Electricity | ($/kWh): | 0.12 |

1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing East)  
Deciduous tree, 36-ft tall and 24-ft crown spread, 22-ft away from building  

Avoided Peak Electricity ($/Avoid kW): 65

| Annual Energy Use | Unshaded Base Case | East | Shade South | West | ET Cooling | Reduced Wind | East Shade + ET + Wind | South Shade + ET + Wind | West Shade + ET + Win |
|---|---|---|---|---|---|---|---|---|---|
| **Heat (MBtu)** | 170.10 | 171.11 | 171.57 | 170.43 | 170.10 | 162.49 | | | |
| $ | 850.50 | 855.55 | 857.85 | 852.15 | 850.50 | 812.45 | | | |
| MBtu diff / tree | | -1.01 | -1.47 | -0.33 | 0.00 | 2.54 | 1.53 | 1.07 | 2.21 |
| $ diff / tree | | -5.05 | -7.35 | -1.65 | 0.00 | 12.68 | 7.63 | 5.33 | 11.03 |
| % diff / tree | | -0.60 | -0.90 | -0.20 | 0.00 | 1.49 | 0.89 | 0.59 | 1.29 |
| | | | | | | | | | |
| **Cool (kWh)** | 1928 | 1831 | 1918 | 1854 | 1789 | 1909 | | | |
| $ | 231.37 | 219.74 | 230.19 | 222.49 | 214.65 | 229.02 | | | |
| kWh diff / tree | | 97 | 10 | 74 | 46 | 7 | 150.00 | 63.00 | 127.00 |
| $ diff / tree | | 11.63 | 1.18 | 8.88 | 5.57 | 0.78 | 17.98 | 7.53 | 15.23 |
| % diff / tree | | 5.03 | 0.51 | 3.84 | 2.41 | 0.34 | 7.78 | 3.26 | 6.59 |
| | | | | | | | | | |
| **Total (MBtu)** | 195.06 | 195.11 | 196.47 | 194.64 | 193.64 | 187.01 | | | |
| $ | 1081.87 | 1075.29 | 1088.04 | 1074.64 | 1065.15 | 1041.47 | | | |
| MBtu diff / tree | | -0.05 | -1.41 | 0.42 | 0.47 | 2.68 | 3.10 | 1.74 | 3.57 |
| $ diff / tree | | 6.58 | -6.17 | 7.23 | 5.57 | 13.47 | 25.62 | 12.87 | 26.27 |
| % diff / tree | | -0.03 | -0.72 | 0.22 | 0.24 | 1.38 | 1.59 | 0.90 | 1.84 |
| | | | | | | | | | |
| **Peak Cool (kW** | 4.49 | 4.49 | 4.49 | 4.29 | 4.24 | 4.41 | | | |
| Avoided $ | 292.00 | 292.00 | 292.00 | 279.00 | 276.00 | 287.00 | | | |
| Kw diff / tree | | 0.00 | 0.00 | 0.20 | 0.08 | 0.03 | 0.11 | 0.11 | 0.31 |
| Avoided $ diff / tree | | 0.00 | 0.00 | 13.00 | 5.33 | 1.67 | 7.00 | 7.00 | 20.00 |
| % diff / tree | | 0.01 | 0.00 | 4.45 | 1.83 | 0.60 | 2.44 | 2.43 | 6.88 |

# Annual Savings from Base Case - 1 Deciduous Tree
## Due to Shade, ET Cooling, and Reduced Wind Speed from 36-ft Tall and 24-ft Wide Tree



1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing East)  
1 tree 22-ft from wall

Appendix C
USDA Forest Service Gen. Tech. Rep. NE-186. 1994.

**Chicago, Illinois**          **Tree Shade Only**

1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing North)

| | Nat. Gas | ($/therm): | 0.5 |
|---|---|---|---|
| | Electricity | ($/kWh): | 0.12 |

### Source Energy Use (kBtu/ sq ft)

| | | Tree Height and Distance from Building | | | | | % Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) |
| **East Tree** | Base Case | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away | **East Tree** | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away |
| Total Heating Use | 84.08 | 84.51 | 84.63 | 84.72 | 84.60 | | -0.5 | -0.65 | -0.76 | -0.62 |
| Total Cooling Use | 8.65 | 8.38 | 8.14 | 7.75 | 7.96 | | 3.17 | 5.89 | 10.43 | 7.98 |
| Total Energy Use | 92.74 | 92.88 | 92.78 | 92.47 | 92.57 | | -0.16 | -0.04 | 0.28 | 0.18 |
| Peak Cool (kW) | 4.20 | 4.19 | 4.19 | 4.19 | 4.19 | | 0.01 | 0.02 | 0.03 | 0.02 |
| **South Tree** | | | | | | **South Tree** | | | | |
| Total Heating Use | 84.08 | 84.50 | 84.69 | 85.11 | 84.70 | | -0.49 | -0.71 | -1.22 | -0.73 |
| Total Cooling Use | 8.65 | 8.61 | 8.61 | 8.42 | 8.61 | | 0.42 | 0.45 | 2.65 | 0.44 |
| Total Energy Use | 92.74 | 93.11 | 93.30 | 93.53 | 93.31 | | -0.41 | -0.61 | -0.86 | -0.62 |
| Peak Cool (kW) | 4.20 | 4.20 | 4.20 | 4.20 | 4.20 | | 0 | 0 | 0 | 0 |
| **West Tree** | | | | | | **West Tree** | | | | |
| Total Heating Use | 84.08 | 84.15 | 84.18 | 84.25 | 84.18 | | -0.08 | -0.11 | -0.2 | -0.12 |
| Total Cooling Use | 8.65 | 8.56 | 8.47 | 8.28 | 8.40 | | 1.09 | 2.05 | 4.34 | 2.91 |
| Total Energy Use | 92.74 | 92.71 | 92.65 | 92.52 | 92.58 | | 0.03 | 0.09 | 0.23 | 0.17 |
| Peak Cool (kW) | 4.20 | 4.13 | 4.09 | 3.94 | 4.04 | | 1.44 | 2.6 | 6.08 | 3.61 |

### Annual Energy Use

| | | Tree Height and Distance from Building | | | | | $ Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) |
| **East Tree** | Base Case | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away | | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away |
| Heating (kBtu) | 173359 | 174232 | 174492 | 174677 | 174433 | **East Tree** | -4 | -6 | -7 | -5 |
| Cooling (kWh) | 1795 | 1738 | 1690 | 1608 | 1652 | | 7 | 13 | 22 | 17 |
| **South Tree** | | | | | | Total | 3 | 7 | 15 | 12 |
| Heating (kBtu) | 173359 | 174213 | 174599 | 175471 | 174626 | **South Tree** | -4 | -6 | -11 | -6 |
| Cooling (kWh) | 1795 | 1788 | 1787 | 1748 | 1788 | | 1 | 1 | 6 | 1 |
| **West Tree** | | | | | | Total | -3 | -5 | -5 | -5 |
| Heating (kBtu) | 173359 | 173499 | 173554 | 173698 | 173561 | **West Tree** | -1 | -1 | -2 | -1 |
| Cooling (kWh) | 1795 | 1776 | 1759 | 1717 | 1743 | | 2 | 4 | 9 | 6 |
| | | | | | | Total | 1 | 3 | 7 | 5 |

### Annual Hours of Use

| | | Tree Height and Distance from Building | | | | | % Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) |
| **East Tree** | Base Case | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away | **East Tree** | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away |
| Heating (hrs) | 4395 | 4424 | 4442 | 4458 | 4445 | | -0.66 | -1.07 | -1.43 | -1.14 |
| Cooling (hrs) | 974 | 961 | 942 | 906 | 927 | | 1.33 | 3.29 | 6.98 | 4.83 |
| **South Tree** | | | | | | **South Tree** | | | | |
| Heating (hrs) | 4395 | 4426 | 4432 | 4478 | 4433 | | -0.71 | -0.84 | -1.89 | -0.86 |
| Cooling (hrs) | 974 | 973 | 973 | 961 | 973 | | 0.1 | 0.1 | 1.33 | 0.1 |
| **West Tree** | | | | | | **West Tree** | | | | |
| Heating (hrs) | 4395 | 4398 | 4401 | 4406 | 4404 | | -0.07 | -0.14 | -0.25 | -0.2 |
| Cooling (hrs) | 974 | 973 | 973 | 970 | 972 | | 0.1 | 0.1 | 0.41 | 0.21 |

## Annual Heating and Cooling Savings From Base Case
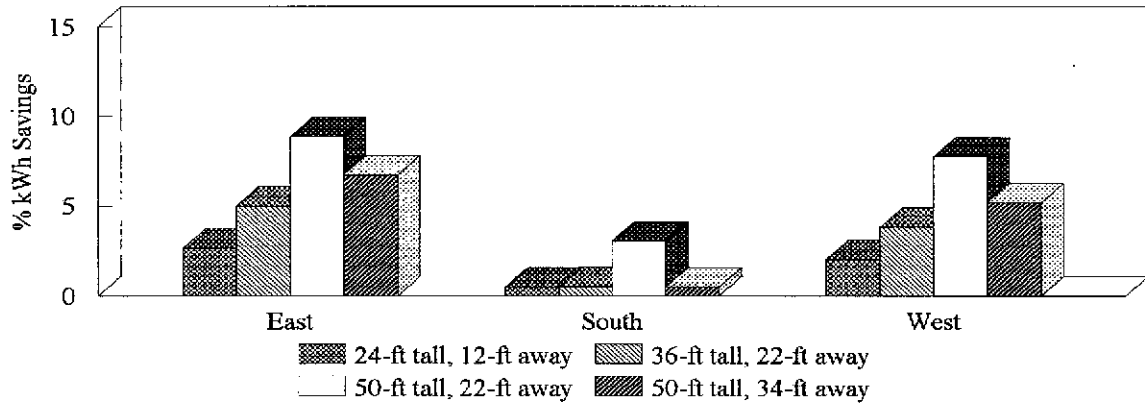### Due to Shade from One Deciduous Tree



Legend:
- 24-ft tall, 12-ft away
- 36-ft tall, 22-ft away
- 50-ft tall, 22-ft away
- 50-ft tall, 34-ft away

1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing North)

## Annual Heating and Cooling Savings From Base Case
### Due to Shade from A Large Deciduous Tree - 22 ft Away
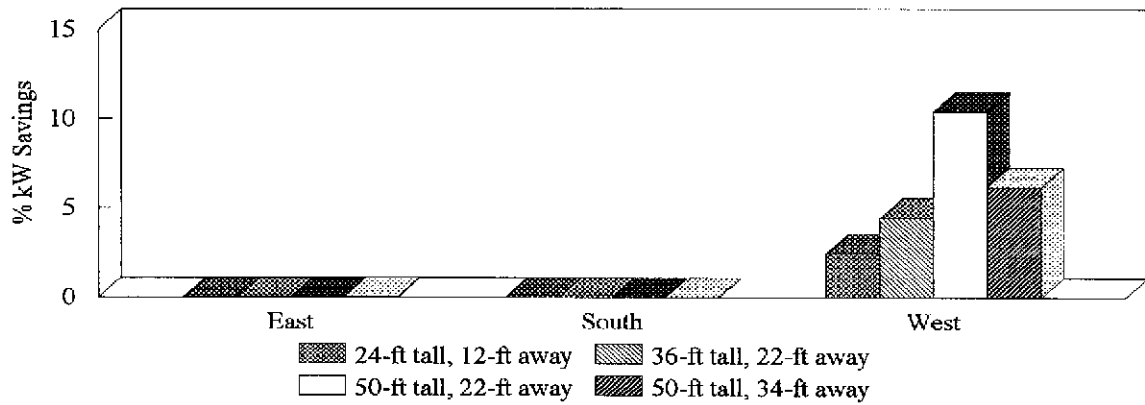


Heating  Cooling  Total Savings
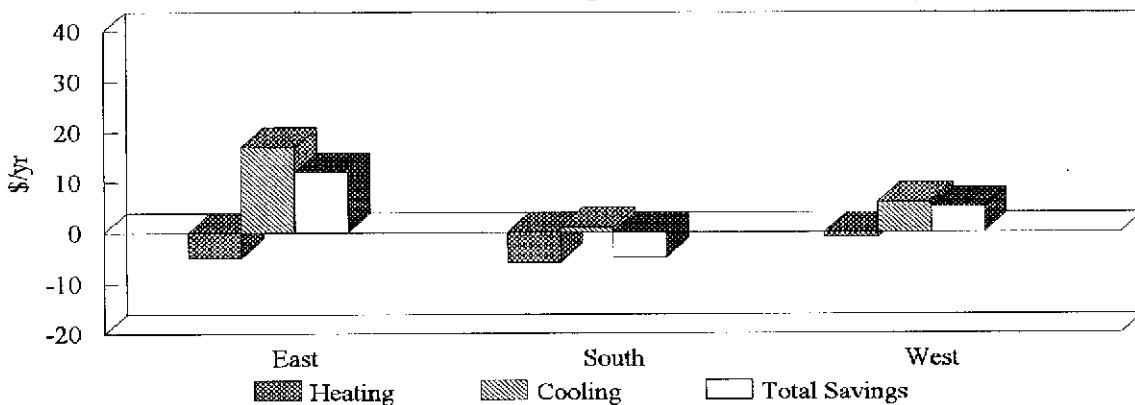
1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing North)

## Annual Percentage Cooling Savings From Base Case
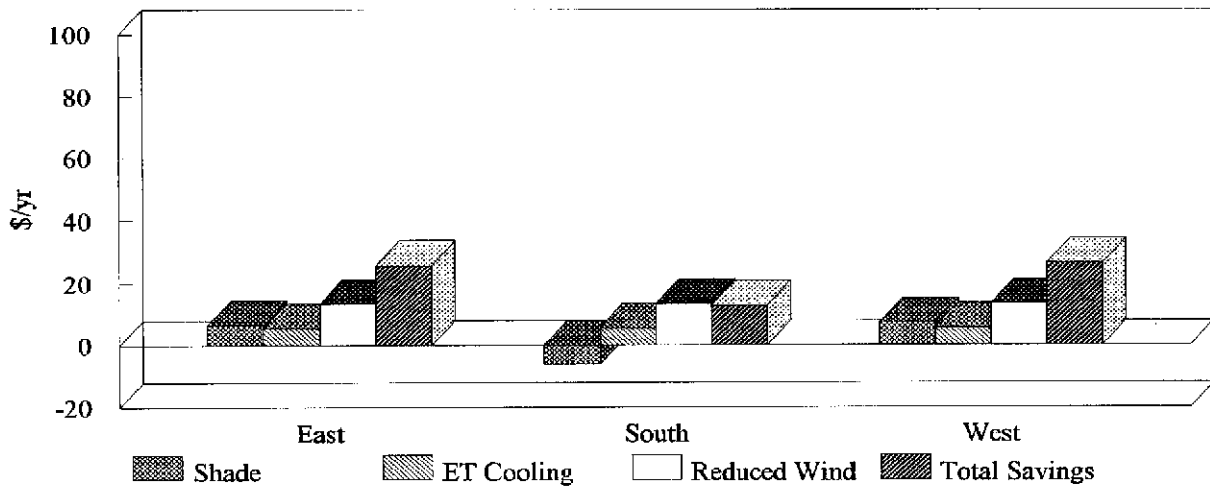### Due to Shade from One Deciduous Tree



24-ft tall, 12-ft away    36-ft tall, 22-ft away
50-ft tall, 22-ft away    50-ft tall, 34-ft away

1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing North)

## Percentage Peak Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



24-ft tall, 12-ft away    36-ft tall, 22-ft away
50-ft tall, 22-ft away    50-ft tall, 34-ft away
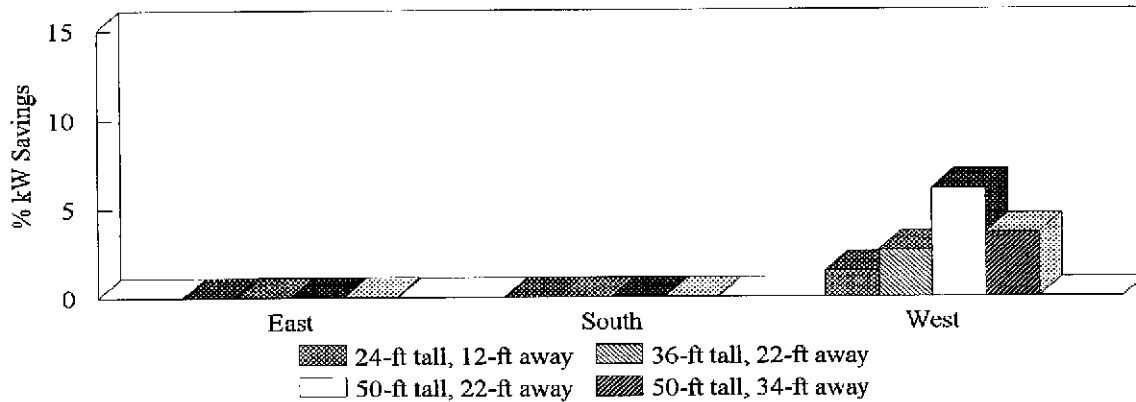
1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing North)

**Chicago, Illinois**        **Energy Analysis**

1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing North)
Deciduous tree, 36-ft tall and 24-ft crown spread, 22-ft away from building

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Nat. Gas | ($/therm): | 0.5 |
| Electricity | ($/kWh): | 0.12 |
| Avoided Peak Electricity | ($/Avoid kW): | 65 |

| Annual Energy Use | Unshaded Base Case | East | Shade South | West | ET Cooling | Reduced Wind | East Shade + ET + Wind | South Shade + ET + Wind | West Shade + ET + Win |
|---|---|---|---|---|---|---|---|---|---|
| **Heat (MBtu)** | 173.36 | 174.49 | 174.60 | 173.55 | 173.36 | 165.70 | | | |
| $ | 866.80 | 872.45 | 873.00 | 867.75 | 866.80 | 828.50 | | | |
| MBtu diff / tree | | -1.13 | -1.24 | -0.19 | 0.00 | 2.55 | 1.42 | 1.31 | 2.36 |
| $ diff / tree | | -5.65 | -6.20 | -0.95 | 0.00 | 12.77 | 7.12 | 6.57 | 11.82 |
| % diff / tree | | -0.70 | -0.70 | -0.10 | 0.00 | 1.47 | 0.77 | 0.77 | 1.37 |
| | | | | | | | | | |
| **Cool (kWh)** | 1795 | 1690 | 1787 | 1759 | 1661 | 1776 | | | |
| $ | 215.45 | 202.76 | 214.47 | 211.04 | 199.28 | 213.08 | | | |
| kWh diff / tree | | 106 | 8 | 37 | 45 | 7 | 158.00 | 60.00 | 89.00 |
| $ diff / tree | | 12.69 | 0.98 | 4.41 | 5.39 | 0.79 | 18.87 | 7.16 | 10.59 |
| % diff / tree | | 5.89 | 0.46 | 2.05 | 2.50 | 0.37 | 8.76 | 3.32 | 4.92 |
| | | | | | | | | | |
| **Total (MBtu)** | 197.06 | 197.15 | 198.26 | 196.89 | 195.68 | 188.97 | | | |
| $ | 1082.25 | 1075.21 | 1087.47 | 1078.79 | 1066.08 | 1041.58 | | | |
| MBtu diff / tree | | -0.09 | -1.20 | 0.17 | 0.46 | 2.70 | 3.07 | 1.96 | 3.33 |
| $ diff / tree | | 7.04 | -5.22 | 3.46 | 5.39 | 13.56 | 25.99 | 13.73 | 22.41 |
| % diff / tree | | -0.05 | -0.61 | 0.09 | 0.23 | 1.37 | 1.55 | 0.99 | 1.69 |
| | | | | | | | | | |
| **Peak Cool (kW** | 4.20 | 4.19 | 4.20 | 4.09 | 3.95 | 4.11 | | | |
| Avoided $ | 273.00 | 273.00 | 273.00 | 266.00 | 257.00 | 267.00 | | | |
| Kw diff / tree | | 0.00 | 0.00 | 0.11 | 0.08 | 0.03 | 0.11 | 0.11 | 0.22 |
| Avoided $ diff / tree | | 0.00 | 0.00 | 7.00 | 5.33 | 2.00 | 7.33 | 7.33 | 14.33 |
| % diff / tree | | 0.02 | 0.00 | 2.60 | 1.96 | 0.64 | 2.62 | 2.60 | 5.20 |

# Annual Savings from Base Case - 1 Deciduous Tree
## Due to Shade, ET Cooling, and Reduced Wind Speed from 36-ft Tall and 24-ft Wide Tree
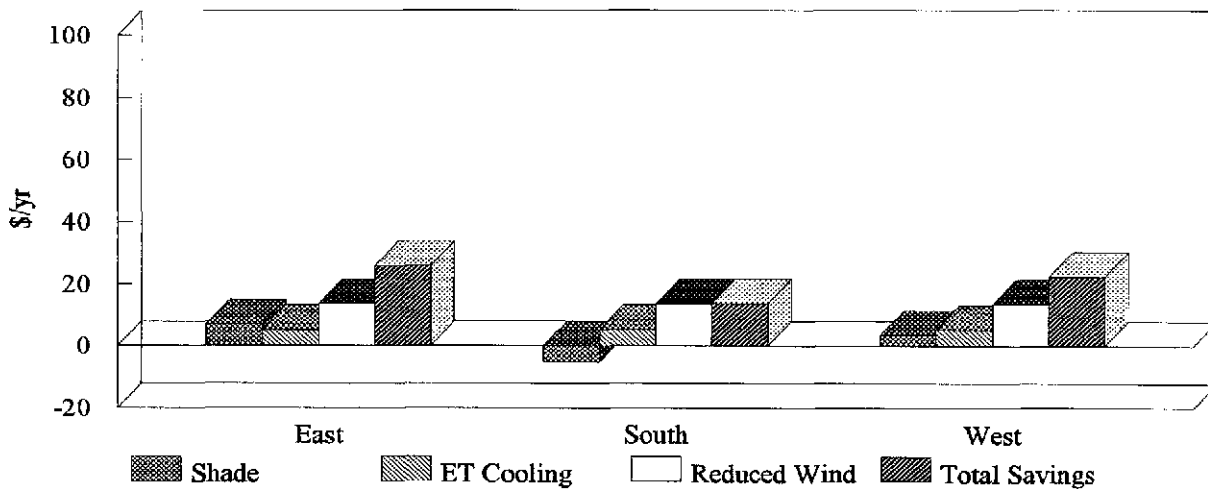


1 Story, Brick Construction - 2,125 sq ft Residence (Front Facing North)
1 tree 22-ft from wall

Chicago, Illinois — Tree Shade Only

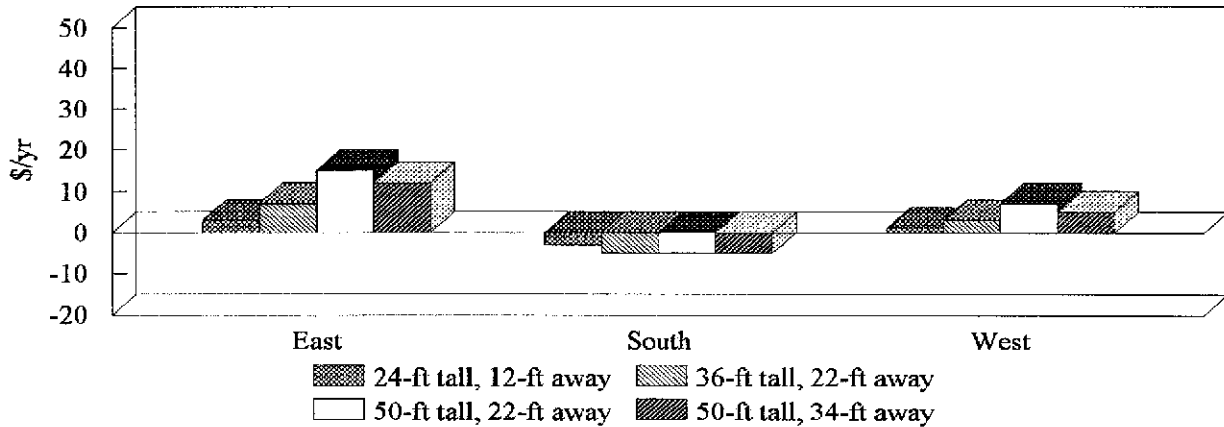2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing East)

| | | | | | Nat. Gas | ($/therm): | 0.5 |
| | | | | | Electricity | ($/kWh): | 0.12 |

**Source Energy Use (kBtu/ sq ft)** — Tree Height and Distance from Building — % Saved from Base Case

| | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
|---|---|---|---|---|---|---|---|---|---|---|
| **East Tree** | | | | | | **East Tree** | | | | |
| Total Heating Use | 108.55 | 108.86 | 108.98 | 109.12 | 109.02 | | -0.28 | -0.4 | -0.53 | -0.44 |
| Total Cooling Use | 10.71 | 10.58 | 10.45 | 10.12 | 10.31 | | 1.19 | 2.46 | 5.51 | 3.75 |
| Total Energy Use | 119.26 | 119.44 | 119.42 | 119.24 | 119.33 | | -0.15 | -0.14 | 0.02 | -0.06 |
| Peak Cool (kW) | 10.09 | 10.09 | 10.09 | 10.09 | 10.09 | | 0 | 0.01 | 0.01 | 0.01 |
| **South Tree** | | | | | | **South Tree** | | | | |
| Total Heating Use | 108.55 | 109.01 | 109.29 | 109.96 | 109.34 | | -0.42 | -0.68 | -1.3 | -0.73 |
| Total Cooling Use | 10.71 | 10.68 | 10.68 | 10.43 | 10.67 | | 0.28 | 0.31 | 2.64 | 0.37 |
| Total Energy Use | 119.26 | 119.69 | 119.97 | 120.39 | 120.01 | | -0.36 | -0.6 | -0.95 | -0.63 |
| Peak Cool (kW) | 10.09 | 10.09 | 10.09 | 10.09 | 10.09 | | 0 | 0 | 0 | 0 |
| **West Tree** | | | | | | **West Tree** | | | | |
| Total Heating Use | 108.55 | 108.64 | 108.69 | 108.82 | 108.71 | | -0.08 | -0.13 | -0.25 | -0.15 |
| Total Cooling Use | 10.71 | 10.56 | 10.38 | 9.85 | 10.19 | | 1.42 | 3.08 | 7.99 | 4.88 |
| Total Energy Use | 119.26 | 119.19 | 119.07 | 118.68 | 118.89 | | 0.05 | 0.15 | 0.49 | 0.31 |
| Peak Cool (kW) | 10.10 | 9.95 | 9.80 | 9.12 | 9.63 | | 1.54 | 3.04 | 9.75 | 4.66 |

**Annual Energy Use** — Tree Height and Distance from Building — $ Saved from Base Case

| | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
|---|---|---|---|---|---|---|---|---|---|---|
| **East Tree** | | | | | | **East Tree** | | | | |
| Heating (kBtu) | 375511 | 376573 | 377002 | 377485 | 377153 | | -5 | -7 | -10 | -8 |
| Cooling (kWh) | 3725 | 3681 | 3634 | 3520 | 3586 | | 5 | 11 | 25 | 17 |
| **South Tree** | | | | | | Total | 0 | 4 | 15 | 9 |
| Heating (kBtu) | 375511 | 377104 | 378083 | 380400 | 378252 | **South Tree** | -8 | -13 | -24 | -14 |
| Cooling (kWh) | 3725 | 3715 | 3714 | 3627 | 3712 | | 1 | 1 | 12 | 2 |
| **West Tree** | | | | | | Total | -7 | -12 | -12 | -12 |
| Heating (kBtu) | 375511 | 375812 | 376014 | 376465 | 376059 | **West Tree** | -2 | -3 | -5 | -3 |
| Cooling (kWh) | 3725 | 3673 | 3611 | 3428 | 3544 | | 6 | 14 | 36 | 22 |
| | | | | | | Total | 4 | 11 | 31 | 19 |

**Annual Hours of Use** — Tree Height and Distance from Building — % Saved from Base Case

| | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
|---|---|---|---|---|---|---|---|---|---|---|
| **East Tree** | | | | | | **East Tree** | | | | |
| Heating (hrs) | 4419 | 4433 | 4442 | 4449 | 4442 | | -0.32 | -0.52 | -0.68 | -0.52 |
| Cooling (hrs) | 765 | 762 | 749 | 733 | 739 | | 0.39 | 2.09 | 4.18 | 3.4 |
| **South Tree** | | | | | | **South Tree** | | | | |
| Heating (hrs) | 4419 | 4439 | 4456 | 4493 | 4458 | | -0.45 | -0.84 | -1.67 | -0.88 |
| Cooling (hrs) | 765 | 765 | 765 | 756 | 764 | | 0 | 0 | 1.18 | 0.13 |
| **West Tree** | | | | | | **West Tree** | | | | |
| Heating (hrs) | 4419 | 4424 | 4428 | 4437 | 4427 | | -0.11 | -0.2 | -0.41 | -0.18 |
| Cooling (hrs) | 765 | 765 | 765 | 757 | 763 | | 0 | 0 | 1.05 | 0.26 |

# Annual Heating and Cooling Savings From Base Case
## Due to Shade from One Deciduous Tree



Legend: 24-ft tall, 12-ft away · 36-ft tall, 22-ft away · 50-ft tall, 22-ft away · 50-ft tall, 34-ft away
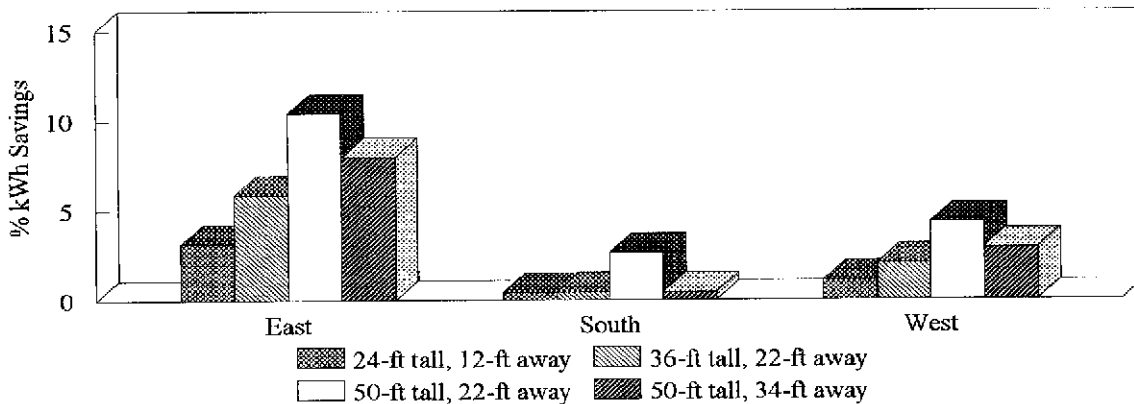
2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing East)

## Annual Heating and Cooling Savings From Base Case
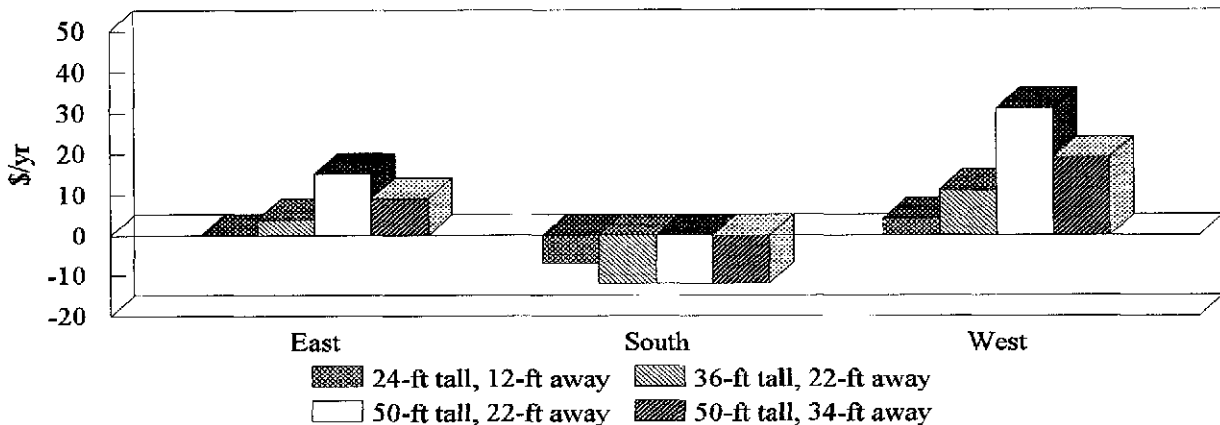### Due to Shade from A Large Deciduous Tree - 22 ft Away



Heating — Cooling — Total Savings

2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing East)

## Annual Percentage Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



24-ft tall, 12-ft away    36-ft tall, 22-ft away
50-ft tall, 22-ft away    50-ft tall, 34-ft away

2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing East)

## Percentage Peak Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



24-ft tall, 12-ft away    36-ft tall, 22-ft away
50-ft tall, 22-ft away    50-ft tall, 34-ft away

2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing East)

**Chicago, Illinois**     **Energy Analysis**

| | | Nat. Gas | ($/therm): | 0.5 |
|---|---|---|---|---|
| 2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing East) | | Electricity | ($/kWh): | 0.12 |
| Deciduous tree, 36-ft tall and 24-ft crown spread, 22-ft away from building | | Avoided Peak Electricity | ($/Avoid kW): | 65 |

| Annual Energy Use | Unshaded Base Case | East | Shade South | West | ET Cooling | Reduced Wind | East Shade + ET + Wind | South Shade + ET + Wind | West Shade + ET + Win |
|---|---|---|---|---|---|---|---|---|---|
| **Heat (MBtu)** | 375.51 | 377.00 | 378.08 | 376.01 | 375.52 | 360.28 | | | |
| $ | 1877.55 | 1885.00 | 1890.40 | 1880.05 | 1877.60 | 1801.40 | | | |
| MBtu diff / tree | | -1.49 | -2.57 | -0.50 | 0.00 | 5.08 | 3.59 | 2.51 | 4.58 |
| $ diff / tree | | -7.45 | -12.85 | -2.50 | -0.02 | 25.38 | 17.91 | 12.51 | 22.86 |
| % diff / tree | | -0.40 | -0.70 | -0.10 | 0.00 | 1.35 | 0.95 | 0.65 | 1.25 |
| | | | | | | | | | |
| **Cool (kWh)** | 3725 | 3634 | 3714 | 3611 | 3438 | 3690 | | | |
| $ | 447.06 | 436.04 | 445.65 | 433.29 | 412.56 | 442.82 | | | |
| kWh diff / tree | | 92 | 12 | 115 | 96 | 12 | 200.00 | 120.00 | 223.00 |
| $ diff / tree | | 11.02 | 1.41 | 13.77 | 11.50 | 1.41 | 23.93 | 14.32 | 26.68 |
| % diff / tree | | 2.46 | 0.32 | 3.08 | 2.57 | 0.32 | 5.35 | 3.20 | 5.97 |
| | | | | | | | | | |
| **Total (MBtu)** | 253.42 | 253.78 | 254.93 | 253.03 | 251.67 | 243.85 | | | |
| $ | 2324.61 | 2321.04 | 2336.05 | 2313.34 | 2290.16 | 2244.22 | | | |
| MBtu diff / tree | | -0.36 | -1.51 | 0.39 | 0.58 | 3.19 | 3.41 | 2.26 | 4.16 |
| $ diff / tree | | 3.57 | -11.44 | 11.27 | 11.48 | 26.80 | 41.85 | 26.84 | 49.55 |
| % diff / tree | | -0.14 | -0.60 | 0.15 | 0.23 | 1.26 | 1.35 | 0.89 | 1.64 |
| | | | | | | | | | |
| **Peak Cool (kW** | 10.09 | 10.09 | 10.09 | 9.80 | 9.54 | 9.93 | | | |
| Avoided $ | 656.00 | 656.00 | 656.00 | 637.00 | 620.00 | 645.00 | | | |
| Kw diff / tree | | 0.00 | 0.00 | 0.30 | 0.19 | 0.06 | 0.24 | 0.24 | 0.54 |
| Avoided $ diff / tree | | 0.00 | 0.00 | 19.00 | 12.00 | 3.67 | 15.67 | 15.67 | 34.67 |
| % diff / tree | | 0.01 | 0.00 | 2.93 | 1.83 | 0.55 | 2.39 | 2.38 | 5.31 |

## Annual Savings from Base Case - 1 Deciduous Tree
### Due to Shade, ET Cooling, and Reduced Wind Speed from 36-ft Tall and 24-ft Wide Tree



Shade    ET Cooling    Reduced Wind    Total Savings

2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing East)
1 tree 22-ft from wall

Chicago, Illinois          **Tree Shade Only**

2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing South)

Nat. Gas   ($/therm):   0.5
Electricity   ($/kWh):   0.12

| Source Energy Use (kBtu/ sq ft) | Tree Height and Distance from Building | | | | | % Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
| **East Tree** | | | | | | **East Tree** | | | |
| Total Heating Use | 111.32 | 111.62 | 111.75 | 111.90 | 111.79 | -0.27 | -0.38 | -0.52 | -0.42 |
| Total Cooling Use | 10.58 | 10.47 | 10.34 | 10.05 | 10.21 | 1.02 | 2.27 | 5.03 | 3.48 |
| Total Energy Use | 121.91 | 122.10 | 122.09 | 121.95 | 122.01 | -0.16 | -0.15 | -0.04 | -0.08 |
| Peak Cool (kW) | 10.60 | 10.60 | 10.60 | 10.60 | 10.60 | 0 | 0.01 | 0.01 | 0.01 |
| **South Tree** | | | | | | **South Tree** | | | |
| Total Heating Use | 111.32 | 111.61 | 111.79 | 112.22 | 111.82 | -0.26 | -0.42 | -0.8 | -0.45 |
| Total Cooling Use | 10.58 | 10.56 | 10.56 | 10.42 | 10.56 | 0.23 | 0.25 | 1.54 | 0.25 |
| Total Energy Use | 121.91 | 122.17 | 122.35 | 122.64 | 122.38 | -0.22 | -0.36 | -0.6 | -0.39 |
| Peak Cool (kW) | 10.60 | 10.60 | 10.60 | 10.60 | 10.60 | 0 | 0 | 0 | 0 |
| **West Tree** | | | | | | **West Tree** | | | |
| Total Heating Use | 111.32 | 111.45 | 111.53 | 111.72 | 111.55 | -0.11 | -0.18 | -0.36 | -0.2 |
| Total Cooling Use | 10.58 | 10.36 | 10.12 | 9.44 | 9.86 | 2.06 | 4.36 | 10.83 | 6.8 |
| Total Energy Use | 121.91 | 121.81 | 121.65 | 121.16 | 121.41 | 0.08 | 0.21 | 0.61 | 0.41 |
| Peak Cool (kW) | 10.60 | 10.41 | 10.21 | 9.30 | 9.99 | 1.81 | 3.71 | 12.22 | 5.77 |

| Annual Energy Use | Tree Height and Distance from Building | | | | | $ Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
| **East Tree** | | | | | | | | | |
| Heating (kBtu) | 385113 | 386152 | 386584 | 387106 | 386740 | **East Tree** -5 | -7 | -10 | -8 |
| Cooling (kWh) | 3682 | 3644 | 3598 | 3496 | 3553 | 5 | 10 | 22 | 15 |
| **South Tree** | | | | | | Total  0 | 3 | 12 | 7 |
| Heating (kBtu) | 385113 | 386116 | 386728 | 388208 | 386832 | **South Tree** -5 | -8 | -15 | -9 |
| Cooling (kWh) | 3682 | 3673 | 3672 | 3625 | 3673 | 1 | 1 | 7 | 1 |
| **West Tree** | | | | | | Total  -4 | -7 | -8 | -8 |
| Heating (kBtu) | 385113 | 385544 | 385820 | 386491 | 385882 | **West Tree** -2 | -4 | -7 | -4 |
| Cooling (kWh) | 3682 | 3606 | 3521 | 3283 | 3431 | 9 | 19 | 48 | 30 |
| | | | | | | Total  7 | 15 | 41 | 26 |

| Annual Hours of Use | Tree Height and Distance from Building | | | | | % Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
| **East Tree** | | | | | | **East Tree** | | | |
| Heating (hrs) | 4538 | 4551 | 4560 | 4573 | 4562 | -0.29 | -0.48 | -0.77 | -0.53 |
| Cooling (hrs) | 745 | 738 | 736 | 721 | 728 | 0.94 | 1.21 | 3.22 | 2.28 |
| **South Tree** | | | | | | **South Tree** | | | |
| Heating (hrs) | 4538 | 4549 | 4559 | 4580 | 4563 | -0.24 | -0.46 | -0.93 | -0.55 |
| Cooling (hrs) | 745 | 744 | 744 | 740 | 744 | 0.13 | 0.13 | 0.67 | 0.13 |
| **West Tree** | | | | | | **West Tree** | | | |
| Heating (hrs) | 4538 | 4542 | 4544 | 4561 | 4548 | -0.09 | -0.13 | -0.51 | -0.22 |
| Cooling (hrs) | 745 | 743 | 742 | 734 | 740 | 0.27 | 0.4 | 1.48 | 0.67 |

# Annual Heating and Cooling Savings From Base Case
## Due to Shade from One Deciduous Tree
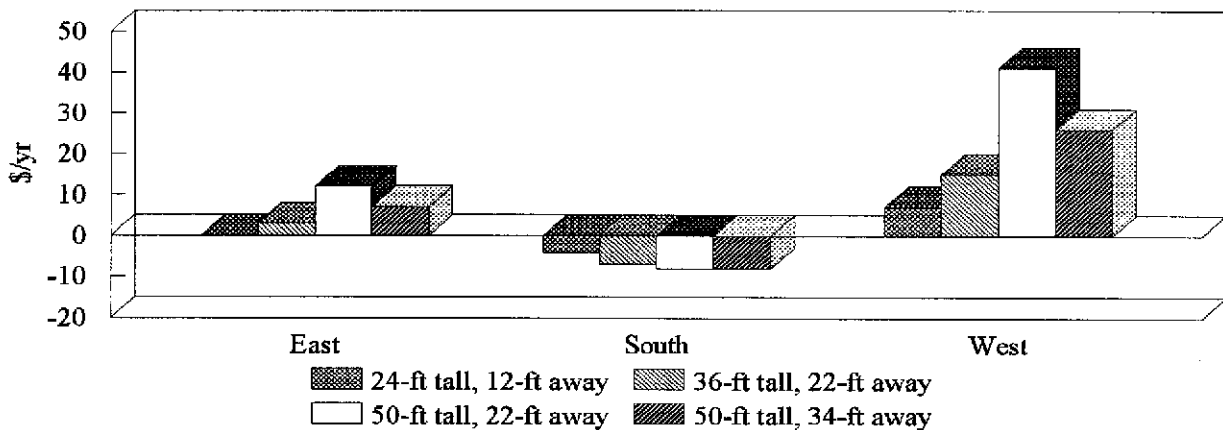


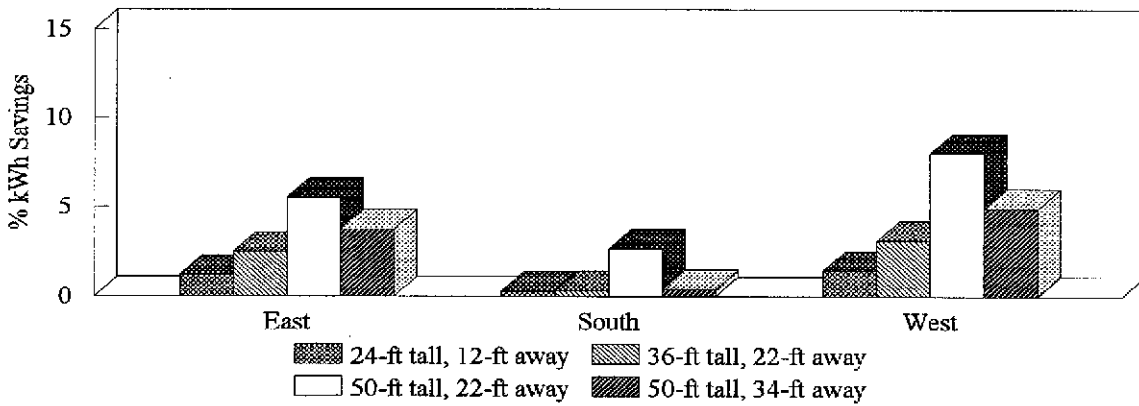2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing South)

## Annual Heating and Cooling Savings From Base Case
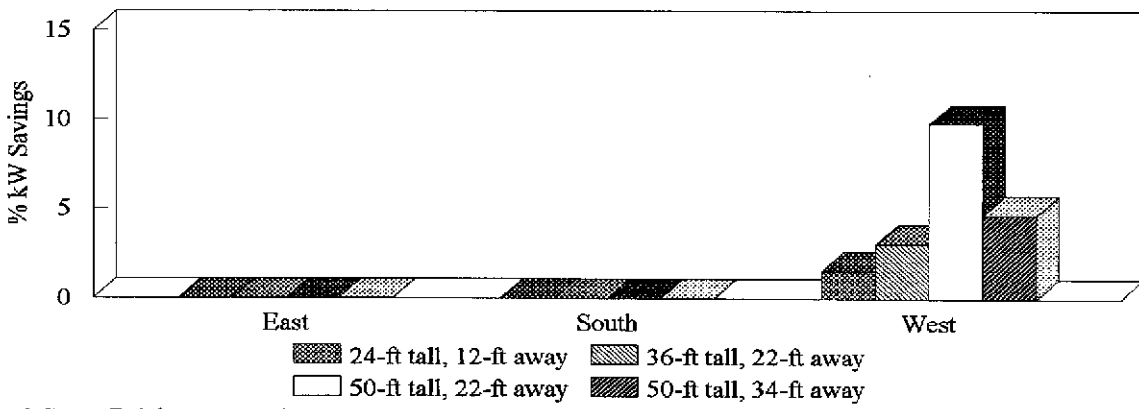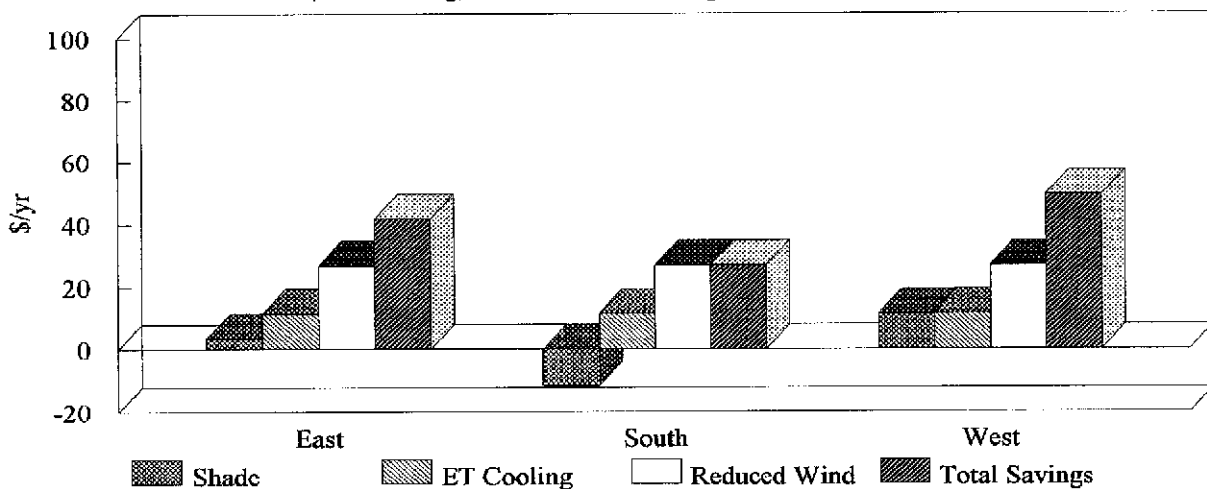### Due to Shade from A Large Deciduous Tree - 22 ft Away
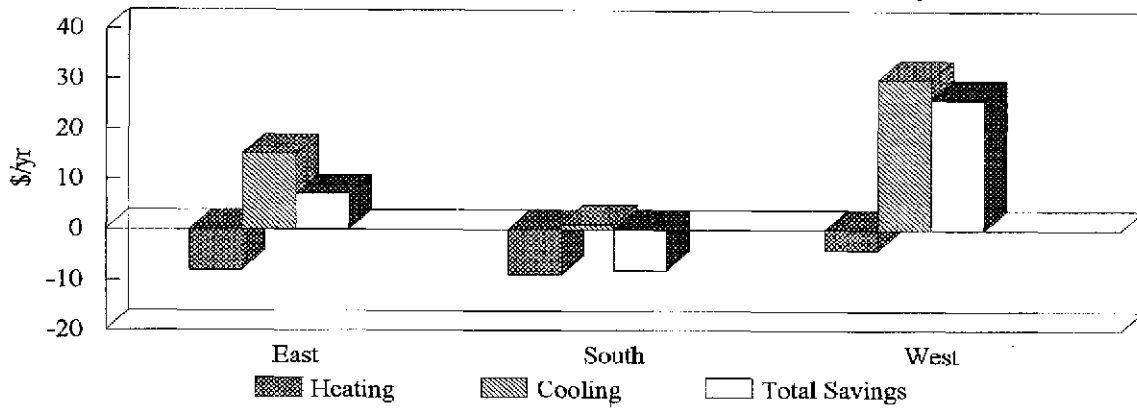


2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing South)

## Annual Percentage Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing South)

## Percentage Peak Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing South)

**Chicago, Illinois**  **Energy Analysis**

| | | | | Nat. Gas | ($/therm): | 0.5 |
| 2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing South) | | | | Electricity | ($/kWh): | 0.12 |
| Deciduous tree, 36-ft tall and 24-ft crown spread, 22-ft away from building | | | | Avoided Peak Electricity | ($/Avoid kW): | 65 |

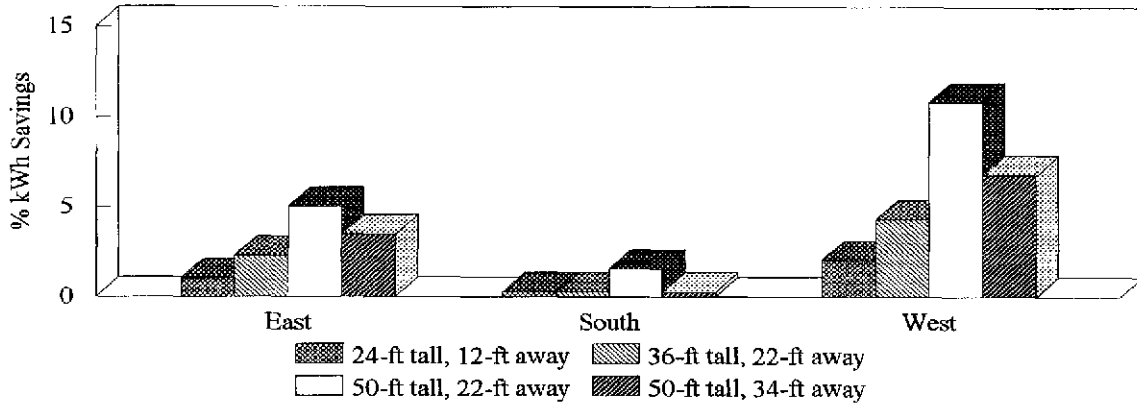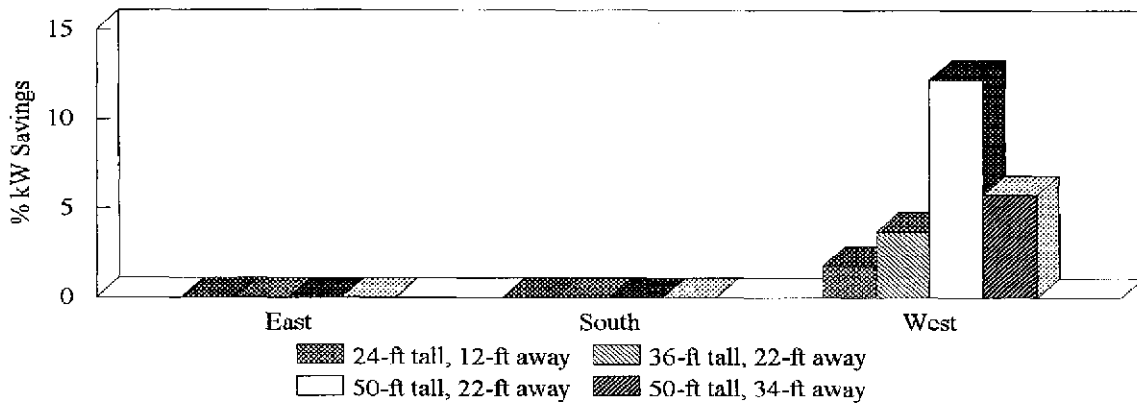| Annual Energy Use | Unshaded Base Case | East | Shade South | West | ET Cooling | Reduced Wind | East Shade + ET + Wind | South Shade + ET + Wind | West Shade + ET + Win |
|---|---|---|---|---|---|---|---|---|---|
| **Heat (MBtu)** | 385.11 | 386.58 | 386.73 | 385.82 | 385.12 | 369.73 | | | |
| $ | 1925.55 | 1932.90 | 1933.65 | 1929.10 | 1925.60 | 1848.65 | | | |
| MBtu diff / tree | | -1.47 | -1.62 | -0.71 | 0.00 | 5.13 | 3.66 | 3.51 | 4.42 |
| $ diff / tree | | -7.35 | -8.10 | -3.55 | -0.02 | 25.63 | 18.26 | 17.51 | 22.06 |
| % diff / tree | | -0.40 | -0.40 | -0.20 | 0.00 | 1.33 | 0.93 | 0.93 | 1.13 |
| | | | | | | | | | |
| **Cool (kWh)** | 3682 | 3598 | 3672 | 3521 | 3400 | 3647 | | | |
| $ | 441.79 | 431.77 | 440.69 | 422.55 | 407.95 | 437.61 | | | |
| kWh diff / tree | | 84 | 9 | 160 | 94 | 12 | 190.00 | 115.00 | 266.00 |
| $ diff / tree | | 10.02 | 1.10 | 19.24 | 11.28 | 1.39 | 22.69 | 13.77 | 31.91 |
| % diff / tree | | 2.27 | 0.25 | 4.36 | 2.55 | 0.32 | 5.14 | 3.12 | 7.22 |
| | | | | | | | | | |
| **Total (MBtu)** | 259.05 | 259.45 | 259.99 | 258.51 | 257.33 | 249.39 | | | |
| $ | 2367.34 | 2364.67 | 2374.34 | 2351.65 | 2333.55 | 2286.26 | | | |
| MBtu diff / tree | | -0.40 | -0.94 | 0.54 | 0.57 | 3.22 | 3.39 | 2.85 | 4.33 |
| $ diff / tree | | 2.67 | -7.00 | 15.69 | 11.26 | 27.03 | 40.96 | 31.29 | 53.98 |
| % diff / tree | | -0.15 | -0.36 | 0.21 | 0.22 | 1.24 | 1.31 | 1.10 | 1.67 |
| | | | | | | | | | |
| **Peak Cool (kW** | 10.60 | 10.60 | 10.60 | 10.21 | 10.05 | 10.43 | | | |
| Avoided $ | 689.00 | 689.00 | 689.00 | 663.00 | 653.00 | 678.00 | | | |
| Kw diff / tree | | 0.00 | 0.00 | 0.39 | 0.19 | 0.06 | 0.24 | 0.24 | 0.63 |
| Avoided $ diff / tree | | 0.00 | 0.00 | 26.00 | 12.00 | 3.67 | 15.67 | 15.67 | 41.67 |
| % diff / tree | | 0.01 | 0.00 | 3.71 | 1.74 | 0.53 | 2.28 | 2.27 | 5.98 |

# Annual Savings from Base Case - 1 Deciduous Tree
## Due to Shade, ET Cooling, and Reduced Wind Speed from 36-ft Tall and 24-ft Wide Tree
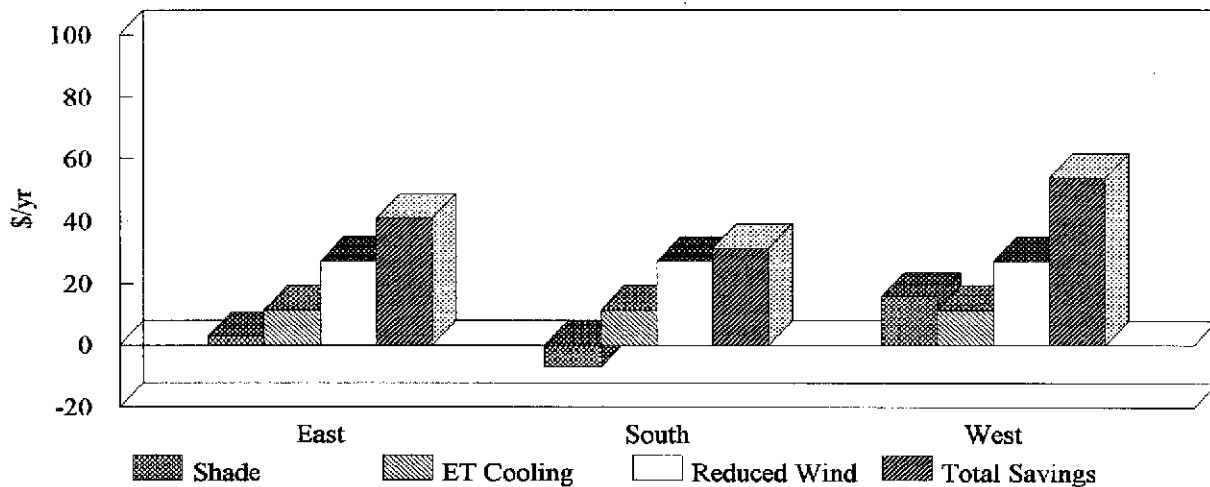


2 Story, Brick Construction - 3,562 sq ft Residence (Front Facing South)
1 tree 22-ft from wall

**Chicago, Illinois**      **Tree Shade Only**

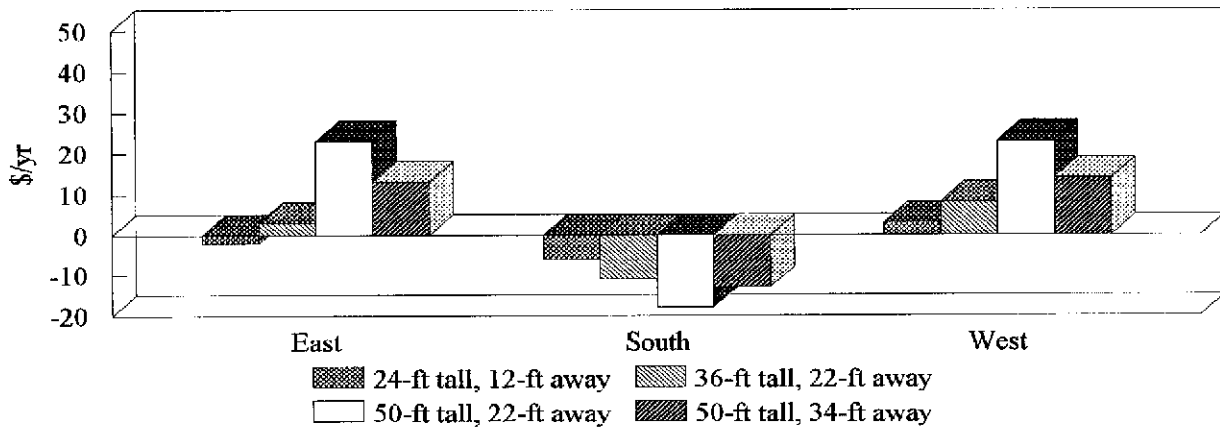3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing East)

| | | | | | | Nat. Gas | ($/therm): | 0.5 |
| | | | | | | Electricity | ($/kWh): | 0.12 |

### Source Energy Use (kBtu/ sq ft)

| | | Tree Height and Distance from Building | | | | | % Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) |
| **East Tree** | Base Case | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away | **East Tree** | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away |
| Total Heating Use | 121.35 | 121.69 | 121.85 | 122.08 | 121.95 | | -0.28 | -0.41 | -0.6 | -0.49 |
| Total Cooling Use | 11.80 | 11.69 | 11.55 | 11.18 | 11.37 | | 0.92 | 2.14 | 5.29 | 3.64 |
| Total Energy Use | 133.16 | 133.39 | 133.40 | 133.26 | 133.32 | | -0.17 | -0.19 | -0.08 | -0.12 |
| Peak Cool (kW) | 16.15 | 16.15 | 16.15 | 16.15 | 16.15 | | 0 | 0 | 0 | 0 |
| **South Tree** | | | | | | **South Tree** | | | | |
| Total Heating Use | 121.35 | 121.61 | 121.77 | 122.29 | 121.83 | | 0.21 | -0.34 | -0.77 | -0.39 |
| Total Cooling Use | 11.80 | 11.79 | 11.79 | 11.67 | 11.79 | | 0.12 | 0.13 | 1.14 | 0.12 |
| Total Energy Use | 133.16 | 133.39 | 133.56 | 133.96 | 133.62 | | -0.18 | -0.3 | -0.6 | -0.35 |
| Peak Cool (kW) | 16.15 | 16.15 | 16.15 | 16.15 | 16.15 | | 0 | 0 | 0 | 0 |
| **West Tree** | | | | | | **West Tree** | | | | |
| Total Heating Use | 121.35 | 121.40 | 121.44 | 121.54 | 121.46 | | -0.04 | -0.07 | -0.16 | -0.08 |
| Total Cooling Use | 11.80 | 11.74 | 11.66 | 11.39 | 11.57 | | 0.48 | 1.18 | 3.52 | 1.99 |
| Total Energy Use | 133.16 | 133.14 | 133.10 | 132.93 | 133.02 | | 0.01 | 0.04 | 0.17 | 0.1 |
| Peak Cool (kW) | 16.15 | 16.06 | 15.97 | 15.44 | 15.86 | | 0.55 | 1.12 | 4.39 | 1.76 |

### Annual Energy Use

| | | Tree Height and Distance from Building | | | | | $ Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) |
| **East Tree** | Base Case | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away | **East Tree** | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away |
| Heating (kBtu) | 715653 | 717658 | 718598 | 719945 | 719151 | **East Tree** | -10 | -15 | -21 | -17 |
| Cooling (kWh) | 6970 | 6906 | 6822 | 6602 | 6717 | | 8 | 18 | 44 | 30 |
| **South Tree** | | | | | | Total | -2 | 3 | 23 | 13 |
| Heating (kBtu) | 715653 | 717130 | 718102 | 721180 | 718467 | **South Tree** | -7 | -12 | -28 | -14 |
| Cooling (kWh) | 6970 | 6962 | 6961 | 6891 | 6962 | | 1 | 1 | 10 | 1 |
| **West Tree** | | | | | | Total | -6 | -11 | -18 | -13 |
| Heating (kBtu) | 715653 | 715913 | 716141 | 716769 | 716259 | **West Tree** | -1 | -2 | -6 | -3 |
| Cooling (kWh) | 6970 | 6937 | 6889 | 6725 | 6832 | | 4 | 10 | 29 | 17 |
| | | | | | | Total | 3 | 8 | 23 | 14 |

### Annual Hours of Use

| | | Tree Height and Distance from Building | | | | | % Saved from Base Case | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) | | Small (24 ft) | Med. (36 ft) | Large (50 ft) | Large (50 ft) |
| **East Tree** | Base Case | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away | **East Tree** | 12 ft Away | 22 ft Away | 22 ft Away | 34 ft Away |
| Heating (hrs) | 4500 | 4508 | 4521 | 4535 | 4526 | | -0.18 | -0.47 | -0.78 | -0.58 |
| Cooling (hrs) | 972 | 964 | 952 | 935 | 943 | | 0.82 | 2.06 | 3.81 | 2.98 |
| **South Tree** | | | | | | **South Tree** | | | | |
| Heating (hrs) | 4500 | 4506 | 4514 | 4548 | 4517 | | -0.13 | -0.31 | 1.07 | -0.38 |
| Cooling (hrs) | 972 | 972 | 972 | 964 | 971 | | 0 | 0 | 0.82 | 0.1 |
| **West Tree** | | | | | | **West Tree** | | | | |
| Heating (hrs) | 4500 | 4500 | 4504 | 4512 | 4506 | | 0 | -0.09 | -0.27 | -0.13 |
| Cooling (hrs) | 972 | 972 | 971 | 967 | 971 | | 0 | 0.1 | 0.51 | 0.1 |

## Annual Heating and Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



Legend: 24-ft tall, 12-ft away   36-ft tall, 22-ft away   50-ft tall, 22-ft away   50-ft tall, 34-ft away

3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing East)

## Annual Heating and Cooling Savings From Base Case
### Due to Shade from A Large Deciduous Tree - 22 ft Away



Heating    Cooling    Total Savings

3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing East)

## Annual Percentage Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



24-ft tall, 12-ft away    36-ft tall, 22-ft away
50-ft tall, 22-ft away    50-ft tall, 34-ft away

3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing East)

## Percentage Peak Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



24-ft tall, 12-ft away    36-ft tall, 22-ft away
50-ft tall, 22-ft away    50-ft tall, 34-ft away
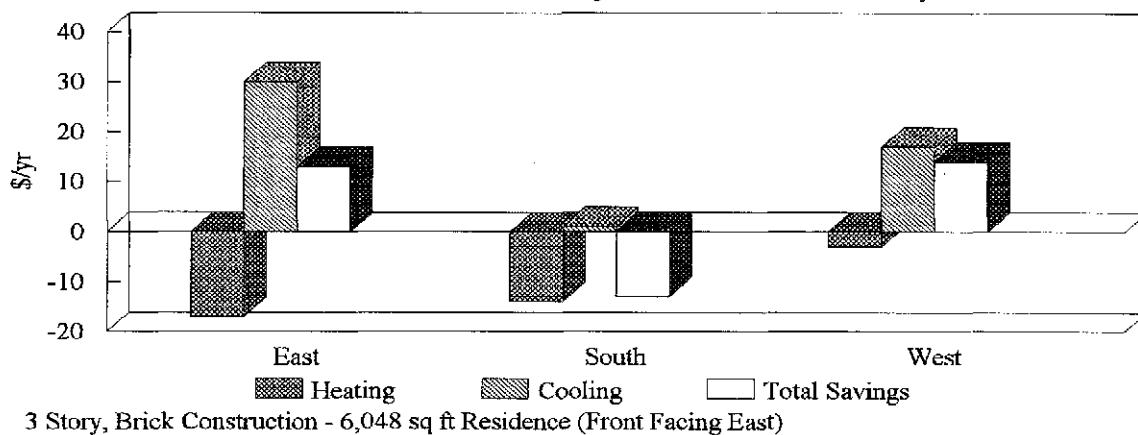
3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing East)
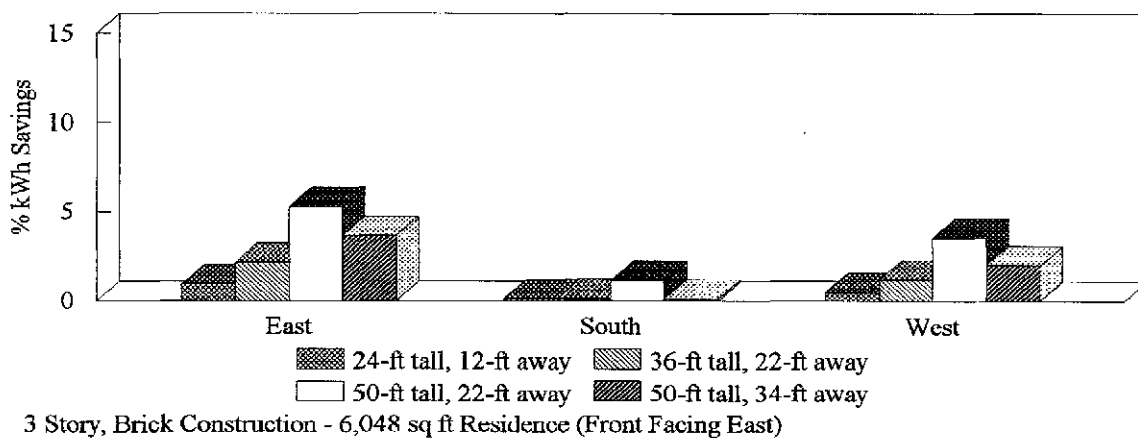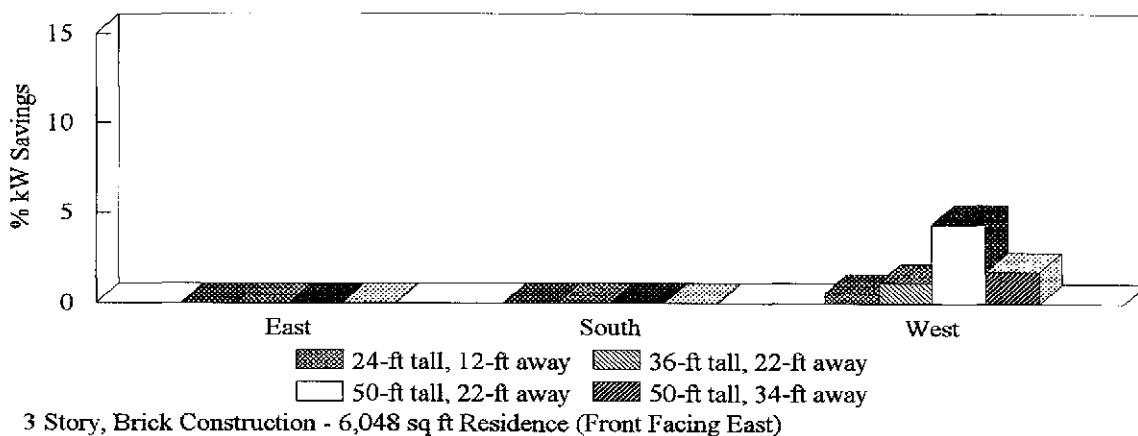
**Chicago, Illinois**  **Energy Analysis**

3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing East)
Deciduous tree, 36-ft tall and 24-ft crown spread, 22-ft away from building

| | | | | | | | Nat. Gas | ($/therm): | 0.5 |
| Electricity | ($/kWh): | 0.12 |
| Avoided Peak Electricity | ($/Avoid kW): | 65 |

| Annual Energy Use | Unshaded Base Case | East | Shade South | West | ET Cooling | Reduced Wind | East Shade + ET + Wind | South Shade + ET + Wind | West Shade + ET + Win |
|---|---|---|---|---|---|---|---|---|---|
| Heat (MBtu) | 715.65 | 718.60 | 718.10 | 716.14 | 715.67 | 684.56 | | | |
| $ | 3578.25 | 3593.00 | 3590.50 | 3580.70 | 3578.35 | 3422.80 | | | |
| MBtu diff / tree | | -2.95 | -2.45 | -0.49 | -0.01 | 10.36 | 7.40 | 7.90 | 9.86 |
| $ diff / tree | | -14.75 | -12.25 | -2.45 | -0.03 | 51.82 | 37.04 | 39.54 | 49.34 |
| % diff / tree | | -0.40 | -0.30 | -0.10 | 0.00 | 1.45 | 1.05 | 1.15 | 1.35 |
| | | | | | | | | | |
| Cool (kWh) | 6970 | 6822 | 6961 | 6889 | 6456 | 6873 | | | |
| $ | 836.46 | 818.60 | 835.36 | 826.62 | 774.77 | 824.76 | | | |
| kWh diff / tree | | 149 | 9 | 82 | 171 | 32 | 352.00 | 212.00 | 285.00 |
| $ diff / tree | | 17.86 | 1.10 | 9.84 | 20.56 | 3.90 | 42.32 | 25.56 | 34.30 |
| % diff / tree | | 2.14 | 0.13 | 1.18 | 2.46 | 0.47 | 5.06 | 3.06 | 4.10 |
| | | | | | | | | | |
| Total (MBtu) | 282.96 | 283.48 | 283.81 | 282.84 | 281.11 | 271.40 | | | |
| $ | 4414.71 | 4411.60 | 4425.86 | 4407.32 | 4353.12 | 4247.56 | | | |
| MBtu diff / tree | | -0.52 | -0.85 | 0.12 | 0.62 | 3.85 | 3.95 | 3.62 | 4.59 |
| $ diff / tree | | 3.11 | -11.15 | 7.39 | 20.53 | 55.72 | 79.36 | 65.10 | 83.64 |
| % diff / tree | | -0.18 | -0.30 | 0.04 | 0.22 | 1.36 | 1.40 | 1.28 | 1.62 |
| | | | | | | | | | |
| Peak Cool (kW | 16.15 | 16.15 | 16.15 | 15.97 | 15.16 | 15.82 | | | |
| Avoided $ | 1049.00 | 1049.00 | 1049.00 | 1038.00 | 986.00 | 1028.00 | | | |
| Kw diff / tree | | 0.00 | 0.00 | 0.18 | 0.33 | 0.11 | 0.44 | 0.44 | 0.62 |
| Avoided $ diff / tree | | 0.00 | 0.00 | 11.00 | 21.00 | 7.00 | 28.00 | 28.00 | 39.00 |
| % diff / tree | | 0.00 | 0.00 | 1.12 | 2.03 | 0.68 | 2.71 | 2.71 | 3.83 |

## Annual Savings from Base Case - 1 Deciduous Tree
### Due to Shade, ET Cooling, and Reduced Wind Speed from 36-ft Tall and 24-ft Wide Tree



Legend: Shade | ET Cooling | Reduced Wind | Total Savings

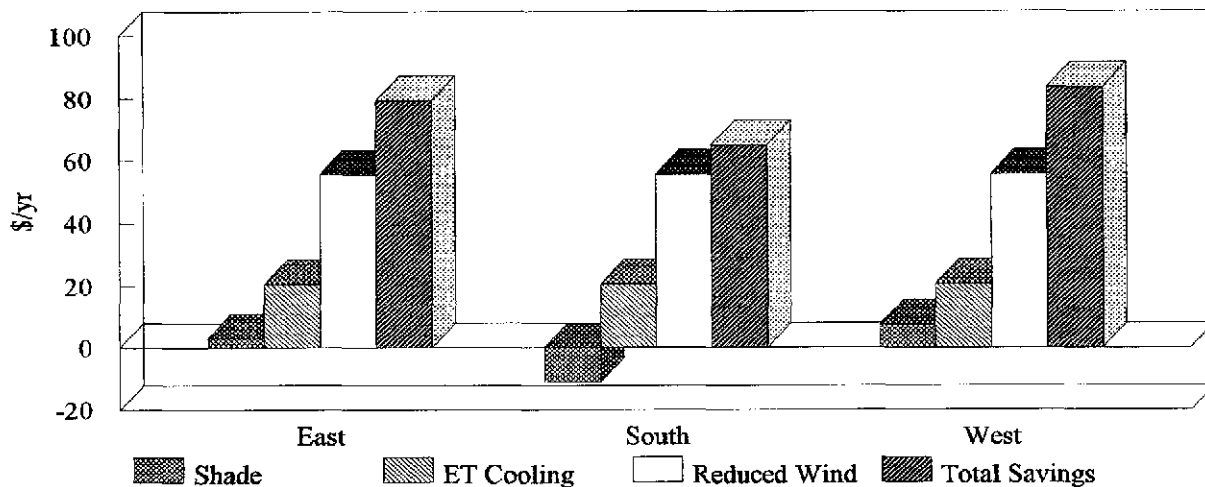3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing East)
1 tree 22-ft from wall

Appendix C

| | | | | | | Nat. Gas | ($/therm): | 0.5 |
|---|---|---|---|---|---|---|---|---|

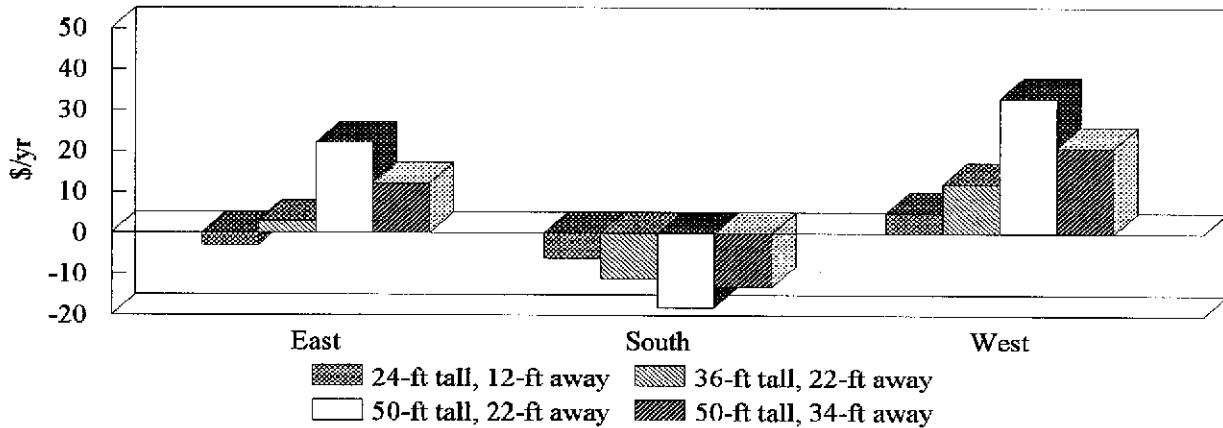3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing South)     Electricity    ($/kWh):    0.12

**Source Energy Use (kBtu/ sq ft)** — Tree Height and Distance from Building — % Saved from Base Case

| East Tree | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | East Tree | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
|---|---|---|---|---|---|---|---|---|---|---|
| Total Heating Use | 120.68 | 121.01 | 121.16 | 121.38 | 121.25 | | -0.27 | -0.4 | -0.58 | -0.47 |
| Total Cooling Use | 12.19 | 12.08 | 11.94 | 11.59 | 11.78 | | 0.84 | 1.99 | 4.87 | 3.34 |
| Total Energy Use | 132.87 | 133.10 | 133.11 | 132.97 | 133.03 | | -0.17 | -0.18 | -0.08 | -0.12 |
| Peak Cool (kW) | 16.69 | 16.69 | 16.69 | 16.69 | 16.69 | | 0 | 0 | 0 | 0 |
| **South Tree** | | | | | | **South Tree** | | | | |
| Total Heating Use | 120.68 | 120.94 | 121.11 | 121.65 | 121.18 | | -0.21 | -0.36 | -0.8 | -0.41 |
| Total Cooling Use | 12.19 | 12.16 | 12.16 | 12.03 | 12.16 | | 0.19 | 0.22 | 1.28 | 0.18 |
| Total Energy Use | 132.87 | 133.11 | 133.27 | 133.68 | 133.34 | | -0.18 | -0.3 | -0.61 | -0.35 |
| Peak Cool (kW) | 16.69 | 16.69 | 16.69 | 16.69 | 16.69 | | 0 | 0 | 0 | 0 |
| **West Tree** | | | | | | **West Tree** | | | | |
| Total Heating Use | 120.68 | 120.75 | 120.80 | 120.95 | 120.83 | | -0.05 | -0.1 | -0.22 | -0.12 |
| Total Cooling Use | 12.19 | 12.09 | 11.98 | 11.60 | 11.84 | | 0.77 | 1.69 | 4.79 | 2.85 |
| Total Energy Use | 132.87 | 132.84 | 132.78 | 132.55 | 132.67 | | 0.02 | 0.07 | 0.24 | 0.15 |
| Peak Cool (kW) | 16.69 | 16.57 | 16.44 | 15.72 | 16.30 | | 0.72 | 1.48 | 5.81 | 2.34 |

**Annual Energy Use** — Tree Height and Distance from Building — $ Saved from Base Case

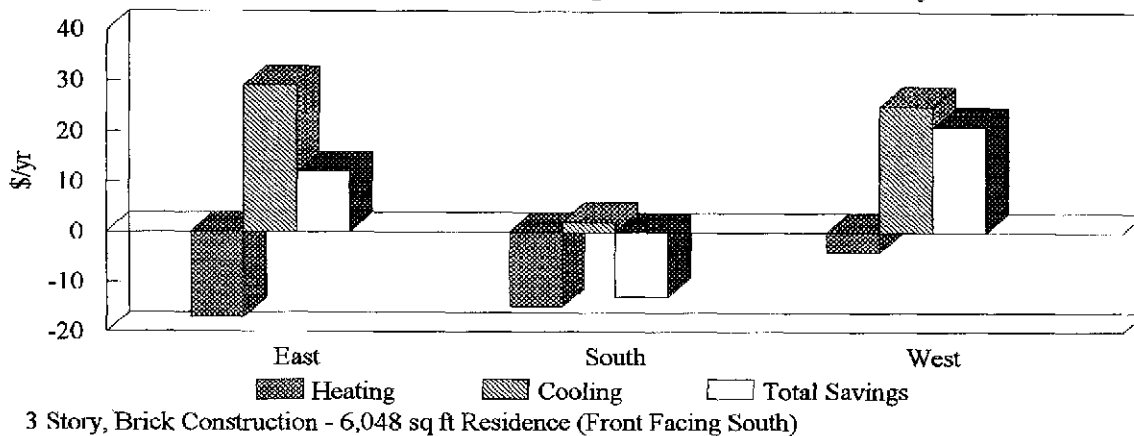| East Tree | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
|---|---|---|---|---|---|---|---|---|---|---|
| Heating (kBtu) | 711700 | 713623 | 714521 | 715797 | 715051 | East Tree | -10 | -14 | -20 | -17 |
| Cooling (kWh) | 7199 | 7138 | 7055 | 6848 | 6959 | | 7 | 17 | 42 | 29 |
| **South Tree** | | | | | | Total | -3 | 3 | 22 | 12 |
| Heating (kBtu) | 711700 | 713229 | 714235 | 717403 | 714607 | South Tree | -8 | -13 | -29 | -15 |
| Cooling (kWh) | 7199 | 7185 | 7183 | 7106 | 7186 | | 2 | 2 | 11 | 2 |
| **West Tree** | | | | | | Total | -6 | -11 | -18 | -13 |
| Heating (kBtu) | 711700 | 712062 | 712382 | 713258 | 712542 | West Tree | -2 | -3 | -8 | -4 |
| Cooling (kWh) | 7199 | 7143 | 7077 | 6854 | 6994 | | 7 | 15 | 41 | 25 |
| | | | | | | Total | 5 | 12 | 33 | 21 |

**Annual Hours of Use** — Tree Height and Distance from Building — % Saved from Base Case

| East Tree | Base Case | Small (24 ft) 12 ft Away | Med. (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away | East Tree | Small (24 ft) 12 ft Away | Med (36 ft) 22 ft Away | Large (50 ft) 22 ft Away | Large (50 ft) 34 ft Away |
|---|---|---|---|---|---|---|---|---|---|---|
| Heating (hrs) | 4470 | 4483 | 4492 | 4504 | 4497 | | -0.29 | -0.49 | -0.76 | -0.6 |
| Cooling (hrs) | 977 | 968 | 956 | 943 | 949 | | 0.92 | 2.15 | 3.48 | 2.87 |
| **South Tree** | | | | | | **South Tree** | | | | |
| Heating (hrs) | 4470 | 4479 | 4483 | 4519 | 4487 | | -0.2 | -0.29 | -1.1 | -0.38 |
| Cooling (hrs) | 977 | 975 | 973 | 964 | 974 | | 0.2 | 0.41 | 1.33 | 0.31 |
| **West Tree** | | | | | | **West Tree** | | | | |
| Heating (hrs) | 4470 | 4479 | 4479 | 4488 | 4482 | | -0.2 | -0.2 | -0.4 | -0.27 |
| Cooling (hrs) | 977 | 974 | 973 | 968 | 972 | | 0.31 | 0.41 | 0.92 | 0.51 |

## Annual Heating and Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing South)

## Annual Heating and Cooling Savings From Base Case
### Due to Shade from A Large Deciduous Tree - 22 ft Away



Legend: Heating, Cooling, Total Savings

3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing South)

## Annual Percentage Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



Legend: 24-ft tall, 12-ft away | 36-ft tall, 22-ft away | 50-ft tall, 22-ft away | 50-ft tall, 34-ft away
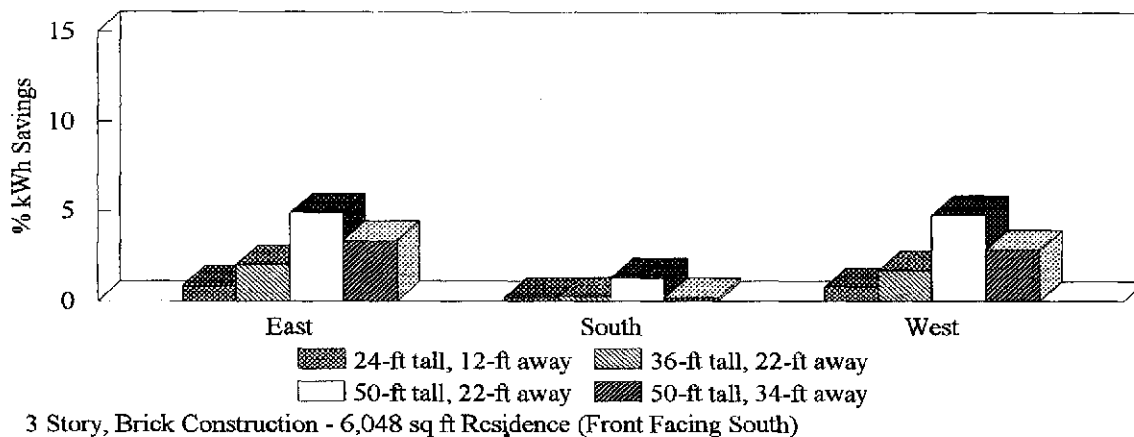
3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing South)

## Percentage Peak Cooling Savings From Base Case
### Due to Shade from One Deciduous Tree



Legend: 24-ft tall, 12-ft away | 36-ft tall, 22-ft away | 50-ft tall, 22-ft away | 50-ft tall, 34-ft away

3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing South)

| | | | | | | Nat. Gas | ($/therm): | 0.5 |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing South) | | | | | | Electricity | ($/kWh): | 0.12 |
| Deciduous tree, 36-ft tall and 24-ft crown spread, 22-ft away from building | | | | | | Avoided Peak Electricity | ($/Avoid kW): | 65 |

| Annual Energy Use | Unshaded Base Case | East | Shade South | West | ET Cooling | Reduced Wind | East Shade + ET + Wind | South Shade + ET + Wind | West Shade + ET + Win |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Heat (MBtu) | 711.70 | 714.52 | 714.23 | 712.38 | 711.71 | 680.68 | | | |
| $ | 3558.50 | 3572.60 | 35/1.15 | 3561.90 | 3558.55 | 3403.40 | | | |
| MBtu diff / tree | | -2.82 | -2.53 | -0.68 | 0.00 | 10.34 | 7.52 | 7.81 | 9.66 |
| $ diff / tree | | -14.10 | -12.65 | -3.40 | -0.02 | 51.70 | 37.58 | 39.03 | 48.28 |
| % diff / tree | | -0.40 | -0.40 | -0.10 | 0.00 | 1.45 | 1.05 | 1.05 | 1.35 |
| | | | | | | | | | |
| Cool (kWh) | 7199 | 7055 | 7183 | 7077 | 6696 | 7111 | | | |
| $ | 863.85 | 846.63 | 861.92 | 849.25 | 803.53 | 853.34 | | | |
| kWh diff / tree | | 143 | 16 | 122 | 168 | 29 | 340.00 | 213.00 | 319.00 |
| $ diff / tree | | 17.22 | 1.93 | 14.60 | 20.11 | 3.50 | 40.83 | 25.54 | 38.21 |
| % diff / tree | | 1.99 | 0.22 | 1.69 | 2.33 | 0.41 | 4.73 | 2.96 | 4.42 |
| | | | | | | | | | |
| Total (MBtu) | 282.35 | 282.85 | 283.21 | 282.16 | 280.55 | 270.86 | | | |
| $ | 4422.35 | 4419.23 | 4433.07 | 4411.15 | 4362.08 | 4256.74 | | | |
| MBtu diff / tree | | -0.50 | -0.86 | 0.19 | 0.60 | 3.83 | 3.93 | 3.57 | 4.62 |
| $ diff / tree | | 3.12 | -10.72 | 11.20 | 20.09 | 55.20 | 78.41 | 64.57 | 86.49 |
| % diff / tree | | -0.18 | -0.31 | 0.07 | 0.21 | 1.36 | 1.39 | 1.27 | 1.64 |
| | | | | | | | | | |
| Peak Cool (kW | 16.69 | 16.69 | 16.69 | 16.44 | 15.71 | 16.36 | | | |
| Avoided $ | 1085.00 | 1085.00 | 1085.00 | 1069.00 | 1021.00 | 1064.00 | | | |
| Kw diff / tree | | 0.00 | 0.00 | 0.25 | 0.33 | 0.11 | 0.44 | 0.44 | 0.69 |
| Avoided $ diff / tree | | 0.00 | 0.00 | 16.00 | 21.33 | 7.00 | 28.33 | 28.33 | 44.33 |
| % diff / tree | | 0.00 | 0.00 | 1.48 | 1.96 | 0.66 | 2.62 | 2.62 | 4.10 |

# Annual Savings from Base Case - 1 Deciduous Tree

## Due to Shade, ET Cooling, and Reduced Wind Speed from 36-ft Tall and 24-ft Wide Tree



Shade    ET Cooling    Reduced Wind    Total Savings
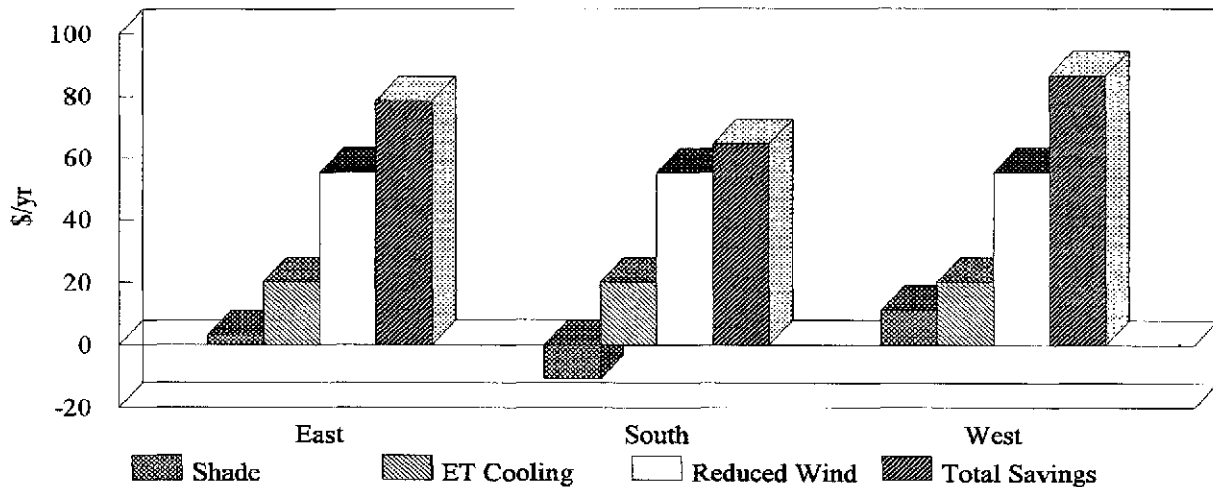
3 Story, Brick Construction - 6,048 sq ft Residence (Front Facing South)
1 tree 22-ft from wall
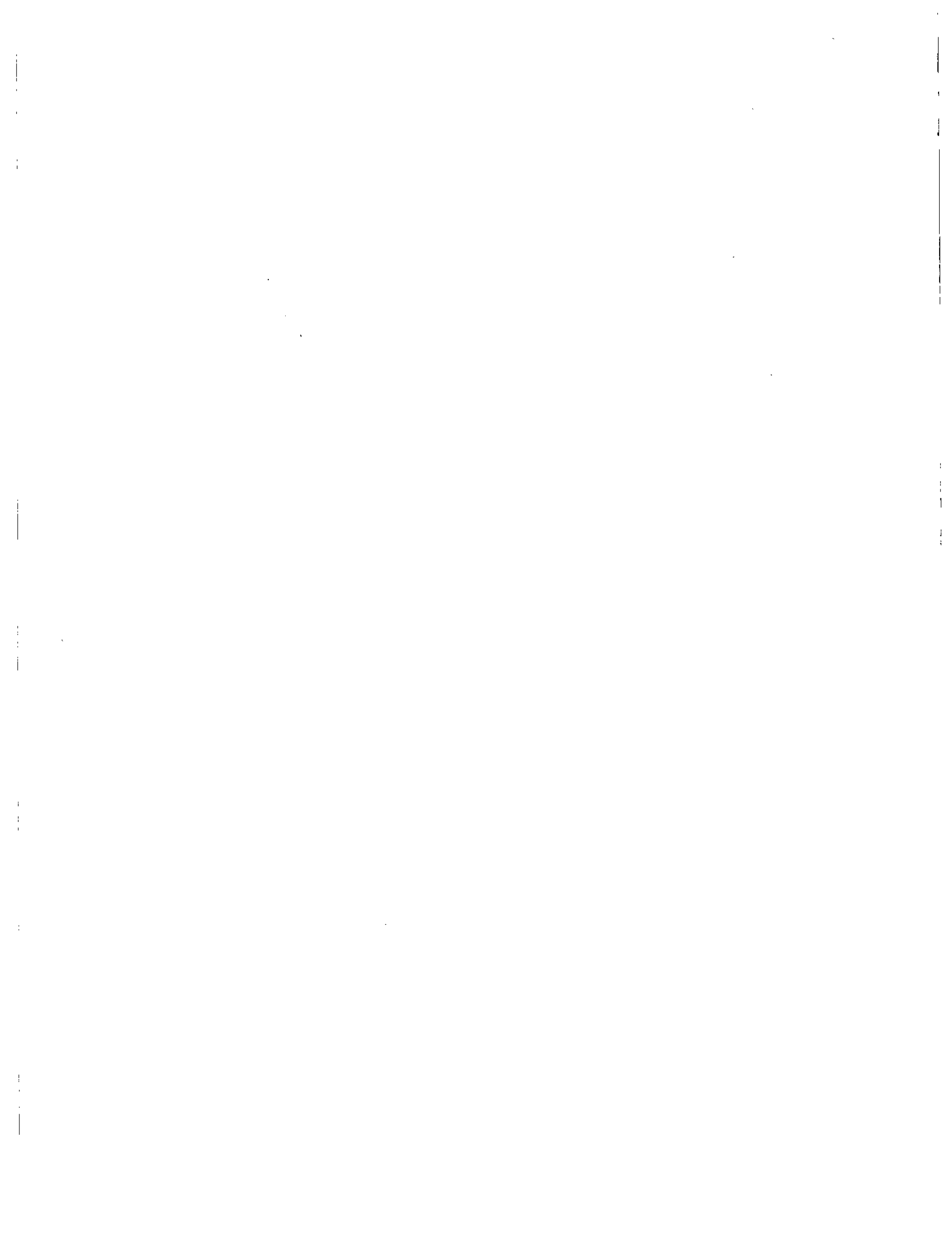
# Appendix D

## Standard Reports for Wood-Framed Base Case Buildings

# Chicago, Illinois

**1 Story - Wood Frame Residence (1,500 sq ft)**
Tree Shade Only

**Space Conditioning Source Energy Use (kBtu/ sq ft)**

| Nat. Gas | ($/therm): | 0.5 |
| --- | --- | --- |
| Electricity | ($/kWh): | 0.12 |

| Year 5 | Base Case | 1 Tree | 2 Tree | 3 Tree | Year 5 | % Saved from Base Case 1 Tree | 2 Tree | 3 Tree |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Total Heating Use | 89.59 | 89.79 | 89.83 | 89.92 | | -0.23 | -0.28 | -0.37 |
| Total Cooling Use | 20.07 | 19.68 | 19.41 | 19.23 | | 1.95 | 3.32 | 4.17 |
| Total Energy Use | 109.66 | 109.47 | 109.24 | 109.15 | | 0.17 | 0.38 | 0.46 |
| Peak Cool (kW) | 7.43 | 7.03 | 6.63 | 6.63 | | 5.38 | 10.76 | 10.76 |
| **Year 10** | | | | | **Year 10** | | | |
| Total Heating Use | 89.59 | 89.85 | 89.96 | 90.11 | | -0.29 | -0.41 | -0.59 |
| Total Cooling Use | 20.07 | 19.27 | 18.60 | 18.06 | | 4 | 7.35 | 10.04 |
| Total Energy Use | 109.66 | 109.12 | 108.55 | 108.17 | | 0.49 | 1.01 | 1.36 |
| Peak Cool (kW) | 7.43 | 6.60 | 5.83 | 5.83 | | 11.13 | 21.55 | 21.55 |
| **Year 15** | | | | | **Year 15** | | | |
| Total Heating Use | 89.59 | 89.91 | 90.03 | 90.29 | | -0.36 | -0.5 | -0.78 |
| Total Cooling Use | 20.07 | 18.88 | 18.02 | 17.10 | | 5.95 | 10.23 | 14.79 |
| Total Energy Use | 109.66 | 108.79 | 108.05 | 107.39 | | 0.8 | 1.46 | 2.07 |
| Peak Cool (kW) | 7.43 | 6.33 | 5.43 | 5.43 | | 14.74 | 26.93 | 26.93 |
| **Year 20** | | | | | **Year 20** | | | |
| Total Heating Use | 89.59 | 89.92 | 90.09 | 90.32 | | -0.37 | -0.56 | -0.82 |
| Total Cooling Use | 20.07 | 18.80 | 17.91 | 16.93 | | 6.33 | 10.78 | 15.66 |
| Total Energy Use | 109.66 | 108.72 | 108.00 | 107.25 | | 0.85 | 1.51 | 2.19 |
| Peak Cool (kW) | 7.43 | 6.28 | 5.37 | 5.37 | | 15.42 | 27.74 | 27.75 |

## Annual Energy Use

| Year 5 | Base Case | 1 Tree | 2 Tree | 3 Tree | | 1991 $ Saved from Base Case 1 Tree | 2 Tree | 3 Tree |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Heating (kBtu) | 129735 | 130031 | 130093 | 130214 | Year 5 | -1 | -2 | -2 |
| Cooling (kWh) | 2941 | 2883 | 2843 | 2818 | | 7 | 12 | 15 |
| | | | | | Total | 6 | 10 | 13 |
| **Year 10** | | | | | **Year 10** | | | |
| Heating (kBtu) | 129735 | 130115 | 130271 | 130498 | | -2 | -3 | -4 |
| Cooling (kWh) | 2941 | 2823 | 2724 | 2645 | | 14 | 26 | 35 |
| | | | | | Total | 12 | 23 | 31 |
| **Year 15** | | | | | **Year 15** | | | |
| Heating (kBtu) | 129735 | 130200 | 130384 | 130752 | | -2 | -3 | -5 |
| Cooling (kWh) | 2941 | 2766 | 2640 | 2506 | | 21 | 36 | 52 |
| | | | | | Total | 19 | 33 | 47 |
| **Year 20** | | | | | **Year 20** | | | |
| Heating (kBtu) | 129735 | 130218 | 130466 | 130803 | | -2 | -4 | -5 |
| Cooling (kWh) | 2941 | 2754 | 2624 | 2480 | | 22 | 38 | 55 |
| | | | | | Total | 20 | 34 | 50 |

## Heating and Air Conditioning Hours of Use

| Year 5 | Base Case | 1 Tree | 2 Tree | 3 Tree | Year 5 | % Saved from Base Case 1 Tree | 2 Tree | 3 Tree |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Heating (hrs) | 4081 | 4090 | 4090 | 4090 | | -0.21 | -0.21 | -0.21 |
| Cooling (hrs) | 1240 | 1232 | 1232 | 1214 | | 0.69 | 0.69 | 2.1 |
| **Year 10** | | | | | **Year 10** | | | |
| Heating (hrs) | 4081 | 4099 | 4099 | 4099 | | -0.42 | -0.42 | -0.42 |
| Cooling (hrs) | 1240 | 1232 | 1232 | 1214 | | 0.69 | 0.69 | 2.1 |
| **Year 15** | | | | | **Year 15** | | | |
| Heating (hrs) | 4081 | 4099 | 4115 | 4115 | | -0.42 | -0.83 | -0.83 |
| Cooling (hrs) | 1240 | 1232 | 1232 | 1206 | | 0.69 | 0.69 | 2.79 |
| **Year 20** | | | | | **Year 20** | | | |
| Heating (hrs) | 4081 | 4099 | 4115 | 4115 | | -0.42 | -0.83 | -0.83 |
| Cooling (hrs) | 1240 | 1232 | 1232 | 1206 | | 0.69 | 0.69 | 2.79 |

## Annual Dollar Savings From Base Case



1,500 sf, 1 story wood frame home in Chicago

Legend: Yr. 5 (13 ft)   Yr. 10 (19 ft)   Yr. 15 (24 ft)   Yr. 20 (25 ft)

## Annual Space Conditioning Energy
### Year 20 – 25 ft tree



Legend: Heating   Cooling

## Annual Cooling Savings from Base Case



Legend: Yr. 5 (13 ft)   Yr. 10 (19 ft)   Yr. 15 (24 ft)   Yr. 20 (25 ft)

## Peak Cooling Savings from Base Case



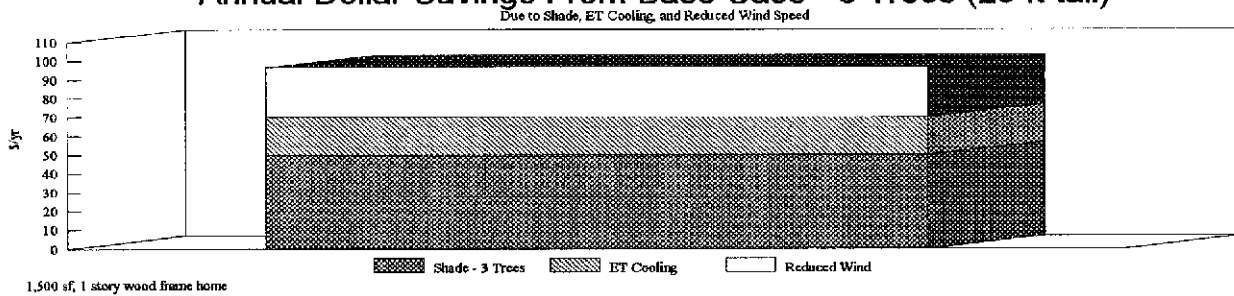Legend: Yr. 5 (13 ft)   Yr. 10 (19 ft)   Yr. 15 (24 ft)   Yr. 20 (25 ft)
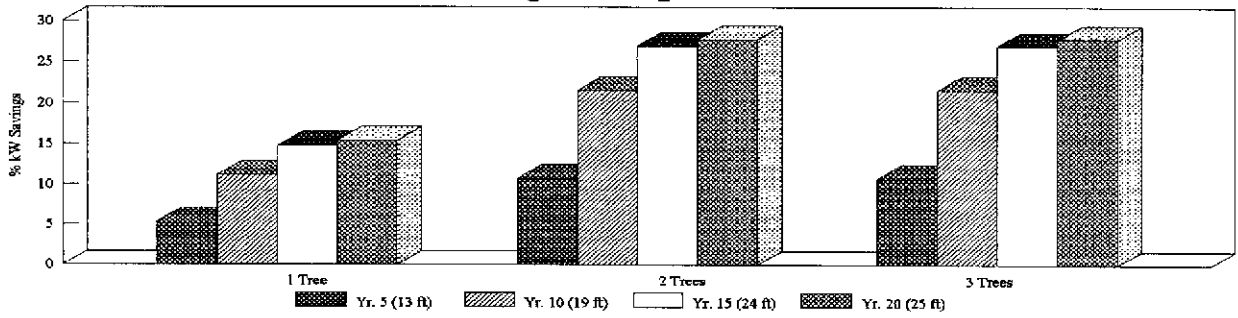
**Chicago, Illinois**
1 Story - Wood Frame
Year 20 - 25 ft trees

**Energy Analysis**
1500 sq ft

| Nat. Gas | ($/therm): | 0.5 |
| Electricity | ($/kWh): | 0.12 |
| Avoided Peak Electricity | ($/Avoid kW): | 65 |

| Annual Energy Use | Unshaded Base Case | 1 Tree | Shade 2 Trees | 3 Trees | ET Cooling | Reduced Wind | 3 Tree+ET + Wind | Avg. Savings Tree/Yr. |
|---|---|---|---|---|---|---|---|---|
| **Heat (MBtu)** | 129.74 | 130.22 | 130.47 | 130.80 | 129.81 | 124.91 | | |
| $ | 648.70 | 651.10 | 652.35 | 654.00 | 649.05 | 624.55 | | |
| MBtu diff | | -0.48 | -0.73 | -1.06 | -0.07 | 4.83 | 3.70 | 1.23 |
| $ diff | | -2.40 | -3.65 | -5.30 | -0.35 | 24.15 | 18.50 | 6.17 |
| % diff | | -0.40 | -0.60 | -0.80 | -0.10 | 3.70 | 2.80 | 0.93 |
| | | | | | | | | |
| **Cool (kWh)** | 2941 | 2754 | 2624 | 2480 | 2770 | 2922 | | |
| $ | 352.87 | 330.53 | 314.82 | 297.62 | 332.36 | 350.62 | | |
| kWh diff | | 186 | 317 | 460 | 171 | 19 | 650 | 216.67 |
| $ diff | | 22.34 | 38.05 | 55.25 | 20.51 | 2.25 | 78.01 | 26.00 |
| % diff | | 6.33 | 10.78 | 15.66 | 5.81 | 0.64 | 22.11 | 7.37 |
| | | | | | | | | |
| **Total (MBtu)** | 164.49 | 163.08 | 162.00 | 160.88 | 162.82 | 159.30 | | |
| $ | 1001.57 | 981.63 | 967.17 | 951.62 | 981.41 | 975.17 | | |
| MBtu diff | | 1.41 | 2.49 | 3.61 | 1.67 | 5.19 | 10.47 | 3.49 |
| $ diff | | 19.94 | 34.40 | 49.95 | 20.16 | 26.40 | 96.51 | 32.17 |
| % diff | | 0.86 | 1.51 | 2.20 | 1.02 | 3.16 | 6.37 | 2.12 |
| | | | | | | | | |
| **Peak Cool (kW** | 7.43 | 6.28 | 5.37 | 5.37 | 7.19 | 7.38 | | |
| Avoided $ | 483.00 | 408.00 | 349.00 | 349.00 | 467.00 | 480.00 | | |
| Kw diff | | 1.15 | 2.06 | 2.06 | 0.24 | 0.05 | 2.35 | 0.78 |
| Avoided $ diff | | 75.00 | 134.00 | 134.00 | 16.00 | 3.00 | 153.00 | 51.00 |
| % diff | | 15.42 | 27.74 | 27.75 | 3.26 | 0.67 | 31.68 | 10.56 |

## Annual Dollar Savings From Base Case - 3 Trees (25 ft tall)
Due to Shade, ET Cooling, and Reduced Wind Speed



Shade - 3 Trees    ET Cooling    Reduced Wind

1,500 sf, 1 story wood frame home

## Average Annual Dollar Savings From Base Case - 1 Tree (25 ft tall)
Due to Shade, ET Cooling, and Reduced Wind Speed



Heating    Cooling

1,500 sf, 1 story wood frame home

# Annual Dollar Savings From Base Case
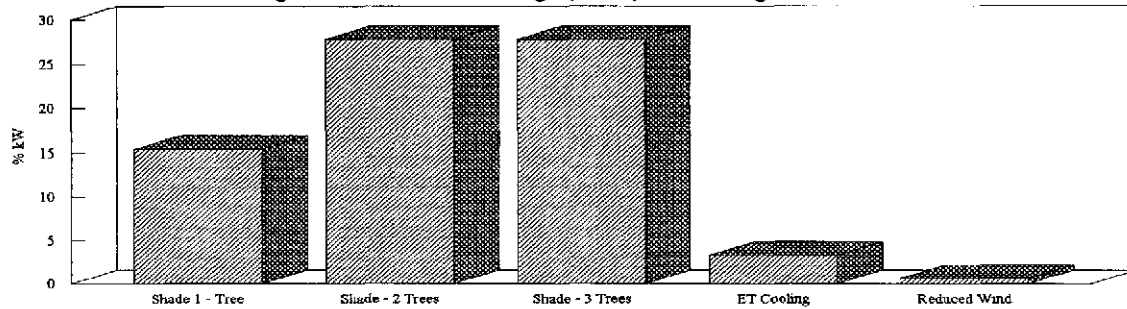


1,500 sf, 1 story wood frame home in Chicago
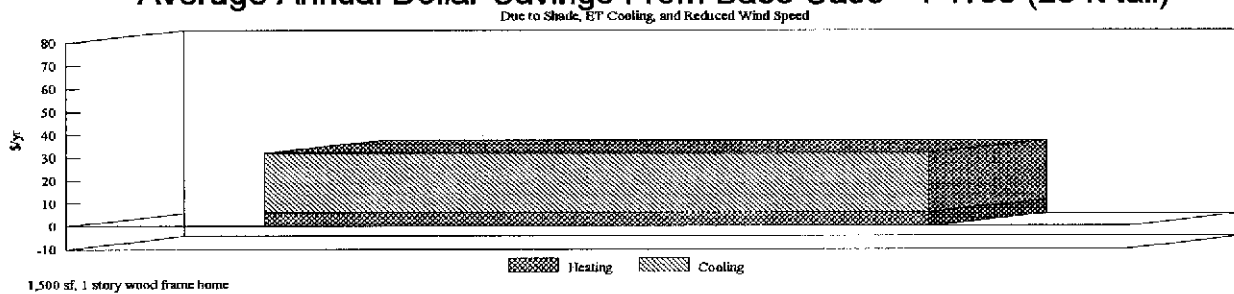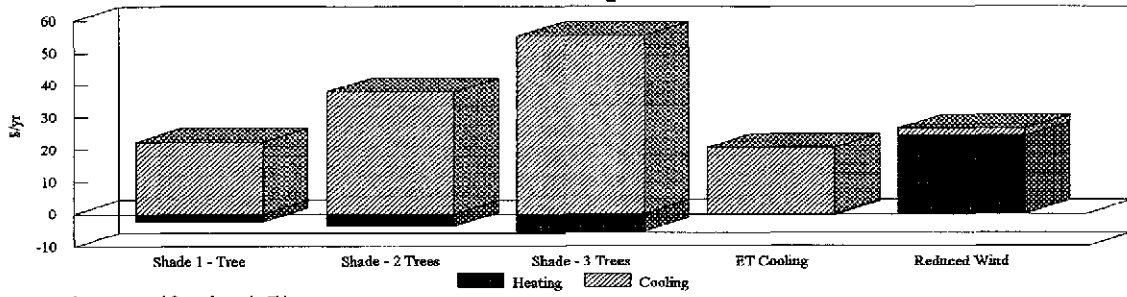
# Annual Dollar Savings From Base Case
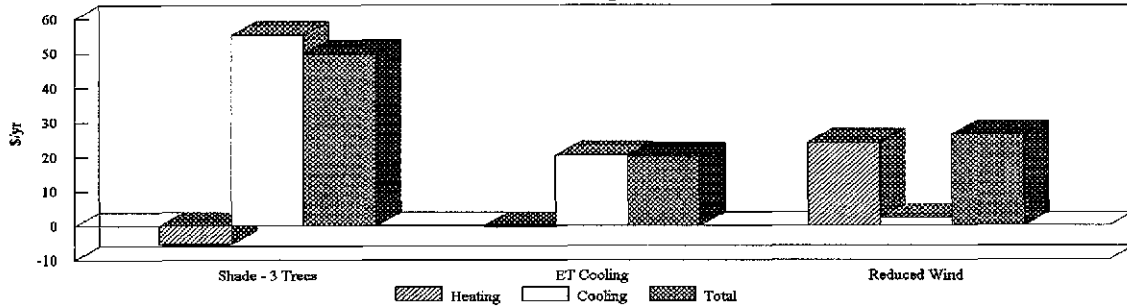


# Percentage Cooling (kWh) Savings From Base Case
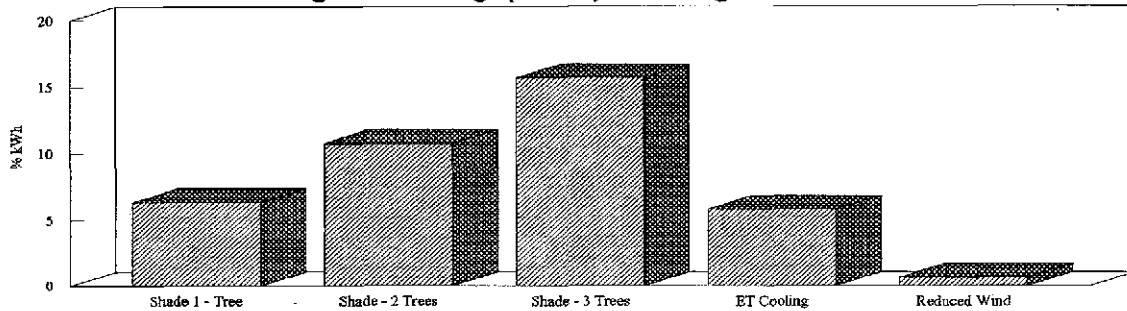


# Percentage Peak Cooling (kW) Savings From Base Case

**Chicago, Illinois** **Tree Shade Only**

2 Story - Wood Frame Residence (1,761 sq ft)

**Space Conditioning Source Energy Use (kBtu/ sq ft)**

| | | | | | Nat. Gas | ($/therm): | 0.5 |
| | | | | | Electricity | ($/kWh): | 0.12 |

| | | | | | | % Saved from Base Case | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Year 5** | Base Case | 1 Tree | 2 Tree | 3 Tree | **Year 5** | 1 Tree | 2 Tree | 3 Tree |
| Total Heating Use | 42.24 | 42.37 | 42.39 | 42.44 | | -0.29 | -0.36 | -0.46 |
| Total Cooling Use | 10.80 | 10.66 | 10.57 | 10.53 | | 1.29 | 2.19 | 2.56 |
| Total Energy Use | 53.05 | 53.03 | 52.96 | 52.97 | | 0.03 | 0.16 | 0.15 |
| Peak Cool (kW) | 5.10 | 4.93 | 4.78 | 4.78 | | 3.27 | 6.36 | 6.36 |
| **Year 10** | | | | | **Year 10** | | | |
| Total Heating Use | 42.24 | 42.44 | 42.52 | 42.64 | | -0.46 | -0.64 | -0.93 |
| Total Cooling Use | 10.80 | 10.43 | 10.13 | 9.94 | | 3.5 | 6.28 | 8.04 |
| Total Energy Use | 53.05 | 52.86 | 52.64 | 52.57 | | 0.35 | 0.77 | 0.89 |
| Peak Cool (kW) | 5.10 | 4.61 | 4.20 | 4.20 | | 9.52 | 17.6 | 17.6 |
| **Year 15** | | | | | **Year 15** | | | |
| Total Heating Use | 42.24 | 42.51 | 42.63 | 42.83 | | -0.62 | -0.91 | -1.39 |
| Total Cooling Use | 10.80 | 10.14 | 9.67 | 9.28 | | 6.15 | 10.49 | 14.13 |
| Total Energy Use | 53.05 | 52.65 | 52.30 | 52.11 | | 0.76 | 1.42 | 1.77 |
| Peak Cool (kW) | 5.10 | 4.29 | 3.75 | 3.75 | | 15.87 | 26.45 | 26.46 |
| **Year 20** | | | | | **Year 20** | | | |
| Total Heating Use | 42.24 | 42.52 | 42.63 | 42.87 | | -0.65 | -0.91 | -1.48 |
| Total Cooling Use | 10.80 | 10.07 | 9.67 | 9.17 | | 6.8 | 10.49 | 15.09 |
| Total Energy Use | 53.05 | 52.59 | 52.30 | 52.04 | | 0.87 | 1.42 | 1.9 |
| Peak Cool (kW) | 5.10 | 4.23 | 3.75 | 3.69 | | 16.98 | 26.45 | 27.66 |

**Annual Energy Use**

| | | | | | | 1991 $ Saved from Base Case | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Year 5** | Base Case | 1 Tree | 2 Tree | 3 Tree | | 1 Tree | 2 Tree | 3 Tree |
| Heating (kBtu) | 71538 | 71746 | 71793 | 71871 | **Year 5** | -1 | -1 | -2 |
| Cooling (kWh) | 1858 | 1834 | 1817 | 1811 | | 3 | 5 | 6 |
| **Year 10** | | | | | Total | 2 | 4 | 4 |
| Heating (kBtu) | 71538 | 71867 | 71999 | 72206 | **Year 10** | -2 | -2 | -3 |
| Cooling (kWh) | 1858 | 1793 | 1741 | 1709 | | 8 | 14 | 18 |
| **Year 15** | | | | | Total | 6 | 12 | 15 |
| Heating (kBtu) | 71538 | 71982 | 72187 | 72535 | **Year 15** | -2 | -3 | -5 |
| Cooling (kWh) | 1858 | 1744 | 1663 | 1596 | | 14 | 23 | 32 |
| **Year 20** | | | | | Total | 12 | 20 | 27 |
| Heating (kBtu) | 71538 | 72004 | 72187 | 72596 | **Year 20** | -2 | -3 | -5 |
| Cooling (kWh) | 1858 | 1732 | 1663 | 1578 | | 15 | 23 | 34 |
| | | | | | Total | 13 | 20 | 29 |

**Heating and Air Conditioning Hours of Use**

| | | | | | | % Saved from Base Case | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Year 5** | Base Case | 1 Tree | 2 Tree | 3 Tree | **Year 5** | 1 Tree | 2 Tree | 3 Tree |
| Heating (hrs) | 3281 | 3289 | 3289 | 3289 | | -0.26 | -0.26 | -0.26 |
| Cooling (hrs) | 1188 | 1179 | 1179 | 1179 | | 0.76 | 0.76 | 0.76 |
| **Year 10** | | | | | **Year 10** | | | |
| Heating (hrs) | 3281 | 3298 | 3306 | 3306 | | -0.52 | -0.78 | -0.78 |
| Cooling (hrs) | 1188 | 1179 | 1179 | 1170 | | 0.76 | 0.76 | 1.5 |
| **Year 15** | | | | | **Year 15** | | | |
| Heating (hrs) | 3281 | 3306 | 3315 | 3323 | | -0.78 | -1.05 | -1.3 |
| Cooling (hrs) | 1188 | 1179 | 1171 | 1153 | | 0.76 | 1.48 | 2.95 |
| **Year 20** | | | | | **Year 20** | | | |
| Heating (hrs) | 3281 | 3306 | 3315 | 3323 | | -0.78 | -1.05 | -1.3 |
| Cooling (hrs) | 1188 | 1171 | 1171 | 1127 | | 1.48 | 1.48 | 5.18 |

# Annual Dollar Savings From Base Case



1,761 sf, 2 story wood frame home in Chicago

# Annual Space Conditioning Energy

Year 20 -- 25 ft tree
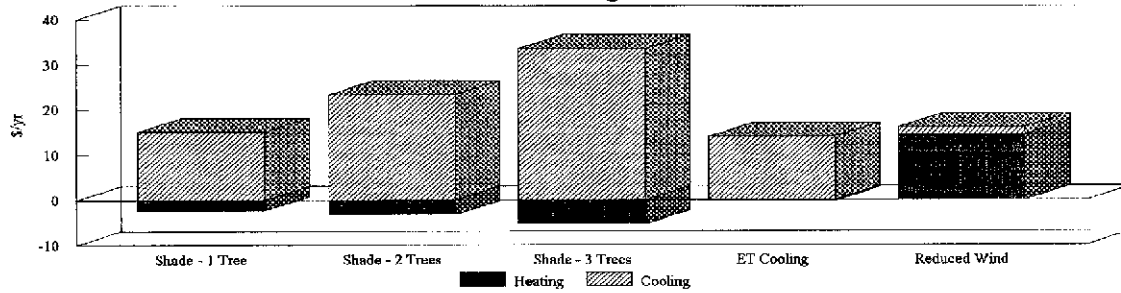


# Annual Cooling Savings from Base Case



# Peak Cooling Savings from Base Case

# Annual Dollar Savings From Base Case



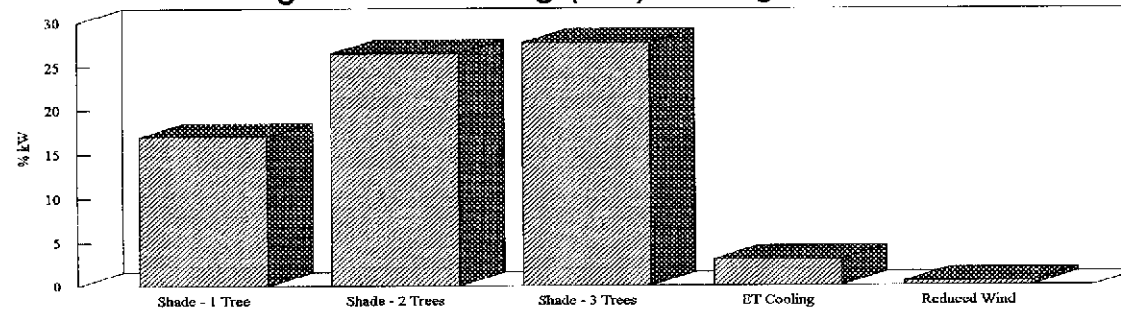1,761 sf, 2 story wood frame home in Chicago

Shade - 1 Tree | Shade - 2 Trees | Shade - 3 Trees | ET Cooling | Reduced Wind

■ Heating ▧ Cooling

# Annual Dollar Savings From Base Case



Shade - 3 Trees | ET Cooling | Reduced Wind

▧ Heating ☐ Cooling ▨ Total

# Percentage Cooling (kWh) Savings From Base Case



Shade - 1 Tree | Shade - 2 Trees | Shade - 3 Trees | ET Cooling | Reduced Wind

# Percentage Peak Cooling (kW) Savings From Base Case



Shade - 1 Tree | Shade - 2 Trees | Shade - 3 Trees | ET Cooling | Reduced Wind

**Chicago, Illinois**　　　　　　　**Energy Analysis**　　　　　Nat. Gas　　(\$/therm):　　0.5
2 Story - Wood Frame　　　　1761 sq ft　　　　　　　　　Electricity　　(\$/kWh):　　0.12
Year 20 - 25 ft trees　　　　　　　　　　Avoided Peak Electricity　(\$/Avoid kW):　　65

| Annual Energy Use | Unshaded Base Case | 1 Tree | Shade 2 Trees | 3 Trees | ET Cooling | Reduced Wind | 3 Tree+ET + Wind | Avg. Savings Tree/Yr. |
|---|---|---|---|---|---|---|---|---|
| **Heat (MBtu)** | 71.54 | 72.00 | 72.19 | 72.60 | 71.59 | 68.65 | | |
| \$ | 357.70 | 360.00 | 360.95 | 363.00 | 357.95 | 343.25 | | |
| MBtu diff | | -0.46 | -0.65 | -1.06 | -0.05 | 2.89 | 1.78 | 0.59 |
| \$ diff | | -2.30 | -3.25 | -5.30 | -0.25 | 14.45 | 8.90 | 2.97 |
| % diff | | -0.60 | -0.90 | -1.50 | -0.10 | 4.00 | 2.40 | 0.80 |
| | | | | | | | | |
| **Cool (kWh)** | 1858 | 1732 | 1663 | 1578 | 1743 | 1845 | | |
| \$ | 222.98 | 207.80 | 199.58 | 189.32 | 209.10 | 221.34 | | |
| kWh diff | | 126 | 195 | 280 | 116 | 14 | 410 | 136.67 |
| \$ diff | | 15.18 | 23.40 | 33.66 | 13.88 | 1.64 | 49.18 | 16.39 |
| % diff | | 6.81 | 10.50 | 15.09 | 6.22 | 0.73 | 22.05 | 7.35 |
| | | | | | | | | |
| **Total (MBtu)** | 93.42 | 92.61 | 92.10 | 91.65 | 92.29 | 90.28 | | |
| \$ | 580.68 | 567.80 | 560.53 | 552.32 | 567.05 | 564.59 | | |
| MBtu diff | | 0.81 | 1.32 | 1.77 | 1.13 | 3.14 | 6.04 | 2.01 |
| \$ diff | | 12.88 | 20.15 | 28.36 | 13.63 | 16.09 | 58.08 | 19.36 |
| % diff | | 0.87 | 1.41 | 1.90 | 1.21 | 3.36 | 6.47 | 2.16 |
| | | | | | | | | |
| **Peak Cool (kW** | 5.10 | 4.23 | 3.75 | 3.69 | 4.94 | 5.07 | | |
| Avoided \$ | 331.00 | 275.00 | 244.00 | 240.00 | 321.00 | 330.00 | | |
| Kw diff | | 0.87 | 1.35 | 1.41 | 0.16 | 0.03 | 1.60 | 0.53 |
| Avoided \$ diff | | 56.00 | 87.00 | 91.00 | 10.00 | 1.00 | 102.00 | 34.00 |
| % diff | | 16.98 | 26.45 | 27.66 | 3.04 | 0.52 | 31.23 | 10.41 |

## Annual Dollar Savings From Base Case - 3 Trees (25 ft. tall)
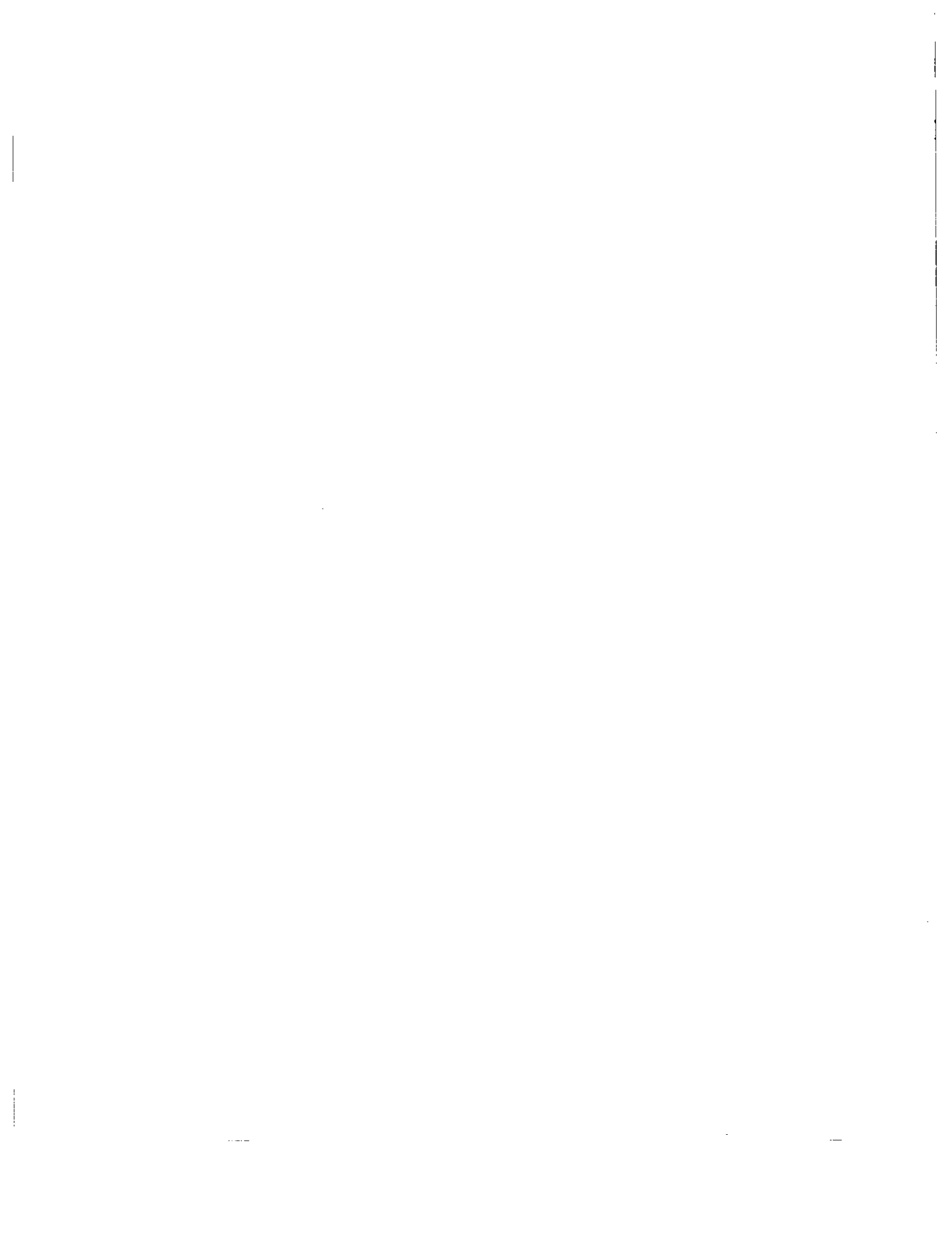Due to Shade, ET Cooling, and Reduced Wind Speed



1,761 sf. 2 story wood frame home

Legend: Shade - 3 Trees　ET Cooling　Reduced Wind

## Average Annual Dollar Savings From Base Case - 1 Tree (25 ft. tall)
Due to Shade, ET Cooling, and Reduced Wind Speed



1,761sf, 2 story wood frame home

Legend: Heating　Cooling
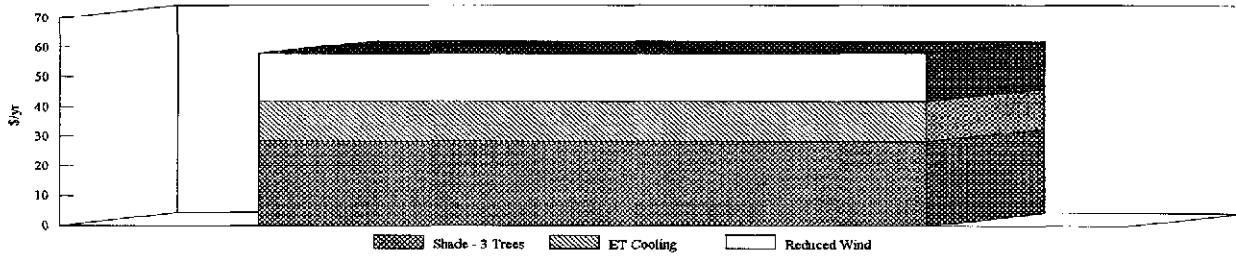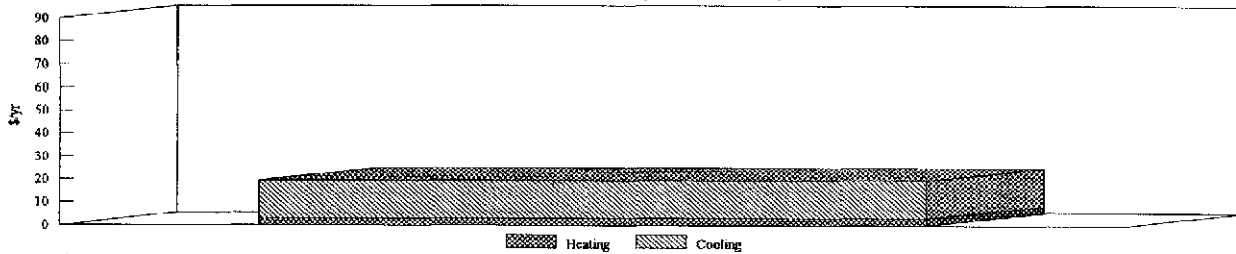
# Appendix E

## Initial Analysis of the Cost-Effectiveness of Shade Trees in Chicago

**ECONOMIC ANALYSIS OF SHADE TREE PROGRAM IN CHICAGO, ILLINOIS**

| 2 Story Wood Frame Building (West-facing) | | Avoided kWh: | $0.015 | | Adjustments: | |
|---|---|---|---|---|---|---|
| 1 household, 3 occupants | | Avoided kW: | $89.00 | | Tree Mortality per Year | |
| 1,761 sq ft floor area | | Cost / tree: | $50.00 | | Years 1-2 : | 5% |
| Cooling: 1,858 kWh/yr ($223), Peak: 5.1 kW | | Trees Planted: | 10,000 | | Years 3-20: | 1% |
| Heating: 71.5 MBtu/yr ($358) | | Discount Rate: | 11% | | AC Present: | 50% |
| | | Inflation Rate: | 4.5% | | | |

| Adjusted Savings Per Planted Tree | | | Adjusted Nominal Savings (All Trees) | | |
|---|---|---|---|---|---|
| kWh/tree | kw/tree | Yr | kWh Saving Total $ | kW Savings Total $ | kWh+kW Total $ |
| 0 | 0.00 | 1 | $78 | $2,529 | $2,607 |
| 2 | 0.01 | 2 | $294 | $9,551 | $9,846 |
| 4 | 0.02 | 3 | $649 | $21,058 | $21,707 |
| 7 | 0.04 | 4 | $1,125 | $36,529 | $37,655 |
| 11 | 0.06 | 5 | $1,709 | $55,461 | $57,170 |
| 15 | 0.08 | 6 | $2,381 | $77,275 | $79,656 |
| 20 | 0.11 | 7 | $3,122 | $101,333 | $104,455 |
| 25 | 0.14 | 8 | $3,911 | $126,957 | $130,868 |
| 30 | 0.16 | 9 | $4,727 | $153,441 | $158,168 |
| 35 | 0.19 | 10 | $5,548 | $180,077 | $185,625 |
| 41 | 0.22 | 11 | $6,352 | $206,165 | $212,516 |
| 45 | 0.25 | 12 | $7,118 | $231,033 | $238,151 |
| 50 | 0.27 | 13 | $7,827 | $254,053 | $261,880 |
| 54 | 0.30 | 14 | $8,462 | $274,657 | $283,119 |
| 57 | 0.31 | 15 | $9,007 | $292,344 | $301,351 |
| 60 | 0.33 | 16 | $9,449 | $306,699 | $316,147 |
| 62 | 0.34 | 17 | $9,778 | $317,393 | $327,171 |
| 64 | 0.35 | 18 | $9,988 | $324,197 | $334,185 |
| 64 | 0.35 | 19 | $10,074 | $326,981 | $337,055 |
| 64 | 0.35 | 20 | $10,035 | $325,717 | $335,751 |
| 712 | 3.90 | | $111,632 | $3,623,452 | $3,735,084 |

**SUMMARY OF ECONOMIC ANALYSIS**

| | PV of Benefits | PV of Costs |
|---|---|---|
| Fixed: | na | $500,000 |
| Variable: | na | na |
| Capacity: | $919,267 | na |
| Energy: | $28,321 | na |
| TOTAL: | $947,588 | $500,000 |

Net Present Value:      $447,588
(Benefits -Costs)

Benefit to Cost Ratio:      1.90
(Benefits / Costs)

Estimated Savings (All Trees):
Average Peak Capacity:    1,948   kW-yr
Average Energy:    356,084   kWh / yr

Estimated Savings (Per Tree Planted):
Average Peak Capacity:    0.19   kW-yr
Average Energy:    35.61   kWh / yr

Assumptions:
1) 20 year analysis from 1993 - 2012
2) 10,000 trees planted in 1993, 1 per residence, at $50/tree, which includes costs of the tree, stakes and other planting materials, program administration, overhead, and 3 year follow-up for tree care and public education (assumes residents plant trees). Costs of Shade Tree Program to SMUD have dropped from $49/ tree in 1990-91 to $35/tree in 1993-94 (Rich Sequest).
3) Assume typical tree planted to shade the west wall is 3-ft wide and tall when planted and reaches 25-ft wide and tall by year 20.
4) Assume annual savings of 170 kWh and 0.93 kW for the 20-year old tree based on previously cited energy simulations.
5) Assume annual energy savings pattern is linked to tree growth, for years 1-20 follows an "S" shaped growth curve.
6) Assume the ratio of savings due to direct shade and indirect effects remains constant over time (as modeled for year 20).
7) Assume adjustment to both energy and capacity savings based on tree mortality at 5% per year during the first 2 years of establishment and 1% per year for the remaining 18 years (25% mortality over 20 years).
8) Assume adjustment to both energy and capacity savings for air conditioning saturation of 50% (half of the homes where tree is planted do not have space cooling device).
9) Assume nominal discount rate of 11%, avoided energy and capacity costs of $.015/kWh and $89/kW-yr, and a 4.5% inflation rate (from Gary Rehof, Least-Cost Planning Dept., Commonwealth Edison).

## ECONOMIC ANALYSIS OF SHADE TREE PROGRAM IN CHICAGO, ILLINOIS

| | | | |
|---|---|---|---|
| 2 Story Brick Building (South-facing) | Avoided kWh: | $0.015 | Adjustments: |
| 2 households, 6 occupants | Avoided kW: | $89.00 | Tree Mortality per Year |
| 3,562 sq ft floor area | Cost / tree: | $50.00 | Years 1-2 : 5% |
| Cooling: 3,682 kWh/yr ($442), Peak: 10.6 kW | Trees Planted: | 10,000 | Years 3-20: 1% |
| Heating: 385 MBtu/yr ($1,925) | Discount Rate: | 11% | AC Present: 50% |
| | Inflation Rate: | 4.5% | |

| Adjusted Savings Per Planted Tree | | | Adjusted Nominal Savings (All Trees) | | |
|---|---|---|---|---|---|
| kWh/tree | kw/tree | Yr | kWh Saving Total $ | kW Savings Total $ | kWh+kW Total $ |
| 1 | 0.00 | 1 | $122 | $1,740 | $1,862 |
| 3 | 0.01 | 2 | $460 | $6,573 | $7,034 |
| 6 | 0.02 | 3 | $1,015 | $14,491 | $15,506 |
| 11 | 0.03 | 4 | $1,761 | $25,138 | $26,899 |
| 17 | 0.04 | 5 | $2,674 | $38,167 | $40,841 |
| 24 | 0.06 | 6 | $3,725 | $53,179 | $56,904 |
| 31 | 0.07 | 7 | $4,885 | $69,735 | $74,620 |
| 39 | 0.09 | 8 | $6,120 | $87,368 | $93,488 |
| 47 | 0.11 | 9 | $7,397 | $105,594 | $112,991 |
| 55 | 0.13 | 10 | $8,681 | $123,924 | $132,605 |
| 63 | 0.15 | 11 | $9,938 | $141,877 | $151,815 |
| 71 | 0.17 | 12 | $11,137 | $158,990 | $170,127 |
| 78 | 0.19 | 13 | $12,247 | $174,833 | $187,079 |
| 84 | 0.20 | 14 | $13,240 | $189,011 | $202,251 |
| 90 | 0.22 | 15 | $14,093 | $201,183 | $215,276 |
| 94 | 0.23 | 16 | $14,785 | $211,061 | $225,846 |
| 98 | 0.23 | 17 | $15,300 | $218,421 | $233,721 |
| 100 | 0.24 | 18 | $15,628 | $223,104 | $238,732 |
| 101 | 0.24 | 19 | $15,762 | $225,019 | $240,782 |
| 100 | 0.24 | 20 | $15,701 | $224,149 | $239,851 |
| 1,114 | 2.68 | | $174,672 | $2,493,558 | $2,668,230 |

### SUMMARY OF ECONOMIC ANALYSIS

| | PV of Benefits | PV of Costs |
|---|---|---|
| Fixed: | na | $500,000 |
| Variable: | na | na |
| Capacity: | $632,614 | na |
| Energy: | $44,314 | na |
| TOTAL: | $676,928 | $500,000 |

Net Present Value: $176,928
(Benefits -Costs)

Benefit to Cost Ratio: 1.35
(Benefits / Costs)

Estimated Savings (All Trees):
Average Peak Capacity: 1,341 kW-yr
Average Energy: 557,166 kWh / yr

Estimated Savings (Per Tree Planted):
Average Peak Capacity: 0.13 kW-yr
Average Energy: 55.72 kWh / yr

Assumptions:
1) 20 year analysis from 1993 - 2012
2) 10,000 trees planted in 1993, 1 per residence, at $50/tree, which includes costs of the tree, stakes and other planting materials, program administration, overhead, and 3 year follow-up for tree care and public education (assumes residents plant trees). Costs of Shade Tree Program to SMUD have dropped from $49/ tree in 1990-91 to $35/tree in 1993-94 (Rich Sequest).
3) Assume typical tree planted to shade the west wall is 3-ft wide and tall when planted and reaches 24-ft wide and 36-ft tall by year 20.
4) Assume annual savings of 266 kWh and 0.64 kW for the 20-year old tree based on previously cited energy simulations.
5) Assume annual energy savings pattern is linked to tree growth, for years 1-20 follows an "S" shaped growth curve.
6) Assume the ratio of savings due to direct shade and indirect effects remains constant over time (as modeled for year 20).
7) Assume adjustment to both energy and capacity savings based on tree mortality at 5% per year during the first 2 years of establishment and 1% per year for the remaining 18 years (25% mortality over 20 years).
8) Assume adjustment to both energy and capacity savings for air conditioning saturation of 50% (half of the homes where tree is planted do not have space cooling device).
9) Assume nominal discount rate of 11%, avoided energy and capacity costs of $.015/kWh and $89/kW-yr, and a 4.5% inflation rate (from Gary Rehof, Least-Cost Planning Dept., Commonwealth Edison).

**Headquarters of the Northeastern Forest Experiment Station is in Radnor, Pennsylvania. Field laboratories are maintained at:**

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Orono, Maine, in cooperation with the University of Maine

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Princetown, West Virginia

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University Park, Pennsylvania, in cooperation with The Pennsylvania State University

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