City of Minneapolis, Minnesota Municipal Tree Resource Analysis

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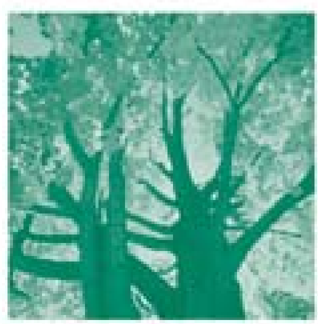
Technical Report to:
Ralph Sievert and Jim Hermann
Forestry Section, Minneapolis Parks and Recreation Board
Minneapolis, Minnesota

—June 2005—





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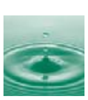
Areas of Research:

 Investment Value

 Energy Conservation

 Air Quality

 Water Quality

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The modeling and analysis tools used in this study have been subjected to peer-review through the publication process. However, this technical report relies on data obtained from other organizations and it has not been subjected to the full peer-review process.

Table of Contents

Executive Summary

Minneapolis, a vibrant city, renowned for its lakes, its livability, and its cultural wealth, maintains trees as an integral component of the urban infrastructure. Research indicates that healthy trees can mitigate impacts associated with the built environment by reducing stormwater runoff, energy consumption, and air pollutants. Trees improve urban life, making Minneapolis a more enjoyable place to live, work, and play, while mitigating the city's environmental impact. Over the years, the Minneapolis Parks and Recreation Board has invested millions in its municipal forest. The primary question that this study asks is *whether the accrued benefits from Minneapolis's municipal forest justify the annual expenditures?*

This analysis combines results of a citywide inventory with benefit–cost modeling data to produce four types of information:

1. Tree resource structure (species composition, diversity, age distribution, condition, etc.)

2. Tree resource function (magnitude of environmental and aesthetic benefits)

3. Tree resource value (dollar value of benefits realized)

4. Tree resource management needs (sustainability, maintenance, costs)

Resource Structure

- Based on the sample tree inventory, there are 198,633 actively managed street trees in Minneapolis. Trees are evenly distributed among the three management zones.

- Minneapolis streets are nearly fully stocked with trees (87% of possible planting spaces contain trees). There is approximately one tree for every two residents, and these street trees shade approximately 11% of the city.

- The sample contained 60 tree species with American elm as the dominant tree. Elms account for 10% of all street trees and 28% of all benefits. This means that sustaining the high level of benefits currently produced by the municipal forest depends largely on preserving these elms. Green ash (16% of total benefits), littleleaf linden (9%), Norway maple (9%), and sugar maple (8%) are subdominant species of importance due to their size and numbers.

- The age structure of Minneapolis's street trees differs from the ideal in having more maturing trees (6–18 inch DBH) and fewer mature and old trees. As these maturing trees age, the benefits they produce will increase. Thus, over the next 50 years, their health and longevity will influence the stability and productivity of Minneapolis's future canopy.

- Trees are generally in good health (75% good or excellent condition), with approximately 2% in need of removal and 42% needing pruning. Conflicts with power lines are few, but 36% of the sampled trees are associated with sidewalk heaves greater than ¼ inch.

Resource Function and Value

- Electricity saved annually in Minneapolis from both shading and climate effects of street trees totals 32,921 MWh, for a retail savings of \$2.5 million (\$12.58 per tree). Total annual savings of natural gas total 441,355 MBtu, for a savings of \$4.3 million, or \$21.78 per tree. Total annual energy savings are valued at \$6.8 million or \$34.36 per tree.

- Citywide, CO_2 emission reductions due to energy savings and sequestration by street trees are 27,611 and 29,526 tons, respectively, valued at \$857,000 (\$4.31 per tree). Release of CO_2 from decomposition and tree-care activities is small (2,012 tons; \$30,175). Net CO_2 reduction is 55,125 tons, valued at \$826,875 or \$4.16 per tree.

- Net air pollutants removed, released, and avoided average 2 lb per tree and are valued at \$1.1 million annually or \$5.71 per tree. Avoided emissions of NO_2 and SO_2 due to energy savings are especially important, totaling about 150 tons and valued at \$830,000. Deposition and interception of pollutants by trees totaled 29 tons (\$185,585), a small benefit explained by the region's relatively clean air.

- The ability of Minneapolis's municipal trees to intercept rain—thereby reducing stormwater runoff—is substantial, estimated at 447.5 million cubic feet annually, or \$9.1 million. Citywide, the average street tree intercepts 1,685 gallons of stormwater, valued at \$45.67, annually.

- The estimated annual benefits associated with aesthetics, property value increases, and other less tangible benefits are approximately \$7.1 million or \$36 per tree.

- Annual benefits total $24.9 million and average $126 per tree. Benefits are fairly evenly distributed among the city's three management zones. Stormwater-runoff reduction, energy savings, and aesthetic/other benefits each account for nearly one-third of total benefits. The tree species providing the greatest percentage of benefits are American elms ($354 per tree, 28%), green ash ($137 per tree, 16%), and littleleaf linden ($112 per tree, 9%) because of their size and numbers.

- Overall, annual benefits are determined largely by tree size. For example, typical small, medium, and large deciduous street trees produce annual benefits totaling $25, $96, and $148, respectively, per tree.

- The MPRB and the City of Minneapolis spent approximately $9.2 million in 2004 maintaining nearly 200,000 street trees, or $46 per tree. Expenditures for tree removal and pruning account for about two-thirds of total costs.

- Minneapolis's municipal tree resource is a valuable asset, providing approximately $15.7 million or $79 per tree in total net annual benefits to the community. Over the years, Minneapolis has invested millions in its municipal forest. Citizens are now receiving a substantial return on that investment—$1.59 in benefits for every $1 spent on tree care. As the urban forest resource matures, continued investment in management is critical to insuring that residents receive a greater return on investment in the future.

Resource Management Needs

Minneapolis's municipal trees are a dynamic resource. Managers of this resource and the community alike can delight in knowing that municipal trees do improve the quality of life in Minneapolis, but the resource is fragile and needs constant care to maximize and sustain the benefits through the foreseeable future. Achieving resource sustainability requires that Minneapolis:

- Continue to invest in efforts to control the loss of its dominant species, American elm, to Dutch elm disease and other stresses.

- Provide maturing trees, poised to create the future canopy, with a 5-year inspection/pruning cycle to insure their health and longevity.

- Focus on young-tree care to reduce future long-term tree-care costs and insure that maturing trees will be productive assets for the community in the years ahead.

- Increase the mix of species being planted to provide adequate diversity and continue planting large-stature trees where space permits.

As Minneapolis continues to mature, it should also continue to grow its tree canopy. This is no easy task, given financial constraints and trends toward higher density development that put space for trees at a premium. The challenge ahead is to better integrate the green infrastructure with the gray infrastructure by providing adequate space for trees and designing plantings to maximize net benefits over the long term, thereby perpetuating a resource that is both functional and sustainable.

Chapter One—Introduction

The Forestry Section of the Minneapolis Parks and Recreation Board (MPRB) actively manages approximately 200,000 trees along streets, as well as a substantial number of park trees. The City believes that the public's investment in stewardship of the urban forest produces benefits that outweigh the costs to the community. Minneapolis is a vibrant city renowned for its lakes, its livability, and its cultural wealth. It maintains trees as an integral component of the city infrastructure. Research indicates that healthy city trees can mitigate impacts associated with urban environs: polluted stormwater runoff, poor air quality, high energy needs for heating and cooling buildings, and heat islands. Healthy street trees increase real estate values, provide neighborhood residents with a sense of place, and foster psychological health. Street and park trees are associated with other intangibles, too, such as increasing community attractiveness for tourism and business and providing wildlife habitat and corridors. The urban forest makes Minneapolis a more enjoyable place to live, work and play, while mitigating the city's environmental impact.

In an era of dwindling public funds and rising costs, however, there is a need to scrutinize public expenditures that are deemed "non-essential," such as planting and maintaining street and park trees. Although the current program has demonstrated its economic efficiency, questions remain regarding the need for the level of service presently provided. Hence, the primary question that this study asks is *whether the accrued benefits from Minneapolis's street trees justify the annual expenditures?*

In answering this question, information is provided to do the following:

1. Assist decision-makers to assess and justify the degree of funding and type of management program appropriate for Minneapolis's urban forest.
2. Provide critical baseline information for evaluating program cost-efficiency and alternative management structures.
3. Highlight the relevance and relationship of Minneapolis's municipal tree resource to local quality of life issues such as environmental health, economic development, and psychological health.
4. Provide quantifiable data to assist in developing alternative funding sources through utility purveyors, air quality districts, federal or state agencies, legislative initiatives, or local assessment fees.

This report consists of seven chapters and two appendices:

Chapter One—Introduction: Describes purpose of the study.

Chapter Two—Minneapolis's Municipal Tree Resource: Describes the current structure of the street tree resource.

Chapter Three—Costs of Managing Minneapolis's Municipal Trees: Details management expenditures for publicly managed trees.

Chapter Four—Benefits of Minneapolis's Municipal Trees: Quantifies estimated value of tangible benefits and calculates net benefits and a benefit–cost ratio for each population segment.

Chapter Five—Management Implications: Evaluates relevancy of this analysis to current programs and describes management challenges for street-tree maintenance.

Chapter Six—Conclusion: Final word on the use of this analysis.

Appendix A—Tree Distribution: Lists species and numbers of trees in street populations.

Appendix B—Methodology and Procedures: Describes benefits, procedures and methodology for calculating structure, function, and value of the urban tree resource.

References: Lists publications cited in the study.

Chapter Two—Minneapolis's Municipal Tree Resource

Tree Numbers

Based on a sample of Minneapolis's street trees conducted by trained volunteers under direction of the Tree Trust, there are approximately 198,633 (standard error [SE] 14,088) street trees actively managed in Minneapolis (*Table 1*). Considering possible errors due to sampling methodology, the actual population is likely to be between 184,545 and 212,721. Tree numbers are fairly evenly distributed among the three management zones, River District (Zone 1), Lakes District (Zone 2), and Minnehaha District (Zone 3) (*Figure 1*).

***Table 1**—Street tree numbers by management zone.*

Zone	# of street trees	SE	% of total
1	60,249	±3,329	30.3
2	64,499	±5,335	32.5
3	73,884	±12,471	37.2
Total	198,633	±14,088	100.0

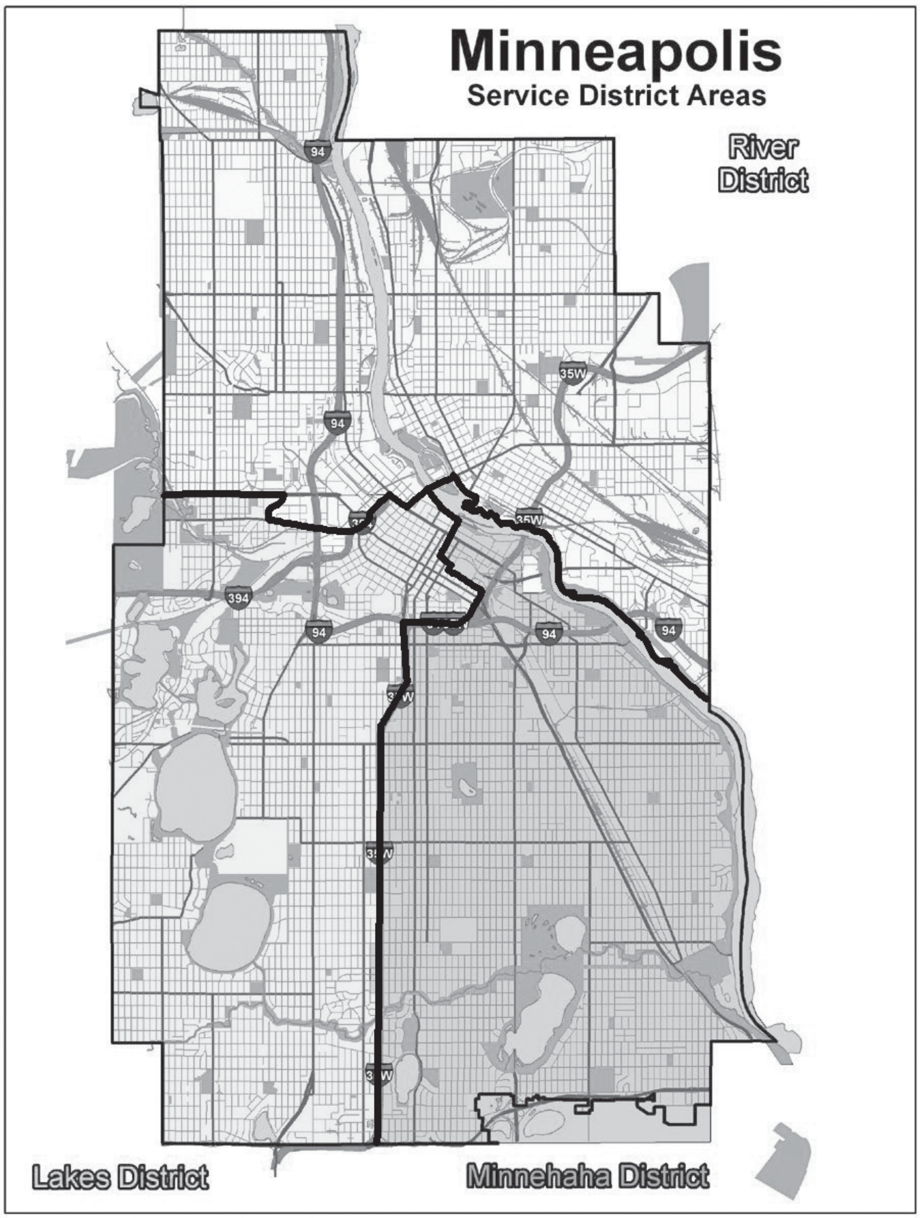


Figure 1—Location of the three management zones in Minneapolis. River District is Zone 1, Lakes District is Zone 2, and Minnehaha District is Zone 3.

Minneapolis's street tree population is primarily composed of large and medium trees (>40 ft tall and 25–40 ft tall at maturity) (61 and 36% of the total, respectively) (*Table 2*). At 99% of the total, deciduous trees clearly dominate the population.

***Table 2**—Citywide street tree percentages by mature size class and tree type.*

Tree type	Large	Medium	Small	Total
Broadleaf deciduous	60.8	35.5	3.4	99.7
Conifer	0.2	0.1	0.1	0.3
Total	60.9	35.6	3.5	100.0

Species Richness, Composition And Diversity

In the sample tree inventory of 4,574 individuals, there were 60 different tree species—a rich assemblage when compared to other cities. McPherson and Rowntree (1989), in their nationwide survey of street-tree populations in 22 U.S. cities, reported a mean of 53 species. Typically, temperate climates such as that in Minneapolis impose more growing restrictions which reduce species richness compared to milder climates.

The predominant street tree species are green ash (*Fraxinus pennsylvanica*, 14.4%), sugar maple (*Acer saccha-*

***Table 3**—Most abundant street tree species in order of predominance by DBH class and tree type*

Species	0-3	3-6	6-12	12-18	18-24	24-30	30-36	36-42	>42	Total	SE	% Total
Broadleaf Deciduous Large (BDL)												
Green ash	1,417	2,656	7,437	10,049	4,825	1,904	398	0	0	28,686	±3,622	14.4%
Sugar maple	3,364	4,870	9,606	7,260	664	89	177	0	0	26,030	±4,485	13.1%
American elm	266	221	177	1,549	3,763	6,507	4,604	1,948	575	19,611	±2,001	9.9%
American basswood	1,328	2,656	3,719	4,206	1,549	266	89	0	0	13,812	±2,644	7.0%
Northern hackberry	885	1,195	3,143	3,143	398	89	0	0	89	8,942	±2,245	4.5%
Silver maple	797	443	1,594	1,240	266	89	177	89	133	4,825	±1,001	2.4%
Elm	885	443	266	487	487	664	797	398	221	4,648	±907	2.3%
White ash	177	177	1,682	1,151	177	0	0	0	0	3,364	±953	1.7%
Basswood	221	354	1,018	575	708	221	44	0	0	3,143	±1,173	1.6%
Red maple	177	354	1,062	841	0	0	0	0	0	2,435	±852	1.2%
BDL other	531	1,417	1,771	708	310	133	133	133	44	5,179	±886	2.6%
Total	10,049	14,786	31,475	31,209	13,148	9,960	6,419	2,568	1,062	120,676	±10,386	60.8%
Broadleaf Deciduous Medium (BDM)												
Norway maple	708	2,700	10,270	8,500	1,195	44	0	44	0	23,462	±2,968	11.8%
Littleleaf linden	708	1,771	6,994	9,208	1,859	177	0	0	0	20,718	±3,790	10.4%
Honeylocust	1,904	2,081	5,047	4,560	708	89	0	0	0	14,387	±2,311	7.2%
Ginkgo	1,062	1,372	1,859	620	44	0	44	0	0	5,002	±1,572	2.5%
BDM other	2,169	1,328	2,169	753	398	133	89	0	0	7,039	±1,354	3.5%
Total	6,552	9,252	26,340	23,639	4,206	443	133	44	0	70,608	±5,244	35.5%
Broadleaf Deciduous Small (BDS)												
BDS other	2,833	1,151	1,505	841	310	89	0	0	0	6,729	±1,129	3.4%
Total	2,833	1,151	1,505	841	310	89	0	0	0	6,729	±1,129	3.4%
Conifer Evergreen Large (CEL)												
CEL other	177	0	44	89	0	0	0	0	0	310	±143	0.2%
Conifer Evergreen Medium (CEM)												
CEM other	44	89	0	44	0	0	0	0	0	177	±175	0.1%
Conifer Evergreen Small (CES)												
CES other	44	0	0	89	0	0	0	0	0	133	±75	0.1%
Citywide Total	19,699	25,277	59,364	55,911	17,663	10,492	6,552	2,612	1,062	198,633	±14,088	100.0%

rum, 13.1%), Norway maple (*Acer platanoides*, 11.8%), littleleaf linden (*Tilia cordata*, 10.4%) and American elm (*Ulmus americana*, 9.9%) (*Table 3*). Together, these species account for 60% of the population. Also, several exceed the general rule that no single species should represent more than 10% of the population (Clark et al. 1997).

This pattern of strong dominance by several species is also evident within management areas (*Table 4*). Sugar maple and green ash are particularly important codominants in Zone 3. Both these species are vulnerable to known pests. Asian longhorned beetle (*Anoplophora glabripennis*) feeds on maples and other species, and the emerald ash borer (*Agrilus planipennis*) has decimated ash trees in nearby states. A catastrophic loss of one or more of these dominant species would leave large structural and functional gaps in Minneapolis's neighborhoods.

Species Importance

Importance values (IV) are particularly meaningful to managers because they indicate a community's reliance on the functional capacity of particular species. This indicator takes into account not only total numbers, but the canopy cover and leaf area, providing a useful comparison to the total population distribution.

Importance value (IV), a mean of three relative values, can, in theory, range between 0 and 100, where an IV of 100 implies total reliance on one species and an IV of 0 suggests no reliance. The 14 most abundant street-tree species listed in *Table 5* constitute 90% of the total street-tree population, 96% of the total leaf area, 95% of total canopy cover, and 94% of total IV.

As *Table 5* illustrates, some species are more important than their population numbers suggest. For example, American elms account for 10% of all street trees. Because of their relatively large size, the amount of leaf area and canopy cover they provide is comparatively great, increasing their importance to 27% when all IV components are considered. Conversely, species such as ginkgo (*Ginkgo biloba*) are less important to the community than their numbers alone suggest.

Minneapolis's street-tree population has a strong pat-

Table 4*—Most abundant street tree species listed by zone with percentage of totals in parentheses.*

Zone	1st (%)	2nd (%)	3rd (%)	4th (%)	5th (%)
1	Norway maple (13.6)	Green ash (13.6)	Littleleaf linden (10.9)	Sugar maple (10.7)	American basswood (8.5)
2	Green ash (16.1)	American elm (13)	Norway maple (11.1)	Littleleaf linden (9.3)	Sugar maple (8.9)
3	Sugar maple (18.8)	Green ash (13.7)	Norway maple (11)	Littleleaf linden (11)	American elm (8.7)
Total	Green ash (14.4)	Sugar maple (13.1)	Norway maple (11.8)	Littleleaf linden (10.4)	American elm (9.9)

Table 5*—Importance values (IV) calculated as the mean of tree numbers, leaf area, and canopy cover for the most abundant street tree species.*

Species	No. of trees	% of total trees	Leaf area (ft^2)	% of total leaf area	Canopy cover (ft^2)	% of total canopy	IV
Green ash	28,686	14.4	63,681,848	14.4	21,439,890	14.9	14.6
Sugar maple	26,030	13.1	26,295,060	6.0	12,180,100	8.4	9.2
Norway maple	23,462	11.8	26,939,320	6.1	13,075,170	9.1	9.0
Littleleaf linden	20,718	10.4	28,550,970	6.5	10,162,700	7.0	8.0
American elm	19,611	9.9	180,586,496	40.9	42,232,248	29.3	26.7
Honeylocust	14,387	7.2	18,027,020	4.1	9,720,876	6.7	6.0
American basswood	13,812	7.0	16,571,160	3.8	6,673,799	4.6	5.1
Northern hackberry	8,942	4.5	11,279,440	2.6	5,885,082	4.1	3.7
Ginkgo	5,002	2.5	1,225,744	0.3	1,053,835	0.7	1.2
Silver maple	4,825	2.4	11,131,020	2.5	3,391,409	2.4	2.4
Elm	4,648	2.3	25,410,990	5.8	5,758,923	4.0	4.0
White ash	3,364	1.7	5,009,319	1.1	1,980,806	1.4	1.4
Basswood	3,143	1.6	6,871,325	1.6	2,260,263	1.6	1.6
Red maple	2,435	1.2	2,685,954	0.6	1,350,106	0.9	0.9
Total for top 1% of all trees	179,066	90.2	424,265,696	96.1	137,165,200	95.1	93.8

tern of dominance, where the dominant species IV is greater than 25, and no subdominants have IVs greater than 15 (McPherson and Rowntree 1989). Street-tree populations with one dominant species may involve lower maintenance costs due to the efficiency of repetitive work, but the risk of incurring large costs exists if decline, disease, or senescence of the dominant species requires large numbers of removals. Clearly, American elms are vulnerable because of their susceptibility to Dutch elm disease (*Ceratocystis ulmi*), as well as their age. At the same time, they have great functional importance in Minneapolis. Although American elms account for only 10% of total street-tree numbers, they comprised 41% of total leaf area and 29% of total canopy cover. The IV value of 26.7 suggests that Minneapolis relies on this species for approximately one-quarter of total benefits.

Street Trees Per Capita

Calculations of street trees per capita are important in determining how well-forested a city is. Assuming a human population of 382,618 (Sievert and Hermann 2004), Minneapolis's ratio of street trees per capita is 0.52—approximately one tree for every two people—well above the mean ratio of 0.37 reported for 22 U.S. cities (McPherson and Rowntree 1989).

Stocking Level

Although this study did not sample empty street-tree planting sites in Minneapolis to estimate stocking level, stocking can be estimated based on total street miles. Assuming there are 1,078 linear miles of streets in Minneapolis (Sievert and Hermann 2004), Minneapolis had an average of 184 trees per street mile. A fully stocked city would have one tree on each side of the street every 50 feet. This translates to 87% of full stocking in Minneapolis. By way of comparison, the mean stocking level for 22 U.S. cities was only 38.4% (McPherson and Rowntree 1989). Hence, there appeared to be relatively few empty planting sites along Minneapolis's streets.

Age Structure

The distribution of ages within a tree population influences present and future costs as well as the flow of benefits. An uneven-aged population allows managers to allocate annual maintenance costs uniformly over many years and assure continuity in overall tree-canopy cover. An ideal distribution has a high proportion of new transplants to offset establishment-related mortality, while the percentage of older trees declines with age (Richards 1982/83).

The age structure (*Figure 2*) for street trees in Minneapolis differs from the ideal in that there are more maturing trees in the 6–18 inch DBH classes, and fewer mature and old trees. We interpret this pattern to mean that a high percentage of trees were planted 20–50 years ago, perhaps to replace trees killed by Dutch elm disease. The relatively small number of trees in the mature (18–24 inch DBH) and old tree categories (>24 inch) suggests that relatively few trees survived this era of transition. The lack of functionally mature trees is serious because mature trees tend to produce the highest level of benefits by virtue of their size. Over time, if maturing trees move into the larger size classes without significant losses, the population will more closely align with the ideal.

Age curves for different tree species help explain their relative importance and suggest how tree management needs may change as these species grow older (*Figure 2*). The population of American elms is largely

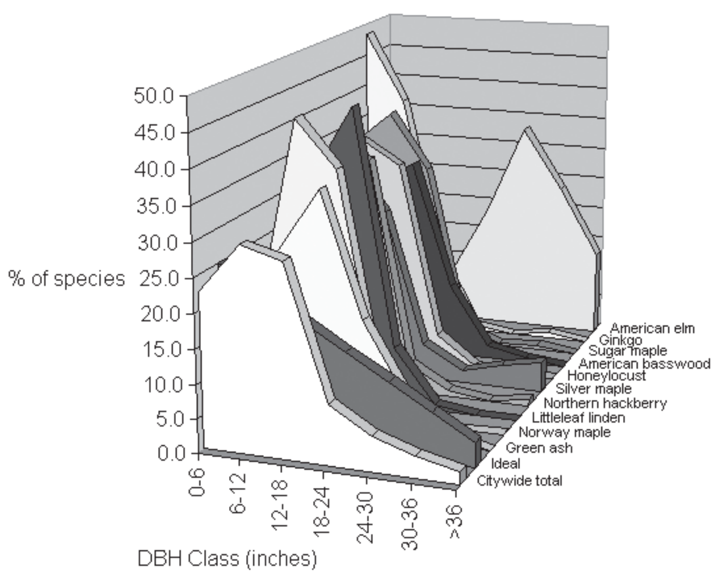


Figure 2—Relative age distribution for 10 most abundant street trees shown with an ideal distribution.

mature. These trees have provided benefits over a long period of time, and because of their leaf area, remain particularly important. The population of silver maples (*Acer saccharinum*) includes a high percentage of young trees, but some old trees as well. Large numbers of ginkgo, sugar maple, and littleleaf linden in the smallest size classes indicate that many were planted in the last 10 years. Because most of these newer plantings are large trees at maturity, they are likely to provide a relatively high level of benefits in the future.

Street-tree populations in each of the three management zones exhibit a similar trend of numerous maturing trees and relatively few mature and old trees (*Figure 3*). Zone 2 has slightly higher percentages of mature and young trees than Zones 1 and 3. Tree functionality should increase as these populations mature.

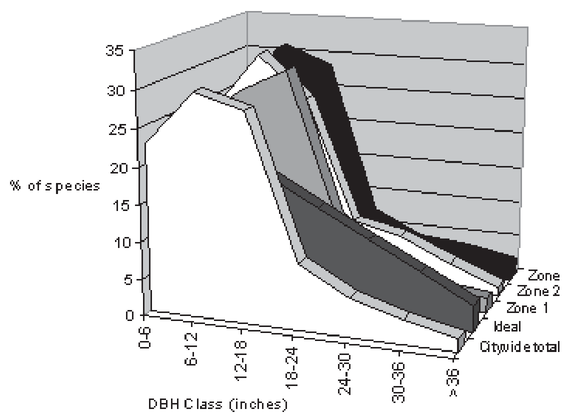


Figure 3—Relative age distribution of all street trees by management zone.

Tree Condition

Tree condition indicates both how well trees are managed and how well they perform given site-specific conditions. Overall, little difference was found among management zones (*Table 6*). Trees in Zone 3 are in slightly better condition than trees in the other two zones.

Table 6*—Tree condition as a percentage by management zone.*

Zone	Dead/dying	Poor	Fair	Good
1	1.3	7.3	20.7	70.7
2	1.7	6.2	17.1	75.0
3	0.7	5.8	15.3	78.1
Total	1.2	6.4	17.5	74.9

Citywide, approximately 75% of trees are in “good” or “very good” condition, 18% are classified as “fair,” 6% are in “poor” condition, and 1% are dead or dying (*Table 6*). These percentages compare favorably with values found in other cities.

The relative performance index (RPI) of each species provides an indication of its suitability to local growing conditions, as well as its performance. Species with larger percentages of trees in good or better condition are likely to provide greater benefits at lower cost than species with more trees in fair or poor condition. Abundant species rated as having the best performance are river birch (*Betula nigra*), northern red oak (*Quercus rubra*), black ash (*Fraxinus nigra*), bur oak (*Quercus macrocarpa*), Amur maple (*Acer ginnala*), and ginkgo. These species are adapted to growing conditions throughout the city. Predominant species with the poorest performance include elms (*Ulmus* spp.), swamp white oak (*Quercus bicolor*), basswood (*Tilia* spp.), pin oak (*Quercus palustris*), and sugar maple. Although slow to start, once established, swamp white oaks have done well. Amongst these five poorer performers, sugar maple and basswood continue to be planted in high numbers.

Tree Canopy

The street tree canopy is estimated at 3,313 acres and covers 11.1% of the city, given a city area of 30,000 acres (Sievert and Hermann 2004). Approximately 37% of the street tree canopy cover is in Zone 3, with 33% in Zone 2, and 30% in Zone 1.

Location and Landuse

Eighty-eight percent of the street trees in Minneapolis are located in planting strips and 6.3% are in front yards. Of the remaining trees, 1.6% are in cutouts, 1.2% are in medians, and 2.8% are in other areas. Seventy-four percent of the sample trees are adjacent to single-family residences. Others are adjacent to multi-home residential (10%), park/vacant (8%), small commercial (5%), and commercial/industrial (4%) land uses.

Maintenance Needs

Understanding species distribution, age structure, and tree condition may aid in estimating proper pruning cycles, but it is important to understand the actual pruning and maintenance needs of the city trees. Not only will this information provide clues as to whether or not the pruning is adequate, but it will also indicate the level of risk and liability associated with the city’s street tree population.

Our random sample of street trees included an assessment of maintenance needs, and showed that 61% of street trees are in need of maintenance (*Table 7*). To promote continued good health and performance, 42% of the trees need pruning to thin and clean the crown, raise low branches (13%), and reduce crown size (2%). Approximately 2.5% of the population needs to be inspected for possible removal, as well as pest/disease problems. Trees classified as requiring removal have se-

Table 7—Maintenance needs by DBH class

Maintenance Type	0-3	3-6	6-12	12-18	18-24	24-30	30-36	36-42	>42	Total	% of Total
None	9,075	9,606	24,525	21,337	5,356	3,276	2,656	1,151	575	77,558	39.0
Stake/Train	531	221	44	44	0	0	0	0	0	841	0.4
Prune - Clean	6,375	7,127	23,551	26,340	9,828	5,179	2,656	930	398	82,384	41.5
Prune - Raise	1,417	6,596	8,411	6,065	1,372	575	266	44	44	24,790	12.5
Prune - Reduce	133	177	1,195	974	354	221	266	44	0	3,364	1.7
Remove	1,771	797	974	575	310	266	177	133	0	5,002	2.5
Treat Pest/Disease	398	753	664	575	443	974	531	310	44	4,692	2.4
Citywide total	19,699	25,277	59,364	55,911	17,663	10,492	6,552	2,612	1,062	198,633	100.0

vere problems, although these are not necessarily related to safety hazards. They may be newly planted dead or dying trees, or they may contain unmanageable defects and hazards. Trees requiring removal and replacement are eyesores at best, and represent substantial costs or public safety hazards at worst.

Maintenance needs are consistent across management zones. Data in *Table 7* can be used with tree-care cost estimates to calculate the amount of funding required to address current management needs.

Conflicts—Sidewalk Heaves and Power Lines

Conflicts between tree roots and infrastructure are of particular concern to street-tree managers due to the large costs associated with repairs. Sidewalk heave involves an additional burden associated with potential legal costs from trip-and-fall incidents. In Minneapolis, where 90% of street trees are located in planting strips or sidewalk cutouts, the potential for these conflicts is high. In our random sample, an estimated 36% (71,494 trees) of all street trees are associated with heave above the 1/4-inch threshold (*Table 8*). Of these, approximately 47% are 0.25–0.5 inches, 21% are 0.5–0.75 inches, and 32% are >0.75 inches.

Table 8*—Estimated current sidewalk heave by zone, and heave class and percentage of all trees conflicting with sidewalks.*

Zone	0.25–0.5 inches	0.5–0.75 inches	>0.75 inches	Total conflicts	% of trees
1	12,749	4,206	5,578	22,533	37.4
2	10,182	4,781	7,216	22,178	34.4
3	10,669	5,888	10,226	26,782	36.3
Citywide total	33,600	14,874	23,020	71,494	36.0

Chapter Three—Costs of Managing Minneapolis's Municipal Trees

Program Expenditures

Costs of Managing Public Trees

Costs are based on a review of expenditures during fiscal year 2004. Annual expenditures by the Minneapolis Park and Recreation Board (MPRB) and the City of Minneapolis for the municipal forestry program were approximately $9.2 million (Sievert and Hermann 2004). The MPRB contributed 17% of their total 2004 operating budget ($48.6 million) or $24 per person (*Table 9*) to the forestry program. With 198,633 actively managed street and park trees, the Forestry Section spends $46 per tree on average during the fiscal year. The per tree expenditure is greater than the 1997 mean value of $19 per tree reported for 256 California cities (Thompson and Ahern 2000), but less than some California communities such as Santa Monica ($53) (McPherson and Simpson 2002) and Berkeley ($65) (Maco et al. 2005). Forestry Section expenditures fall into three categories: tree planting and establishment, pruning and general tree care, and administration.

Table 9—*Minneapolis's annual municipal forestry-related expenditures.*

Program Expenditures	Total $	% of program	$/tree	$/capita
Pruning	2,505,680	27.2	12.61	6.55
Planting	223,855	2.4	1.13	0.59
Removal & Disposal	4,078,585	44.3	20.53	10.66
Inspection	317,779	3.5	1.60	0.83
Administration & Other	1,097,338	11.9	5.52	2.87
Irrigation	95,100	1.0	0.48	0.25
Litter Clean-Up	37,065	0.4	0.19	0.10
Liability & Legal	25,639	0.3	0.13	0.07
Infrastructure Repairs/Mitigation	828,000	9.0	4.17	2.16
Total Expenditures	9,209,041	100.0	46.36	24.07

Tree Planting and Establishment

Quality nursery stock, careful planting, and follow-up care are critical to perpetuation of a healthy urban forest. The city plants and establishes about 4,000 trees annually, 5% at new sites and 95% as replacements for removed trees. Costs are typically about $175 per tree, including $160 for planting (1.5-inch caliper) and $15 for initial staking and watering. These activities consume 2.4% of the program budget or $224,000.

Trees are irrigated with a water truck for two years after planting. It costs approximately $95,100 to irrigate the transplants once a week during the summer months. Adjacent property owners are responsible for watering after establishment.

Pruning, Removals, and General Tree Care

Due to a resurgence of Dutch elm disease during the past few years, Minneapolis has had to shift funds from pruning to tree removal and disposal. In FY2004 expenditures for pruning were $2.5 million, or 58% of the amount spent for pruning in 2002 ($4.3 million). Pruning costs in 2004 accounted for 27% of total expenditures. About 30,000 trees are pruned by in-house crews at an average cost of $83 per tree. Since 2002 the pruning cycle has increased from 5 to about 7 years.

In 2004, the Forestry Section removed 6,500 trees, about 5,000 of which were elms. The expenditure is normally $4.1 million (including stump removal and wood waste disposal), and these removal costs account for 44% of the annual budget. A larger amount was spent during FY2004, when over 10,000 elms were removed due to unusually virulent Dutch elm disease. Emergency funds were used to meet this one-time expense.

In Minneapolis, all waste wood is recycled, with most of it burned to generate electricity. A small percentage of the material is turned into mulch and used in local parks. Approximately 70% of the removed trees are replaced with new plantings.

On-site inspections and service requests cost the division approximately $317,779 (3.5%) in FY2004. The MPRB Forestry Section does not use pesticides, and therefore, has no expenditure for pest management.

Administration

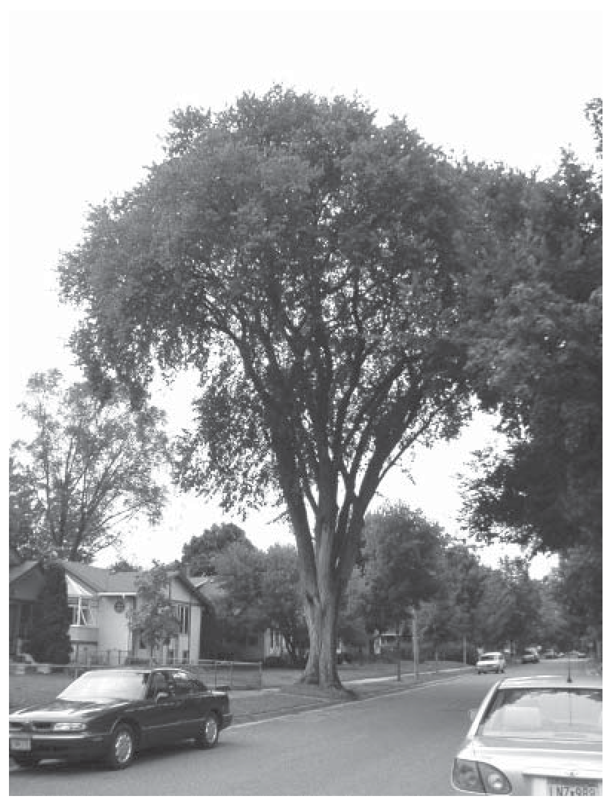
Approximately 12% of all program expenditures are for administration, totaling $1.1 million. This item includes salaries and benefits of supervisory staff that performs planning and management functions, training, ordinance enforcement, plan review, as well as contract development and supervision.

External Tree-Related Expenditures

Tree-related expenditures accrue to the city that are not captured in the Forestry Section's budget. Annual costs for litter and storm clean-up costs due to annual street-tree leaf fall are approximately $37,065.

Shallow roots that heave sidewalks, crack curbs, and damage driveways are an important aspect of mature tree care. Once problems occur, the city should attempt to remediate the problem without removing the tree. Strategies include ramping the sidewalk over the root, grinding concrete to level surfaces, and removing and replacing concrete in conjunction with root pruning. In total, approximately $800,000 is spent on sidewalk replacement. An additional $25,000 is spent on curb and gutter repair; $3,000 is spent on sewer/water line repairs and other infrastructure damage. The total expenditure for infrastructure repair and mitigation in FY2004 was $828,000, or 9% of all annual expenditures.

Annual expenditures for trip-and-fall claims, property-damage payments, and legal staff time required to process tree-related claims can be substantial in cities with large trees and old infrastructure. Fortunately, in Minneapolis costs are only about $20,000 for legal counsel fees and $6,000 in property damage awards. The total amount for FY2004 was $25,639.



Chapter Four—Benefits of Minneapolis's Municipal Trees

Introduction

City trees work ceaselessly, providing ecosystem services that directly improve human health and quality of life. In this section the benefits of Minneapolis's street trees are described. It should be noted that this is not a full accounting because some benefits are intangible or difficult to quantify (e.g., impacts on psychological health, crime, and violence). Also, our limited knowledge about the physical processes at work and their interactions makes these estimates imprecise (e.g., fate of air pollutants trapped by trees and then washed to the ground by rainfall). Tree growth and mortality rates are highly variable. A true and full accounting of benefits and costs must consider variability among sites throughout the city (e.g., tree species, growing conditions, maintenance practices), as well as variability in tree growth. Therefore, these estimates provide first-order approximations that indicate tree value. Our approach is a general accounting of the benefits produced by municipal trees in Minneapolis—an accounting with an accepted degree of uncertainty that can nonetheless provide a platform from which decisions can be made (Maco and McPherson 2003). Methods used to quantify and price these benefits are described in more detail in Appendix B.

Energy Savings

Trees modify climate and conserve energy in three principal ways:

1. Shading reduces the amount of radiant energy absorbed and stored by built surfaces.

2. Transpiration converts moisture to water vapor and thus cools the air by using solar energy that would otherwise result in heating of the air.

3. Wind-speed reduction reduces the movement of outside air into interior spaces and conductive heat loss where thermal conductivity is relatively high (e.g., glass windows) (Simpson 1998).

Trees and other vegetation within building sites may lower air temperatures 5°F (3°C) compared to outside the greenspace (Chandler 1965). At the larger scale of urban climate (6 miles or 10 km square), temperature differences of more than 9°F (5°C) have been observed between city centers and more vegetated suburban areas (Akbari et al. 1992). The relative importance of these effects depends on the size and configuration of trees

and other landscape elements (McPherson 1993). Tree spacing, crown spread, and vertical distribution of leaf area influence the transport of warm air and pollutants along streets and out of urban canyons. Appendix B provides additional information on specific contributions that trees make toward energy savings.

Electricity and Natural Gas Results

Electricity saved annually in Minneapolis (*Table 10*) from both shading and climate effects of street trees totals 32,921 MWh, for a retail savings of $2.5 million ($12.58 per tree). Total annual savings of natural gas total 441,355 MBtu, for a savings of $4.3 million ($21.78 per tree). Net energy savings are split: 63% winter heating and 37% summer air conditioning. Total citywide savings are valued at $6.8 million (SE $483,981). Average savings per tree are $34.36, and are evenly distributed among the three management zones.

Species producing the greatest annual energy benefits as a percentage of total benefits are American elm (23%), green ash (16%), and Norway maple (11%). Benefits exceeded the average on a per-tree basis for American elm ($79 per tree), other elms ($49), green ash ($37), and hackberry ($35).

Atmospheric Carbon Dioxide Reductions

Urban forests can reduce atmospheric CO_2 in two ways:

1. Trees directly sequester CO_2 as woody and foliar biomass while they grow.
2. Trees near buildings can reduce the demand for heating and air conditioning, thereby reducing emissions associated with electric power production and consumption of natural gas.

On the other hand, CO_2 is released by vehicles, chain saws, chippers, and other equipment during the process of planting and maintaining trees. Eventually, all trees die and most of the CO_2 that has accumulated in their woody biomass is released into the atmosphere through decomposition unless the wood is recycled.

Carbon Dioxide Reductions

As *Table 11* shows, CO_2 reductions depend on the species present and the age of the trees. Citywide, reductions of CO_2 due to sequestration and lowered energy plant emissions due to reduced energy use are 29,526 tons ($2.23 per tree) and 27,611 tons ($2.09 per tree), respectively, or a total of 57,137 tons valued at $857,000 ($4.31 per tree). Release of CO_2 from decomposition (1,931 tons; $29,000) and tree-care activities (1,203 tons; $1,200) was small, totaling 2,012 tons valued at $30,175 ($0.15 per tree). Net CO_2 reduction was 55,125 tons with an implied value of $826,875 (SE $58,644), or $4.16 per tree.

American elm (18%), green ash (18%), littleleaf linden (12%), and Norway maple (11%) accounted for nearly 60% of the CO_2 benefits produced by street trees. Species with the highest per-tree savings were American elm ($7.62), other elms ($6.36), and silver maple ($5.34). Citywide, total sequestered CO_2 (29,526 tons) was slightly greater than reduced CO_2 emissions (27,611

Table 10*—Cooling, heating, and net annual energy savings produced by predominant street tree species.*

Species	Electricity (MWh)	Natural gas (Mbtu)	Total ($)	SE ($)	% of total tree nos.	% of total $	Avg. $/tree
Green ash	5,189	67,827	1,058,555	(±133,663)	14.43	15.51	36.90
Sugar maple	3,117	39,984	628,391	(±108,274)	13.10	9.21	24.13
Norway maple	3,527	49,252	750,382	(±94,933)	11.81	11	31.97
Littleleaf linden	2,925	38,512	599,443	(±109,660)	10.43	8.77	28.93
American elm	7,391	99,875	1,539,771	(±157,075)	9.86	22.55	78.51
Honeylocust	2,306	30,661	475,465	(±76,364)	7.23	6.96	33.04
American basswood	1,798	24,660	378,152	(±72,390)	6.94	5.53	27.37
Northern hackberry	1,470	20,268	310,226	(±77,894)	4.5	4.55	34.68
Ginkgo	279	3,720	57,619	(±18,110)	2.51	0.83	11.52
Silver maple	746	9,574	150,485	(±31,212)	2.43	2.21	31.19
Elm	1,092	14,875	228,625	(±44,588)	2.33	3.34	49.18
White ash	526	6,378	102,445	(±29,028)	1.69	1.5	30.45
Basswood	518	7,066	108,597	(±40,530)	1.58	1.59	34.54
Red maple	347	4,480	70,245	(±24,567)	1.23	1.02	28.85
Other street trees	1,690	24,224	365,646	(±39,884)	9.85	5.36	18.69
Citywide total	32,922	441,355	6,824,046	(±483,981)	100	100	34.36

Table 11—*CO2 reductions, releases, and net benefits produced by street trees.*

Species	Seques-tered (lb)	Decomp. release (lb)	Maint. release (lb)	Avoided (lb)	Net total (lb)	Total ($)	SE ($)	% of total trees	% of total $	Ave. $/tree
Green ash	11,425,290	606,301	31,172	8,704,013	19,491,830	146,189	(±18,459)	14.43	17.68	5.09
Sugar maple	4,679,400	245,752	19,167	5,227,723	9,642,203	72,317	(±12,460)	13.10	8.75	2.77
Norway maple	6,436,856	263,400	20,453	5,916,429	12,069,430	90,521	(±11,452)	11.81	10.94	3.85
Littleleaf linden	8,080,738	281,214	2,436	4,906,777	12,703,870	95,279	(±17,430)	10.43	11.52	4.59
American elm	8,916,231	1,352,698	41,922	12,397,820	19,919,430	149,396	(±15,240)	9.86	18.06	7.61
Honeylocust	4,087,017	118,494	1,692	3,867,226	7,834,057	58,755	(±9,437)	7.23	7.11	4.07
American basswood	3,161,114	184,655	12,004	3,016,197	5,980,652	44,855	(±8,587)	6.94	5.42	3.25
Northern hackberry	1,157,974	56,784	7,595	2,466,296	3,559,891	26,699	(±6,704)	4.5	3.23	2.99
Ginkgo	238,970	12,684	2,816	467,762	691,232	5,184	(±1,629)	2.51	0.62	1.03
Silver maple	2,293,107	110,378	567	1,252,141	3,434,302	25,757	(±5,342)	2.43	3.11	5.34
Elm	2,431,705	314,292	7,288	1,831,017	3,941,141	29,559	(±5,765)	2.33	3.56	6.36
White ash	1,036,713	35,996	396	882,756	1,883,077	14,123	(±4,002)	1.69	1.71	4.19
Basswood	1,195,120	66,582	3,295	869,571	1,994,814	14,961	(±5,584)	1.58	1.80	4.76
Red maple	596,220	20,631	286	582,125	1,157,428	8,681	(±3,036)	1.23	1.04	3.56
Other street trees	3,314,831	193,082	9,318	2,834,241	5,946,673	44,600	(±4,865)	9.85	5.38	2.27
Citywide total	59,051,280	3,862,943	160,409	55,222,088	110,250,000	826,875	(±58,644)	100	100	4.15

tons). This can be explained by the fact that Minneapolis has a relatively clean mix of fuels used to produce energy to heat and cool buildings, influencing potential CO_2 emission reductions. Furthermore, Minneapolis's summertime climate is mild, resulting in relatively lower cooling loads than in Sun Belt cities.

Air Quality Improvement

Urban trees improve air quality in five main ways:

1. Absorbing gaseous pollutants (ozone, nitrogen oxides) through leaf surfaces.
2. Intercepting particulate matter (e.g., dust, ash, dirt, pollen, smoke).
3. Reducing emissions from power generation by reducing energy consumption.
4. Releasing oxygen through photosynthesis.
5. Transpiring water and shading surfaces, resulting in lower local air temperatures, thereby reducing ozone levels.

In the absence of the cooling effects of trees, higher air temperatures contribute to ozone formation. On the other hand, most trees emit various biogenic volatile organic compounds (BVOCs) such as isoprenes and monoterpenes that can contribute to ozone formation. The ozone-forming potential of different tree species varies considerably (Benjamin and Winer 1998). The contribution of BVOC emissions from city trees to ozone formation depends on complex geographic and atmospheric interactions that have not been studied in most cities.

Avoided Pollutants

Energy savings result in reduced air-pollutant emissions of nitrogen dioxide (NO_2), small particulate matter (PM_{10}), volatile organic compounds (VOCs), and sulfur dioxide (SO_2) (*Table 12*). Together, 175.1 tons of pollutants valued at $976,446 ($4.92 per tree) are avoided annually. Avoided NO_2 and SO_2 account for 45% and 43% of the monetary benefit, respectively.

Deposition and Interception

Annual pollutant uptake by trees (pollutant deposition and particulate interception) in Minneapolis is 29.4 tons (*Table 12*) with a total value of $185,585 or $0.93 per tree. Ozone uptake accounts for approximately 57% of the total dollar benefit, while PM_{10} interception (30%) accounts for most of the remainder. Benefits from avoid-

Table 12*—Deposition, avoided and BVOC emissions, and net air-quality benefits produced by predominant street tree species.*

Species	Deposition (lb)				Avoided (lb)				Released						
	O_3	NO_2	PM_{10}	SO_2	NO_2	PM_{10}	VOC	SO_2	BVOC (lb)	Net total (lb)	Total ($)	SE ($)	% of total trees	% of total $	Average $/tree
Green ash	3,824	611	2,084	172	24,484	3,586	3,424	23,521	0	61,706	174,341	(±22,014)	14.4	15.4	6.08
Sugar maple	1,608	274	1,037	71	14,618	2,147	2,051	14,120	-1,464	34,462	95,586	(±16,470)	13.1	8.4	3.67
Norway maple	3,116	538	1,727	138	16,963	2,463	2,346	16,010	-852	42,448	119,625	(±15,134)	11.8	10.5	5.10
Littleleaf linden	2,574	444	1,405	114	13,860	2,028	1,935	13,280	-1,400	34,239	95,717	(±17,510)	10.4	8.4	4.62
American elm	12,945	2,205	6,409	572	35,190	5,131	4,893	33,498	0	100,843	289,441	(±29,526)	9.9	25.5	14.76
Honeylocust	2,002	330	1,032	91	10,916	1,596	1,523	10,446	-1,235	26,701	74,498	(±11,965)	7.2	6.6	5.18
American basswood	1,031	175	625	46	8,608	1,253	1,194	8,163	-1,068	20,028	55,499	(±10,624)	7.0	4.9	4.02
Northern hackberry	849	147	531	38	7,044	1,024	976	6,671	0	17,281	48,753	(±12,241)	4.5	4.3	5.45
Ginkgo	178	31	105	8	1,319	193	184	1,263	-71	3,210	8,992	(±2,826)	2.5	0.8	1.80
Silver maple	936	159	507	41	3,500	514	491	3,380	-624	8,904	24,796	(±5,143)	2.4	2.2	5.14
Elm	1,963	314	903	88	5,206	758	723	4,947	0	14,902	42,795	(±8,346)	2.3	3.8	9.21
White ash	225	36	146	10	2,436	360	345	2,385	0	5,944	16,675	(±4,725)	1.7	1.5	4.96
Basswood	421	67	226	19	2,471	360	343	2,350	0	6,258	17,718	(±6,612)	1.6	1.6	5.64
Red maple	357	61	183	16	1,631	239	229	1,572	-138	4,149	11,649	(±4,074)	1.2	1.0	4.78
Other street trees	1,745	292	930	83	8,165	1,182	1,125	7,661	-533	20,651	58,248	(±6,354)	9.9	5.1	2.98
Citywide total	33,774	5,683	17,850	1,507	156,411	22,834	21,785	149,268	-7,386	401,726	1,134,334	(±80,450)	100.0	100.0	5.71

ed emissions are 5.3 times greater than from deposition. Relatively low concentrations of air pollutants in Minneapolis contribute to low benefits due to deposition.

BVOC Emissions

Biogenic volatile organic compound (BVOC) emissions from trees are small. At a total of 3.7 tons, these emissions account for 12.5% of net uptake and are valued as a cost to the city of $27,697. Sugar maple (−$1,464) and littleleaf linden (−$1,400) produce the most BVOC emissions.

Net Air-Quality Improvement

Net air pollutants removed, released, and avoided have a substantial value, $1.1 million annually (SE $80,450). On average, the benefit per tree is $5.71. Trees vary dramatically in their ability to produce net air-quality benefits. Large-canopied trees with large leaf surface areas and low BVOC emissions produce the greatest benefits. American elm (26%), green ash (15%), and Norway maple (11%) account for 52% of total net benefits. Annually, on a per-tree basis, valuable street trees include American elm ($14.67), other elms ($9.21), green ash ($6.08), and basswood ($5.64).

Stormwater-Runoff Reductions

According to federal Clean Water Act regulations, municipalities must obtain a permit for managing their stormwater discharges into water bodies. Each city's program must identify the Best Management Practices it will implement to reduce its pollutant discharge. Trees are mini-reservoirs, controlling runoff at the source because their leaves and branch surfaces intercept and store rainfall, thereby reducing runoff volumes and erosion of watercourses, as well as delaying the onset of peak flows. Healthy urban trees can reduce the amount of runoff and pollutant loading in receiving waters in three primary ways:

1. Leaves and branch surfaces intercept and store rainfall, thereby reducing runoff volumes and delaying the onset of peak flows.
2. Root growth and decomposition increase the capacity and rate of soil infiltration by rainfall and reduce overland flow.
3. Tree canopies reduce soil erosion and surface transport by diminishing the impact of raindrops on barren surfaces.

Minneapolis's municipal trees intercept 44.75 million cubic feet of stormwater annually, or 1,685 gal per tree on average (*Table 13*). The total value of this benefit to the city is $9 million (SE $643,399), or $45.67 per tree.

When averaged over the entire street tree population, certain species are much better at reducing stormwater runoff than others. Leaf type and area, branching pattern and bark, as well as tree size and shape all affect the amount of precipitation trees can intercept and hold to avoid direct runoff. Stormwater reduction benefits for street trees range from $4 to $190. Trees that perform well include American elm, other elms, silver maple,

Table 13—*Annual stormwater reduction benefits produced by predominant street tree species.*

Species	Rainfall intercept. (Ccf)	Total $	SE	% of total trees	% of total $	Avg. $/tree
Green ash	68,789	1,394,504	(±176,083)	14.4	15.4	48.61
Sugar maple	23,241	471,150	(±81,181)	13.1	5.2	18.10
Norway maple	25,498	516,899	(±65,395)	11.8	5.7	22.03
Littleleaf linden	29,990	607,958	(±111,218)	10.4	6.7	29.34
American elm	184,140	3,732,916	(±380,802)	9.9	41.2	190.35
Honeylocust	14,918	302,416	(±48,571)	7.2	3.3	21.02
American basswood	15,903	322,393	(±61,716)	7.0	3.6	23.34
Northern hackberry	9,316	188,863	(±47,421)	4.5	2.1	21.12
Ginkgo	1,051	21,307	(±6,697)	2.5	0.2	4.26
Silver maple	13,020	263,951	(±54,745)	2.4	2.9	54.70
Elm	29,107	590,058	(±115,078)	2.3	6.5	126.94
White ash	5,074	102,857	(±29,145)	1.7	1.1	30.56
Basswood	7,474	151,512	(±56,546)	1.6	1.7	48.20
Red maple	2,417	48,997	(±17,136)	1.2	0.5	20.12
Other street trees	17,562	356,031	(±38,835)	9.9	3.9	18.20
Citywide total	447,500	9,071,809	(±643,399)	100.0	100.0	45.66

and green ash. Poor performers are species with relatively little leaf and stem surface area, such as ginkgo. Interception by American elm alone accounts for 41% of the total dollar benefit. Interception is quite evenly distributed by management zone: 30%, 33%, and 37% for Zones 1, 2, and 3, respectively.

Property Values and Other Benefits

Many benefits attributed to urban trees are difficult to translate into economic terms. Beautification, privacy, shade that increases human comfort, wildlife habitat, sense of place and well-being are products that are difficult to price. However, the value of some of these benefits may be captured in the property values of the land on which trees stand. To estimate the value of these "other" benefits, research that compares differences in sales prices of houses was used to estimate the contribution associated with trees. The difference in sales price reflects the willingness of buyers to pay for the benefits and costs associated with trees. This approach has the virtue of capturing what buyers perceive as both the benefits and costs of trees in the sales price. Some limitations to using this approach in Minneapolis include the difficulty associated with 1) determining the value of individual street trees adjacent to private properties and 2) the need to extrapolate results from front-yard trees on residential properties to street trees in various locations (e.g., commercial vs. residential).

The estimated total annual benefit associated with property value increases and other less tangible benefits is approximately $7.1 million (SE $501,877), or $36 per tree on average (*Table 14*). The magnitude of this benefit is related to the local median sales price for single family homes ($218,000 in Minneapolis), as well as tree growth rates. This $36 per tree benefit is on par with other communities that have similar median home values. For example, benefits in Glendale, AZ, and Fort Collins, CO, average $22 and $52 per tree (McPherson et al. 2002, 2005) where the median home sales prices are $144,000 and $212,000.

Tree species that produce the highest average annual benefits are American elm ($63 per tree), honeylocust (*Gleditsia triacanthos*) ($57 per tree), silver maple ($48 per tree), and white ash (*Fraxinus americana*) ($45 per tree), while ginkgo ($5 per tree), other smaller street tree species ($17 per tree), and American basswood ($21 per tree) are examples of trees that produced the least benefits. Property value and other benefits are evenly distributed among management areas, reflecting a diverse mix of species and ages across the city.

Total Annual Net Benefits and Benefit–Cost Ratio (BCR)

Total annual benefits produced by Minneapolis's street trees are estimated to have a value of $24.9 million (SE $1.77 million) ($126 per tree, $32/capita) (*Table 15*). Given uncertainty associated with sampling tree numbers, the actual annual benefit is likely to fall between $23.2 million and $26.7 million. The average annual benefit is estimated to range from $117–134 per tree and $70–88/capita. Over the same period, tree-related expenditures are estimated at nearly $9.2 million. Net

Table 14*—Total annual increases in property value produced by street trees.*

Species	Total ($)	SE ($)	% of total trees	% of total $	Avg. $/tree
Green ash	1,149,556	(±145,154)	14.4	16.2	40.06
Sugar maple	591,877	(±101,983)	13.1	8.4	22.73
Norway maple	693,144	(±87,692)	11.8	9.8	29.54
Littleleaf linden	916,381	(±167,639)	10.4	13.0	44.22
American elm	1,226,137	(±125,081)	9.9	17.3	62.52
Honeylocust	816,085	(±131,072)	7.2	11.5	56.72
American basswood	283,664	(±54,302)	7.0	4.0	20.54
Northern hackberry	250,617	(±62,927)	4.5	3.5	28.03
Ginkgo	26,044	(±8,186)	2.5	0.4	5.21
Silver maple	233,319	(±48,392)	2.4	3.3	48.34
Elm	195,384	(±38,105)	2.3	2.8	42.02
White ash	150,068	(±42,522)	1.7	2.1	44.59
Basswood	120,178	(±44,852)	1.6	1.7	38.24
Red maple	89,708	(±31,374)	1.2	1.3	36.84
Other street trees	334,207	(±36,455)	9.9	4.7	17.07
Citywide total	7,076,370	(±501,877)	100.0	100.0	35.63

Table 15—Benefit–cost summary for all street trees.

Benefits	Total ($)	SE ($)	$/tree	SE ($/tree)	$/capita	SE ($/capita)
Energy	6,824,046	(±483,981)	34.36	(±2.44)	8.79	(±.62)
CO2	826,875	(±58,644)	4.16	(±.3)	1.06	(±.08)
Air quality	1,134,334	(±80,450)	5.71	(±.41)	1.46	(±.1)
Stormwater	9,071,809	(±643,399)	45.67	(±3.24)	11.68	(±.83)
Aesthetic/Other	7,076,370	(±501,877)	35.63	(±2.53)	9.11	(±.65)
Total Benefits	24,933,434	(±1,766,384)	125.53	(±8.89)	32.10	(±2.27)
Costs						
Pruning	2,505,680		12.61		6.55	
Tree and stump removal	4,078,585		20.53		10.66	
Irrigation	95,100		0.48		0.25	
Inspection/Service	317,779		1.60		0.83	
Planting	223,855		1.13		0.59	
Administration	1,097,338		5.52		2.87	
Litter clean-up	37,065		0.19		0.10	
Infrastructure repairs	828,000		4.17		2.16	
Liability/Claims	25,639		0.13		0.07	
Total Costs	9,209,041		46.36		24.07	
Net Benefits	15,724,393	(±1,766,384)	79.16	(±8.89)	8.03	(±2.27)

annual benefits are estimated to fall between $14 million and $17 million (midpoint $15.7 million), or $70–88 per tree (midpoint $79 per tree) and $5.76–10.30/capita (midpoint $8/capita). The Minneapolis municipal forest currently returns $1.59 ($1.47–1.70) to the community for every $1 spent on management.

Minneapolis municipal trees have beneficial effects on the environment. Approximately 72% of the annual benefits are environmental services. Benefits associated with stormwater-runoff reduction represent 36% of the total benefits. Energy savings are 27% of total benefits, while air quality (5%), and carbon dioxide reductions (3%) account for the remaining environmental benefits. As in most cities, annual increases in property value are a substantial benefit produced by trees in Minneapolis, accounting for 29% of total annual benefits.

Average annual benefits vary among species due to differences in sizes and growth rates (*Figure 4*). Not surprisingly, American elm ($354 per tree, 28%) and other large elm species ($234 per tree, 4%) produce the greatest average benefits. Silver maple (3%), green ash (16%), littleleaf linden (9%), honey locust (7%), white ash (2%), and basswood (2%) produce annual benefits that range between $100 and $150 per tree. Although the average annual benefit per tree is only $71 for sugar maples and $93 for Norway maples, they account for 8% and 9% of total benefits, respectively, due to their abundance.

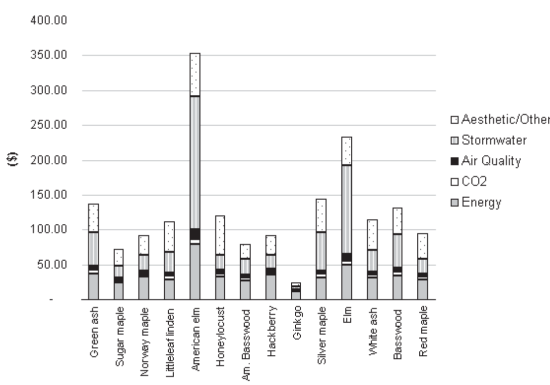


Figure 4—Average annual benefits per street tree species.

While species vary in their ability to produce benefits, common characteristics of trees within tree type classes aid in identifying the most beneficial types of street trees in Minneapolis (*Figure 5*). Minneapolis's large deciduous trees (mature height greater than 40 ft) produce the greatest average annual benefits, valued at $148 per tree (SE $12.87). Medium trees (mature height 25–40 ft) produce substantial benefits as well ($96 per tree [SE

$7.12]). Small deciduous trees (mature height <25 ft) produce the least average annual benefits, only $25 per tree (SE $4.25). When considering total benefits, large trees provide the highest average return for the investment dollar. Increased value is primarily due to increased stormwater runoff reduction and property value benefits associated with greater leaf area. From an environmental perspective, large and medium deciduous trees provide the highest level of benefits on Minneapolis's streets. *Figure 6* describes the average annual benefits per tree according to management zone and reflects differences in tree types and population ages. Differences across zones are not pronounced: average annual benefits range from $123 per tree (SE $11.70) in Zone 3 to $127 per tree in Zones 1 (SE $17.27) and 2 (SE $12.31).

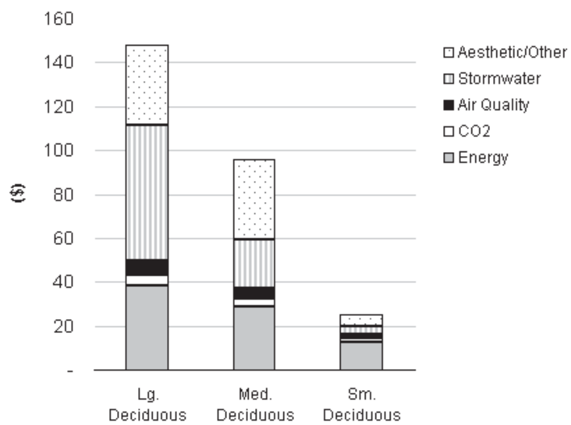


Figure 5—Average annual street tree benefits per tree by tree type.

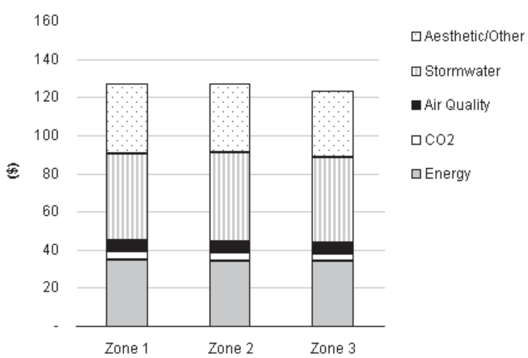


Figure 6—Average annual benefits per tree by management zone.

Chapter Five—Management Implications

Minneapolis's urban forest reflects the values, lifestyles, preferences, and aspirations of current and past residents. It is a dynamic legacy, on one hand dominated by trees planted over 50 years ago and, at the same time, constantly changing as new trees are planted and others mature. Although this study provides a "snapshot" in time of the resource, it also serves as an opportunity to speculate about the future. Given the status of Minneapolis's street tree population, what future trends are likely and what management challenges will need to be met to achieve urban forest sustainability?

Achieving resource sustainability will produce long-term net benefits to the community while reducing the associated costs incurred with managing the resource. The structural features of a sustainable urban forest include adequate complexity (species and age diversity), well-adapted healthy trees, appropriate tree numbers and cost-efficient management. Focusing on these components—resource complexity, resource extent, and maintenance—will help refine broader municipal tree management goals.

Resource Complexity

Achieving greater species diversity and age diversity are important challenges for the Minneapolis Forestry Section. American elm trees account for 14% of the tree population and produce 28% of total benefits, but are threatened once again by Dutch elm disease, which is spread by the elm bark beetle (*Scolytus multistriatus*). Most of the trees are nearing the end of their functional life cycle. Critical to the future of Minneapolis's forest is selection of transplants that will grow to perpetuate the canopy cover provided by American elms. Ideally, a more diverse mix of species will be planted: some proven performers, some species that are more narrowly adapted, and a small percentage of new introductions for evaluation. Proven performers include trees like the hackberry (*Celtis occidentalis*), basswood, and red and white oaks (*Quercus rubra* and *Q. alba*). A substantial number of these species have grown to maturity and have proven to thrive under a wide range of growing conditions. Although each has some deficiencies, overall they are the dependable workhorses of Minneapolis's urban forest. Examples of more narrowly adapted species that have proven well-suited in certain situations are crabapple (*Malus* spp.) and Japanese tree lilac (*Syringa reticulata*) under powerlines, honeylocust (*Gleditsia triacanthos*) in cutouts, pin oak (*Quercus palustris*) in wider planting strips, and sugar and red maple in residential areas. New introductions include cultivars of elms that have been developed to replace American elm, including 'Prospector,' 'Frontier,' 'Pioneer,' and 'Valley Forge,' a DED-resistant American elm.

Figure 7 displays trends in new and replacement trees, with sugar maple, honeylocust, green ash, and American basswood being most common. These species have proven to be well adapted in Minneapolis, and should produce the substantial benefits in the future that the community depends upon. Among the species shown, only Japanese tree lilac and crabapple are small trees. New introductions include elm cultivars, swamp white oak, and black ash. Hence, it appears that a diverse mix of large tree species is being planted, with an eye towards increasing structural complexity in the long term.

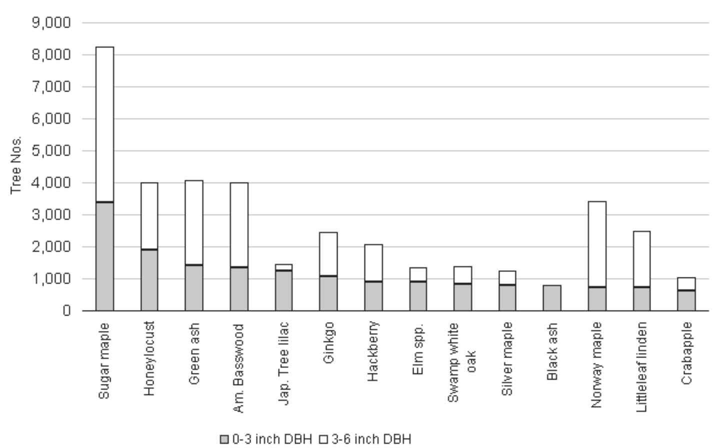


Figure 7—Municipal trees being planted in the highest numbers.

The second critical issue facing the managers of Minneapolis's urban forest is the overabundance of maturing trees in the 6–18 inch DBH size classes. These trees account for nearly 60% of the population, and perpetuating the high level of benefits currently produced depends on the continued growth and longevity of maturing trees.

Figure 8 shows the most abundant species in the maturing size classes. Norway maple, sugar maple, green ash, and littleleaf linden are the top four species, each accounting for over 16,000 trees. Next in importance are the honeylocust, American basswood, and hackberry, each accounting for 6,000 to 10,000 trees. Fortunately, all these species are large growing and relatively well-adapted to local conditions. All have proven their adaptability and longevity. Therefore, it appears likely that many of the currently maturing trees will move into mature size classes and begin to replace benefits lost as more of the older elms are removed.

One concern is the large number of Norway and sugar maples in the young and maturing age classes. Sugar maple is the most abundant young tree species, and Norway maple the most abundant maturing species. If pests, diseases, or abiotic stressors decimated these two species of trees, the future of Minneapolis's urban forest would be in peril. Reduced reliance on these species, and green ash, seems prudent given recent increased attacks from exotic pests and the dire consequences associated with loss of American elms.

Resource Extent

Canopy cover, or more precisely the amount and distribution of leaf surface area, is the driving force behind the urban forest's ability to produce benefits for the community. As canopy cover increases, so do the benefits afforded by leaf area. Maximizing the return on this investment is contingent upon maximizing and maintaining the canopy cover of these trees.

Increasing the street-tree canopy cover is not a necessity at present in Minneapolis. Most plantable spaces are filled and use of large trees as replacements is encouraged wherever sites allow.

Maintenance

Retaining Minneapolis's canopy cover is a concern due to threats to the American elms and the city's reliance on this dominant species. Removing diseased trees has taxed budgets and shifted funds away from maintaining the health of other trees through regular pruning on a 5-year cycle.

Several years ago the Forestry Section cared for Minneapolis's municipal trees within the recommended pruning cycle of 3–6 years (Miller 1997)—a practice that appeared to be paying off. Trees were producing sizeable benefits and were in relatively good condition. However, battling DED has begun to put other trees at risk. Funding will be needed to continue combating DED, as well as to continue providing regular care to the relatively large number of maturing trees.

The citywide age distribution of all trees does not correspond to the "ideal" distribution as described above, having elevated numbers of maturing trees, adequate numbers of young trees and lower numbers of functionally mature trees (see *Figure 2*). This distribution suggests that a strong young-tree-care program is imperative, as is targeted maintenance for maturing trees. Pruning young trees biannually for structure and form will more than pay off in the long term because fewer resources will be required to maintain them. Regular inspection and pruning of maturing trees will insure that they transition into functionally mature trees that will perform at their peak for many years.

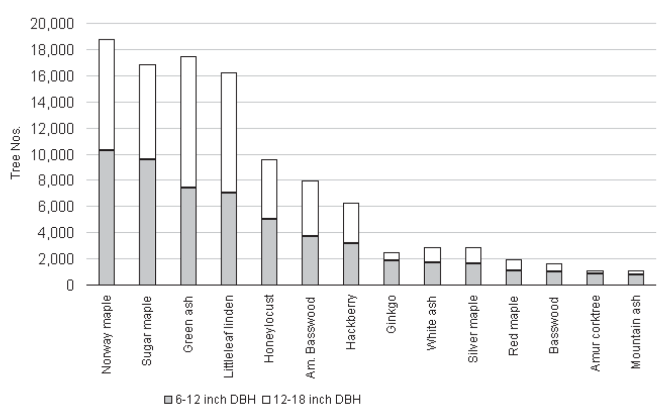


Figure 8—Minneapolis's most important maturing trees. These will be relied upon to replace senescing American elms.

Chapter Six—Conclusions

The approach used in this analysis not only provides sufficient data to describe structural characteristics of the street-tree population, but by using tree-growth data modeled for Minneapolis, assesses the ecosystem services trees provide the city and its residents. In addition, the benefit–cost ratio has been calculated and management needs identified. The approach is based on established tree-sampling, numerical-modeling, and statistical methods and provides a general accounting of the benefits produced by street trees in Minneapolis that can be used to make informed management and planning decisions.

Minneapolis's municipal trees are a valuable asset, providing approximately $25 million ($125 per tree) in gross annual benefits. Benefits to the community are most pronounced for stormwater-runoff reductions and increased local property values, but energy savings are also significant. Thus, street trees are found to play a particularly important role in maintaining the environmental and aesthetic qualities of the city. Minneapolis spent approximately $9.2 million in 2004 maintaining its nearly 200,000 street trees or $46 per tree. Expenditures for tree removal account for about one-half of total costs.

After costs are taken into account, Minneapolis's municipal tree resource provides approximately $15.7 million (SE $1.8 million), or $79 per tree in total net annual benefits to the community. Over the years, Minneapolis has invested millions in its municipal forest. Citizens are now beginning to see a return on that investment—receiving $1.59 in benefits for every $1 spent on tree care. As the resource matures, continued investment in management is critical to insuring that residents receive a greater return on investment in the future.

Minneapolis's municipal trees are a tremendously dynamic resource. Managers of this resource and the community alike can delight in knowing that street trees do improve the quality of life in the city. However, the city's trees are also a fragile resource that needs constant care to maximize and sustain production of benefits into the future. The challenge will be to continue to grow the city's canopy cover as the population structure changes and the city continues to grow, putting space for trees at a premium.

Management recommendations derived from this analysis are fourfold: 1) Continue to invest in efforts to control the loss of the dominant species, American elm; 2) prune and inspect maturing trees that are poised to replace the older trees on a 5-year cycle; 3) recognize that adequate young-tree care will be especially important through the near future to insure future benefits and reduce long-term costs; and 4) increase the mix of species being planted to insure adequate diversity in the future. These recommendations build on a history of exemplary management that has put the city on course to provide an urban forest resource that is both functional and sustainable.

Appendix A—Tree Distribution

Botanical name	Common name	0-3	3-6	6-12	12-18	18-24	24-30	30-36	36-42	>42	Total	SE
Broadleaf Deciduous Large												
Fraxinus pennsylvanica	Green ash	1,417	2,656	7,437	10,049	4,825	1,904	398	0	0	28,686	(±3,622)
Acer saccharum	Sugar maple	3,364	4,870	9,606	7,260	664	89	177	0	0	26,030	(±4,485)
Ulmus americana	American elm	266	221	177	1,549	3,763	6,507	4,604	1,948	575	19,611	(±2,001)
Tilia americana	American basswood	1,328	2,656	3,719	4,206	1,549	266	89	0	0	13,812	(±2,644)
Celtis occidentalis	Northern hackberry	885	1,195	3,143	3,143	398	89	0	0	89	8,942	(±2,245)
Acer saccharinum	Silver maple	797	443	1,594	1,240	266	89	177	89	133	4,825	(±1,001)
Ulmus spp.	Elm	885	443	266	487	487	664	797	398	221	4,648	(±907)
Fraxinus americana	White ash	177	177	1,682	1,151	177	0	0	0	0	3,364	(±953)
Tilia spp.	Basswood	221	354	1,018	575	708	221	44	0	0	3,143	(±1,173)
Acer rubrum	Red maple	177	354	1,062	841	0	0	0	0	0	2,435	(±852)
Acer spp.	Maple	133	398	575	354	133	0	0	0	0	1,594	(±488)
Quercus macrocarpa	Bur oak	0	354	0	44	44	89	44	0	0	575	(±290)
Acer nigrum	Black maple	44	44	310	89	0	0	0	0	0	487	(±197)
Quercus palustris	Pin oak	89	0	310	0	44	0	0	44	0	487	(±216)
Quercus rubra	Northern red oak	0	310	89	44	0	0	0	0	0	443	(±193)
Catalpa spp.	Catalpa	44	44	133	0	44	0	44	0	0	310	(±113)
Juglans nigra	Black walnut	0	177	89	44	0	0	0	0	0	310	(±265)
Populus spp	Cottonwood	0	0	44	0	0	0	44	89	44	221	(±115)
Quercus alba	White oak	44	89	0	89	0	0	0	0	0	221	(±115)
Carya spp.	Hickory	0	0	177	0	0	0	0	0	0	177	(±144)
Populus deltoides	Eastern cottonwood	44	0	0	44	44	0	0	0	0	133	(±75)
Quercus spp.	Oak	44	0	0	0	0	44	0	0	0	89	(±62)
Betula papyrifera	Paper birch	44	0	0	0	0	0	0	0	0	44	(±44)
Gymnocladus dioicus	Kentucky coffeetree	44	0	0	0	0	0	0	0	0	44	(±44)
Populus tremuloides	Quaking aspen	0	0	44	0	0	0	0	0	0	44	(±44)
Total		10,049	14,786	31,475	31,209	13,148	9,960	6,419	2,568	1,062	120,676	(±10,386)
Broadleaf Deciduous Medium												
Acer platanoides	Norway maple	708	2,700	10,270	8,500	1,195	44	0	44	0	23,462	(±2,968)
Tilia cordata	Littleleaf linden	708	1,771	6,994	9,208	1,859	177	0	0	0	20,718	(±3,790)
Gleditsia triacanthos	Honeylocust	1,904	2,081	5,047	4,560	708	89	0	0	0	14,387	(±2,311)
Ginkgo biloba	Ginkgo	1,062	1,372	1,859	620	44	0	44	0	0	5,002	(±1,572)
Quercus bicolor	Swamp white oak	841	531	89	0	44	89	0	0	0	1,594	(±564)
Phellodendron amurense	Amur corktree	0	266	841	266	0	0	0	0	0	1,372	(±792)
Fraxinus spp.	Ash	133	266	443	221	266	44	0	0	0	1,372	(±469)
Fraxinus nigra	Black ash	797	0	44	44	0	0	0	0	0	885	(±622)
Acer negundo	Boxelder	133	89	266	177	0	0	0	0	0	664	(±344)
Betula nigra	River birch	44	89	310	0	0	0	0	0	0	443	(±437)
Ulmus pumila	Siberian elm	89	0	44	44	89	0	44	0	0	310	(±143)
Betula spp.	Birch	89	89	0	0	0	0	0	0	0	177	(±123)
Robinia psuedoacacia	Black locust	44	0	0	0	0	0	44	0	0	89	(±62)
Aesculus glabra	Ohio buckeye	0	0	44	0	0	0	0	0	0	44	(±44)
Quercus ellipsoidalis	Northern pin oak	0	0	44	0	0	0	0	0	0	44	(±44)
Salix spp.	Willow	0	0	44	0	0	0	0	0	0	44	(±44)
Total		6,552	9,252	26,340	23,639	4,206	443	133	44	0	70,608	(±5,244)

Botanical name	Common name	0-3	3-6	6-12	12-18	18-24	24-30	30-36	36-42	>42	Total	SE
Broadleaf Deciduous Small												
Malus spp.	Apple	620	398	531	89	0	44	0	0	0	1,682	(±582)
Syringa reticulata	Japanese tree lilac	1,240	221	0	0	0	0	0	0	0	1,461	(±464)
Sorbus spp.	Mountain ash	177	89	797	310	0	44	0	0	0	1,417	(±475)
Morus spp.	Mulberry	0	44	89	398	310	0	0	0	0	841	(±705)
Acer ginnala	Amur maple	310	133	0	0	0	0	0	0	0	443	(±221)
Ostrya virginiana	Eastern hophornbeam	221	44	44	0	0	0	0	0	0	310	(±226)
Pyrus spp.	Pear	0	177	0	0	0	0	0	0	0	177	(±123)
Alnus spp.	Alder	133	0	0	0	0	0	0	0	0	133	(±131)
Prunus virginiana	Common chokecherry	44	0	44	0	0	0	0	0	0	89	(±62)
Syringa spp.	Lilac	89	0	0	0	0	0	0	0	0	89	(±87)
Prunus spp.	Plum	0	44	0	0	0	0	0	0	0	44	(±44)
Rhus spp.	Sumac	0	0	0	44	0	0	0	0	0	44	(±44)
Total		2,833	1,151	1,505	841	310	89	0	0	0	6,729	(±1,129)
Conifer Evergreen Large												
Pinus strobus	Eastern white pine	133	0	44	0	0	0	0	0	0	177	(±106)
Pinus nigra	Austrian pine	0	0	0	44	0	0	0	0	0	44	(±44)
Pinus resinosa	Red pine	0	0	0	44	0	0	0	0	0	44	(±44)
Pinus sylvestris	Scotch pine	44	0	0	0	0	0	0	0	0	44	(±44)
Total		177	0	44	89	0	0	0	0	0	310	(±143)
Conifer Evergreen Medium												
Picea pungens	Blue spruce	44	44	0	44	0	0	0	0	0	133	(±131)
Picea mariana	Black spruce	0	44	0	0	0	0	0	0	0	44	(±44)
Total		44	89	0	44	0	0	0	0	0	177	(±175)
Conifer Evergreen Small												
Juniperus spp.	Juniper	44	0	0	89	0	0	0	0	0	133	(±75)
Total		44	0	0	89	0	0	0	0	0	133	(±75)
Citywide Total		19,699	25,277	59,364	55,911	17,663	10,492	6,552	2,612	1,062	198,633	(±14,088)

Appendix B—Methodology and Procedures

This analysis combines results of a citywide inventory with benefit–cost modeling data to produce four types of information:

1. Resource structure (species composition, diversity, age distribution, condition, etc.)
2. Resource function (magnitude of environmental and aesthetic benefits)
3. Resource value (dollar value of benefits realized)
4. Resource management needs (sustainability, pruning, planting, and conflict mitigation)

This Appendix describes street tree sampling, tree growth modeling, and the model inputs and calculations used to derive the aforementioned outputs.

Street Tree Sampling

During the summer of 2004, 83 volunteers collected street tree data for this study under supervision of the Tree Trust. Technical volunteers received about 8 hours of training, while community volunteers did not attend the training, but collected data with someone who received training. Tree inventory data were collected as a pilot test using protocols for STRATUM (Street Tree Resource Analysis Tool for Urban Forest Managers) and handheld computers (PDAs). A sample of 405 street segments was randomly drawn using Tiger Line Files and comprised 3% of the total street segments (13,499). During July and August volunteers collected the following data on 4,577 trees: species, DBH, crown diameter, location, land use, condition of wood and foliage, maintenance needs, conflicts with sidewalks and powerlines. The data were downloaded to a central desktop computer, quality checked, archived, and sent to the research team in Davis, CA.

Population Estimates

Sample tree inventory data were imported into STRATUM, where equations exist to estimate the mean tree population and its standard error. The equations are based on statistics for a simple random sample of street segments:

Sample mean = $\bar{y} = \frac{1}{n}\left(y_1 + y_2 + \cdots + y_n\right)$ Equation 1

Estimate of the population total = $\hat{t} = N\bar{y}$ Equation 2

Sample variance = $s^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2$ Equation 3

Est. variance of the sample mean= $\hat{v}(\bar{y}) = \left(\frac{N-n}{N}\right)\frac{s^2}{n}$ Equation 4

Standard error (SE) of the sample mean = $\sqrt{\hat{v}(\bar{y})}$ Equation 5

Est. variance of the est. of the total= $\hat{v}(\hat{t}) = N^2\hat{v}(\bar{y})$ Equation 6

Standard error (SE) of the estimated total = $\sqrt{\hat{v}(\hat{t})}$ Equation 7

Growth Modeling

Also in progress during summer of 2003 was a complete inventory of Minneapolis's street trees under the direction of the Forestry Section. By spring 2003, the inventory included 35,106 trees. The City indicated that trees were representative of the remaining population and the inventory was suitable for sampling to develop growth models representative of the predominant tree species.

Tree growth models developed from Minneapolis data were used as the basis for modeling tree growth. Using Minneapolis's tree inventory, a stratified random sample of 17 tree species was measured to establish relations between tree age, size, leaf area and biomass for comparison with the regional growth curves.

For both the regional and local growth models, information spanning the life cycle of predominant tree species was collected. The inventory was stratified into nine DBH classes:

- 0–3 inches (0–7.62 cm)
- 3–6 inches (7.62–15.24 cm)
- 6–12 inches (15.24–30.48 cm
- 12–18 inches (30.48–45.72 cm)
- 18–24 inches (45.72–60.96 cm)
- 24–30 inches (60.96–76.2 cm)
- 30–36 inches (76.2–91.44)
- 36–42 inches (91.44–106.68 cm)
- >42 inches (>106.68 cm).

Thirty to 50 trees of each species were randomly selected to be surveyed, along with an equal number of alternative trees. Tree measurements included DBH (to nearest 0.1 cm by sonar measuring device), tree crown and bole height (to nearest 0.5 m by clinometer), crown diameter in two directions (parallel and perpendicular to nearest street to nearest 0.5 m by sonar measuring device), tree condition and location. Replacement trees were sampled when trees from the original sample population could not be located. Tree age was determined by street tree managers. Fieldwork was conducted in June and July 2004.

Crown volume and leaf area were estimated from computer processing of tree crown images obtained using a digital camera. The method has shown greater accuracy than other techniques (±20% of actual leaf area) in estimating crown volume and leaf area of open-grown trees (Peper and McPherson 2003).

Linear regression was used to fit predictive models—with DBH as a function of age—for each of the sampled species. Predictions of leaf surface area (LSA), crown diameter, and height metrics were modeled as a function of DBH using best-fit models (Peper et al. 2001).

Identifying And Calculating Benefits

Annual benefits for Minneapolis's municipal trees were estimated for the fiscal year 2004. Growth rate modeling information was used to perform computer-simulated growth of the existing tree population for one year and account for the associated annual benefits. This "snapshot" analysis assumed that no trees were added to, or removed from, the existing population during the year. (Calculations of CO2 released due to decomposition of wood from removed trees did consider average annual mortality.) This approach directly connects benefits with tree-size variables such DBH and LSA. Many functional benefits of trees are related to processes that involve interactions between leaves and the atmosphere (e.g., interception, transpiration, photosynthesis); therefore, benefits increase as tree canopy cover and leaf surface area increase.

For each of the modeled benefits, an annual resource unit was determined on a per-tree basis. Resource units are measured as kWh of electricity saved per tree; kBtu of natural gas conserved per tree; lbs of atmospheric CO_2 reduced per tree; lbs of NO_2, PM_{10}, and VOCs reduced per tree; ft^3 of stormwater runoff reduced per tree; and ft^2 of leaf area added per tree to increase property values.

Prices were assigned to each resource unit (e.g., heating/cooling energy savings, air-pollution absorption, stormwater-runoff reduction) using economic indicators of society's willingness to pay for the environmental benefits trees provide. Estimates of benefits are initial approximations as some benefits are difficult to quantify (e.g., impacts on psychological health, crime, and violence). In addition, limited knowledge about the physical processes at work and their interactions makes estimates imprecise (e.g., fate of air pollutants trapped by trees and then washed to the ground by rainfall). Therefore, this method of quantification provides first-order approximations. It is meant to be a general accounting of the benefits produced by urban trees—an accounting with an accepted degree of uncertainty that can, nonetheless, provide a science-based platform for decision-making.

Energy Savings

Buildings and paving, along with little tree canopy cover and soil cover, increase the ambient temperatures within a city. Research shows that even in temperate climate zones temperatures in urban centers are steadily increasing by approximately 0.5°F per decade. Winter benefits of this warming do not compensate for the detrimental effects of increased summertime temperatures. Because the electricity demand of cities increases about 1–2% per 1°F increase in temperature, approximately 3–8% of the current electric demand for cooling is used to compensate for this urban heat island effect (Akbari et al. 1992).

Warmer temperatures in cities have other implications. Increases in CO_2 emissions from fossil-fuel power plants, increased municipal water demand, unhealthy ozone levels, and human discomfort and disease are all symptoms associated with urban heat islands. In Minneapolis, there are opportunities to ameliorate the problems associated with hardscape through strategic tree planting and stewardship of existing trees thereby creating street and park landscapes that reduce storm water runoff, conserve energy and water, sequester CO_2, attract wildlife, and provide other aesthetic, social, and economic benefits.

For individual buildings, street trees can increase energy efficiency in summer and increase or decrease energy efficiency in winter, depending on their location. During the summer, the sun is low in the eastern and western sky for several hours each day. Tree shade to protect east—and especially west—walls helps keep buildings cool. In the winter, allowing the sun to strike the southern side of buildings can warm interior spaces.

Trees reduce air movement into buildings and conductive heat loss from buildings. The rates at which outside air moves into a building can increase substantially with wind speed. In cold, windy weather, the entire volume of air, even in newer or tightly sealed homes, may change every 2–3 hours. Trees can reduce wind speed and resulting air infiltration by up to 50%, translating into potential annual heating savings of 25% (Heisler 1986). Decreasing wind speed reduces heat transfer through conductive materials as well. Cool winter winds, blowing against single-pane windows, can contribute significantly to the heating load of homes and buildings

Calculating Electricity and Natural Gas Benefits

Calculations of annual building energy use per residential unit (unit energy consumption [UEC]) were based on computer simulations that incorporated building, climate, and shading effects, following methods outlined by McPherson and Simpson (1999). Changes in UECs due to the effects of trees (ΔUECs) were calculated on a per-tree basis by comparing results before and after adding trees. Building characteristics (e.g., cooling and heating equipment saturations, floor area, number of stories, insulation, window area, etc.) are differentiated by a building's vintage, or age of construction: pre-1950, 1950–1980, and post-1980. For example, all houses from 1950–1980 vintage are assumed to have the same floor area, and other construction characteristics. Shading effects for each of the 21 tree species were simulated at three tree-to-building distances, for eight orientations and for nine tree sizes.

The shading coefficients of the trees in leaf (gaps in the crown as a percentage of total crown silhouette) were estimated using a photographic method that has been shown to produce good estimates (Wilkinson 1991). Crown areas were obtained using the method of Peper and McPherson (2003) from digital photographs of trees from which background features were digitally removed. Values for tree species that were not sampled, and leaf-off values for use in calculating winter shade, were based on published values where available (McPherson 1984; Hammond et al. 1980). Where published values were not available, visual densities were assigned based on taxonomic considerations (trees of the same genus were assigned the same value) or observed similarity to known species. Foliation periods for deciduous trees were obtained from the literature (McPherson 1984; Hammond et al. 1980) and adjusted for Minneapolis's climate based on consultation with forestry supervisors.

Average energy savings per tree were calculated as a function of distance and direction using tree location distribution data specific to Minneapolis (i.e. frequency of trees located at different distances from buildings [setbacks] and tree orientation with respect to buildings). Setbacks were assigned to four distance classes: 0–20 ft, 20–40 ft, 40–60 ft and >60 ft. It was assumed that street trees within 60 ft of buildings provided direct shade on walls and windows. Savings per tree at each location were multiplied by tree distribution to determine location-weighted savings per tree for each species and DBH class, independent of location. Location-weighted savings per tree were multiplied by number of trees of each species and DBH class and then summed to find total savings for the city. Tree locations were based on the stratified random sample conducted in summer 2003.

Land use (single-family residential, multifamily residential, commercial/industrial, other) for right-of-way trees was based on the same tree sample. Park trees were distributed according to the predominant land use surrounding each park. A constant tree distribution was used for all land uses.

Three prototype buildings were used in the simulations to represent pre-1950, 1950–1980, and post-1980 construction practices for Minneapolis (North Central region) (Ritschard et al. 1992). Building footprints were modeled as square, which was found to be reflective of average impacts for a large number of buildings (Simpson 2002). Buildings were simulated with 1.5-ft overhangs. Blinds had a visual density of 37%, and were assumed to be closed when the air conditioner was operating. Summer and winter thermostat settings were 78°F and 68°F during the day, respectively, and 60°F at night. Unit energy consumptions were adjusted to account for equipment saturations (percentage of structures with different types of heating and cooling equipment such as central air conditioners, room air conditioners, and evaporative coolers) (*Table B-1*).

Weather data for a typical meteorological year (TMY2) from Minneapolis were used (Marion and Urban 1995). Dollar values for energy savings were based on electricity and natural gas prices of \$0.066/kWh and \$0.098/therm (Xcelenergy 2004 and Centerpoint Energy 2004).

Single-Family Residence Adjustments

Unit energy consumptions for simulated single-family residences were adjusted for type and saturation of heating and cooling equipment, and for various factors (F) that modified the effects of shade and climate on heating and cooling loads:

$$\Delta UEC_x = \Delta UEC^{sh}_{SFD} \times F^{sh} + \Delta UEC^{cl}_{SFD} \times F^{cl} \qquad \text{Equation 8}$$

where

$$F^{sh} = F_{equipment} \times APSF \times F_{adjacent\ shade} \times F_{multiple\ tree}$$

$$F^{cl} = F_{equipment} \times PCF$$

$$F_{equipment} = Sat_{CAC} + Sat_{window} \times 0.25 + Sat_{evap} \times (0.33 \text{ for cooling and } 1.0 \text{ for heating}).$$

Changes in energy use for higher density residential and commercial structures were calculated from single-family residential results adjusted by average potential shade factors (APSF) and potential climate factors (PCF); values were set to 1.0 for single family residential buildings.

Subscript *x* refers to residential structures with 1, 2–4 or ≥5 units, *SFD* to simulated single-family detached structures, *sh* to shade, and *cl* to climate effects.

Total change in energy use for a particular land use was found by multiplying the change in UEC per tree by the number of trees (N):

$$\text{Total change} = N \times \Delta UEC_x \qquad \text{Equation 9}$$

Estimated shade savings for all residential structures were adjusted to account for shading of neighboring buildings and for overlapping shade from trees adjacent to one another. Homes adjacent to those with shade trees may benefit from the trees on the neighboring properties. For example, 23% of the trees planted for the Sacramento Shade program shaded neighboring homes, resulting in an additional estimated energy savings equal to 15% of that found for program participants; this value was used here ($F_{adjacent\ shade}$ = 1.15). In addition, shade from multiple trees may overlap, resulting in less building shade from an added tree than would result if there were no existing trees. Simpson (2002) estimated that the fractional reductions in average cooling and heating energy use were approximately 6% and 5% percent per tree, respectively, for each tree added after the first. Simpson (1998) also found an average of 2.5–3.4 existing trees per residence in Sacramento. A multiple tree reduction factor of 85% was used here, equivalent to approximately three existing trees per residence.

In addition to localized shade effects, which were assumed to accrue only to street trees within 18–60 ft of buildings, lowered air temperatures and wind speeds due to neighborhood tree cover (referred to as climate effects) produce a net decrease in demand for summer cooling and winter heating. Reduced wind speeds by themselves may increase or decrease cooling demand, depending on the circumstances. To estimate climate effects on energy use, air-temperature and wind-speed reductions as a function of neighborhood canopy cover were estimated from published values following McPherson and Simpson (1999), then used as input for the building-energy-use simulations described earlier. Peak summer air temperatures were assumed to be reduced by 0.4°F for each percentage increase in canopy cover. Wind speed reductions were based on the change in total tree plus building canopy cover resulting from the addition of the particular tree being simulated (Heisler 1990). A lot size of 10,000 ft^2 was assumed.

Cooling and heating effects were reduced based on the type and saturation of air conditioning (*Table B-1*) or heating (*Table B-2*) equipment by vintage. Equipment factors of 33 and 25% were assigned to homes with evaporative coolers and room air conditioners, respectively. These factors were combined with equipment saturations to account for reduced energy use and savings compared to those simulated for homes with central air conditioning ($F_{equipment}$). Building vintage distribution was combined with adjusted saturations to compute combined vintage/saturation factors for air conditioning (*Table B-3*). Heating loads were converted to fuel use based on efficiencies in *Table B-2*. The “other” and “fuel oil” heating equipment types were assumed to be natural gas for the purpose of this analysis. Building vintage distributions were combined with adjusted saturations to compute combined vintage/saturation factors for natural gas and electric heating (*Table B-3*).

Multi-Family Residence Analysis

Unit energy consumptions (UECs) from single-family residential UECs were adjusted for multi-family residences (MFRs) to account for reduced shade resulting from common walls and multi-story construction. To do this, potential shade factors (PSFs) were calculated as ratios of exposed wall or roof (ceiling) surface area to total surface area, where total surface area includes common walls and ceilings between attached units in addition to exposed surfaces (Simpson 1998). A PSF of 1 indicates that all exterior walls and roofs are exposed and could be shaded by a tree, while a PSF of 0 indicates that no shading is possible (i.e., the common wall between duplex units). Potential shade factors were estimated separately for walls and roofs for both single- and multi-story structures. Average potential shade factors were 0.74 for multi-family residences of 2–4 units and 0.41 for ≥5 units.

Unit energy consumptions were also adjusted to account for the reduced sensitivity of multi-family buildings with common walls to outdoor temperature changes. Since estimates for these PCFs were unavailable for multi-family structures, a multi-family PCF value of 0.80 was selected (less than single-family detached PCF of 1.0 and greater than small commercial PCF of 0.40; see next section).

Commercial and Other Buildings

Reductions in unit energy consumptions for commercial/industrial (C/I) and industrial/transportation (I/T) land uses due to presence of trees were determined in a manner similar to that used for multi-family land uses. Potential shade factors of 0.40 were assumed for small C/I, and 0.0 for large C/I. No energy impacts were ascribed to large C/I structures since they are expected to have surface-to-volume ratios an order of magnitude larger than smaller buildings and less extensive window area. Average potential shade factors for I/T structures were estimated to lie between these extremes; a value of 0.15 was used here. However, data relating I/T land use to building-space conditioning were not readily available, so no energy impacts were ascribed to I/T structures. A multiple tree reduction factor of 0.85 was used, and no benefit was assigned for shading of buildings on adjacent lots.

Potential climate-effect factors of 0.40, 0.25 and 0.20 were used for small C/I, large C/I and I/T, respectively. These values are based on estimates by Akbari (1992)

Table B1—*Saturation adjustments for cooling (%).*

	Single family detached			Mobile homes			Single-family attached			Multi-family 2-4 units			Multi-family 5+ units			Commercial/ industrial		Institutional/ Transportation
	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	Small	Large	
Cooling equipment factors																		
Central air/ heat pump	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Evaporative cooler	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33
Wall/window unit	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
None	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cooling saturations																		
Central air/ heat pump	14	63	76	14	63	76	14	63	76	14	63	76	14	63	76	86	86	86
Evaporative cooler	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wall/window unit	59	23	5	59	23	5	59	23	5	59	23	5	59	23	5	9	9	9
None	27	14	19	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5
Adjusted cooling saturation	28	69	77	28	69	77	28	69	77	28	69	77	28	69	80	88	88	88

Table B2—Saturation adjustments for heating (%, except AFUE [fraction] and HSPF [kBtu/kWh).

	Single family detached			Mobile homes			Single-family attached			Multi-family 2-4 units			Multi-family 5+ units			Commercial/ industrial		Institutional/ Transportation
	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	Small	Large	
Equipment efficiencies																		
AFUE	0.75	0.78	0.78	0.75	0.78	0.78	0.75	0.78	0.78	0.75	0.78	0.78	0.75	0.78	0.78	0.78	0.78	0.78
HSPF	6.8	6.8	8	6.8	6.8	8	6.8	6.8	8	6.8	6.8	8	6.8	8	8	8	8	8
HSPF	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412	3.412
Electric heat saturations																		
Electric resistance	6.7	6.0	8.9	6.7	6.0	8.9	6.7	6.0	8.9	6.7	6.0	8.9	6.7	6.0	8.9	4.9	4.9	4.9
Heat pump	11.5	13.3	19.7	11.5	13.3	19.7	11.5	13.3	19.7	11.5	13.3	19.7	11.5	13.3	19.7	5.4	5.4	5.4
Adjusted electric heat saturations	3.3	3.7	5.4	3.3	3.7	5.4	3.3	3.7	5.4	3.3	3.7	5.4	3.3	3.7	5.4	1.7	1.7	1.7
Natural gas and other heating saturations																		
Natural gas	72.7	61.3	52.4	72.7	61.3	52.4	72.7	61.3	52.4	72.7	61.3	52.4	72.7	61.3	52.4	89.7	89.7	89.7
Oil	0.0	1.6	2.4	0.0	1.6	2.4	0.0	1.6	2.4	0.0	1.6	2.4	0.0	1.6	2.4	0.0	0.0	0.0
Other	9.1	17.7	16.7	9.1	17.7	16.7	9.1	17.7	16.7	9.1	17.7	16.7	9.1	17.7	16.7	0.0	0.0	0.0
NG heat saturations	82	81	71	82	81	71	82	81	71	82	81	71	82	81	71	90	90	90

Table B3—Building vintage distribution and combined vintage/saturation factors for heating and air conditioning.

	Single family detached			Mobile homes			Single-family attached			Multi-family 2-4 units			Multi-family 5+ units			Commercial/ industrial		Institutional/ Transportation
	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	pre-1950	1950-1980	post-1980	Small	Large	
Vintage distribution by building type	62	30	9	62	30	9	32	30	9	62	30	9	62	30	9	100	100	100
Tree distribution by vintage and building type	45.2	21.7	6.39	0.19	0.09	3.25	1.56	0.46	1.77	1.77	0.85	0.25	3.92	1.88	0.55	2.1	1.2	8.6
Combined vintage, equipment saturation factors for cooling																		
Cooling factor: shade	12.6	15.0	4.83	0.05	0.06	0.02	0.79	0.93	0.31	0.36	0.42	0.14	0.45	0.52	0.17	0.6	1.1	0.0
Cooling factor: climate	12.8	14.6	4.94	0.05	0.06	0.02	0.75	0.87	0.29	0.23	0.26	0.09	0.51	0.60	0.20	0.6	1.1	0.0
Combined vintage, equipment saturation for heating																		
Heating factor, natural gas: shade	36.2	17.7	4.46	0.15	0.07	0.02	2.29	1.08	0.28	1.05	0.49	0.13	1.29	0.61	0.16	0.6	0.2	0.0
Heating factor, electric: shade	1.4	0.8	0.33	0.01	0.0	0.0	0.09	0.05	0.02	0.04	0.02	0.01	0.05	0.03	0.01	0.01	0.0	0.0
Heating factor, natural gas: climate	37.0	17.5	4.56	0.08	0.04	0.01	2.54	1.20	0.31	0.62	0.29	0.08	1.56	0.74	0.19	2.2	4.4	0.0
Heating factor, electric: climate	1.5	0.8	0.34	0.0	0.0	0.0	0.10	0.06	0.02	0.02	0.01	0.01	0.06	0.03	0.01	0.04	0.08	0.0

and others who observed that commercial buildings are less sensitive to outdoor temperatures than houses.

The beneficial effects of shade on UECs tend to increase with conditioned floor area (CFA) for typical residential structures. As building surface area increases so does the area shaded. This occurs up to a certain point because the projected crown area of a mature tree (approximately 700–3,500 ft^2) is often larger than the building surface areas being shaded. As surface area increases, however, a point is reached at which no additional area is shaded. At this point, ΔUECs will tend to level off as CFA increases. Since information on the precise relationships between change in UEC, CFA, and tree size is not available, it was conservatively assumed that ΔUECs in Equation 8 did not change for C/I and I/T land uses.

Atmospheric Carbon Dioxide Reduction

Sequestration of CO_2 (the net storage rate in above- and below-ground biomass over the course of one growing season) is calculated for each species using the tree-growth equations for DBH and height, described above, to calculate either tree volume or biomass. Equations from Pillsbury et. al (1998) are used when calculating volume. Fresh weight (kg/m^3) and specific gravity ratios from Alden (1995, 1997) are then applied to convert volume to biomass. When volumetric equations for urban trees are unavailable, biomass equations derived from data collected in rural forests are applied (Tritton and Hornbeck 1982; Ter-Mikaelian and Korzukhin 1997).

Carbon dioxide released through decomposition of dead woody biomass varies with characteristics of the wood itself, the fate of the wood (e.g., amount left standing, chipped, or burned), and local soil and climatic conditions. Recycling of urban waste is now prevalent, and we assume here that most material is chipped and applied as landscape mulch. Calculations were conservative because they assumed that dead trees are removed and mulched in the year that death occurs, and that 80% of their stored carbon is released to the atmosphere as CO_2 in the same year. Total annual decomposition is based on the number of trees in each species and age class that die in a given year and their biomass. Tree survival rate is the principal factor influencing decomposition. Tree mortality for Minneapolis was 1.0% per year for the first five years after planting and 0.6% every year thereafter (Sievert and Hermann 2004). Finally, CO_2 released during tree maintenance was estimated to be 0.13 lb CO_2/cm DBH based on annual fuel consumption of gasoline (2,851 gal) and diesel fuel (15,702 gal) (Sievert and Hermann 2004).

Calculating Avoided CO_2 Emissions

Reducing building energy use reduces emissions of CO_2. Emissions were calculated as the product of energy use and CO_2 emission factors for electricity and heating. Heating fuel is largely natural gas and electricity in Minneapolis. The fuel mix for electrical generation included natural gas (2.6%), hydroelectric (1.9%), nuclear (26.1%), coal (65%), and other (4.6%) (U.S. EPA 2003).

Emissions factors for electricity (lb/MWh) and natural gas (lb/MBtu) fuel mixes are given in *Table B-4*. The monetary value of avoided CO_2 was \$0.0075/lb based on average high and low estimates for emerging carbon trading markets (CO2e.com 2002) (*Table B-4*).

Table B-4*—Emissions factor and monetary values for CO_2 and criteria air pollutants.*

Pollutant	Emission Factor		Implied value ($/lb)[c]
	Electricity (lb/MWh)[a]	Natural gas (lb/MBtu)[b]	
CO_2	1,677.0	118.0	0.008
NO_2	3.911	0.1020	3.34
SO_2	4.966	0.0006	2.06
PM_{10}	0.666	0.0075	2.84
VOCs	0.657	0.0054	3.75

[a]USEPA, eGRID 2002, except Ottinger. et al. 1990 for VOCs

[b]USEPA 1998

[c]CO2 from CO2e.com (2001). Other values based on the methods of Wang and Santini (1995) using emissions concentrations from USEPA (2004) and population estimates from the Metropolitan Council (2004)

Improving Air Quality

Calculating Other Avoided Emissions

Reductions in building energy use also result in reduced emissions of criteria air pollutants (those for which a national standard has been set by the EPA) from power plants and space-heating equipment. This analysis considered volatile organic hydrocarbons (VOCs) and nitrogen dioxide (NO_2)—both precursors of ozone (O_3) formation—as well as sulfur dioxide (SO_2) and particulate matter of <10 micron diameter (PM_{10}). Changes in average annual emissions and their monetary values were calculated in the same way as for CO_2, again using utility-specific emission factors for electricity and heating fuels (U.S. EPA 2003). The price of emissions savings were derived from models that calculate the marginal cost of controlling different pollutants to meet air quality standards (Wang and Santini 1995). Emissions concentrations were obtained from U.S. EPA (2004) (*Table B-4*), and population estimates from the Metropolitan Council (2004) (*Table B-4*).

Calculating Deposition and Interception

Trees also remove pollutants from the atmosphere. The hourly pollutant dry deposition per tree is expressed as the product of the deposition velocity $V_d = 1/(R_a + R_b + R_c)$, pollutant concentration (C), canopy projection (CP) area, and time step. Hourly deposition velocities for each pollutant were calculated using estimates for the resistances R_a, R_b, and R_c estimated for each hour over a year using formulations described by Scott et al. (1998). Hourly concentrations for NO_2, SO_2 , O_3 and PM_{10} and hourly meteorological data (i.e., air temperature, wind speed, solar radiation) for Minneapolis and the surrounding area for 2003 were obtained from the Minnesota Pollution Control Agency and the University of Minnesota, respectively. The year 2003 was chosen because data were available and because 2003 closely approximated long-term, regional climate records.

For deciduous species, deposition was determined only when trees were in-leaf. A 50% re-suspension rate was applied to PM_{10} deposition. Methods described in the section Methodology for Calculating Avoided Emissions were used to value emissions reductions; NO_2 prices were used for ozone since ozone-control measures typically aim at reducing NO_2.

Calculating BVOC Emissions

Emissions of biogenic volatile organic carbon (sometimes called biogenic hydrocarbons or BVOCs) associated with increased ozone formation were estimated for the tree canopy using methods described by McPherson et al. (1998). In this approach, the hourly emissions of carbon in the form of isoprene and monoterpene are expressed as products of base emission factors and leaf biomass factors adjusted for sunlight and temperature (isoprene) or simply temperature (monoterpene). Annual dry foliar biomass was derived from field data collected in Minneapolis, MN, during the summer of 2004. The amount of foliar biomass present for each year of the simulated tree's life was unique for each species. Hourly air temperature and solar radiation data for 2003 described in the pollutant uptake section were used as model inputs.

Hourly emissions were summed to get annual totals. This is a conservative approach, since the benefits associated with lowered summertime air temperatures and the resulting reduced hydrocarbon emissions from biogenic as well as anthropogenic sources were not accounted for. The cost of these emissions is based on control cost estimates and was valued at \$0.657/lb for Minneapolis (*Table B-4*).

Reducing Stormwater Runoff

Calculating Stormwater Runoff Reductions

A numerical simulation model was used to estimate annual rainfall interception (Xiao et al. 1998). The interception model accounts for water intercepted by the tree, as well as throughfall and stem flow. Intercepted water is stored on canopy leaf and bark surfaces. Once the storage capacity of the tree canopy is exceeded, rainwater temporarily stored on the tree surface will drip from the leaf surface and flow down the stem surface to the ground. Some of the stored water will evaporate. Tree canopy parameters related to stormwater-runoff reductions include species, leaf and stem surface area, shade coefficient (visual density of the crown), tree height, and foliation period. Wind speeds were estimated for different heights above the ground; from this, rates of evaporation were estimated.

The volume of water stored in the tree crown was calculated from crown-projection area (area under tree dripline), leaf area indices (LAI, the ratio of leaf surface area to crown projection area), and the depth of water captured by the canopy surface. Species-specific shading coefficient, foliation period, and tree surface saturation storage capacity influence the amount of projected throughfall. Tree surface saturation was 0.04 inches for all three trees. Hourly meteorological and rainfall data for 2003 from the Minnesota Meteorological Network (MNMET) (station: St. Paul Campus Climatological Observatory, MN; latitude 44°56′52″N, longitude 93°06′13″W) were used for this simulation. Annual precipitation during 2003 was 24.5 inches (623.3 mm), close to the recent 30-year-average annual precipitation of 28.4 inches (721.6 mm). Storm events less than 0.1 inches (2.5 mm) were assumed not to produce runoff and were dropped from the analysis. More complete descriptions of the interception model can be found in Xiao et al. (1998, 2000).

Minneapolis has constructed a number of holding ponds for stormwater retention/detention. Land acquisition costs for a typical 5-acre pond are approximately \$3 million and construction costs are \$3.3 million (Profaizer 2004). Ponds can be as deep as 20 ft and be wet or dry. The annual cost for operation and maintenance, including snow removal, is \$3,000. Assuming a 20-year life before dredging and reconstruction, the total life-cycle cost is \$6.36 million. A pond of this size will store 9 ac-ft of runoff and fill approximately four times over the course of a year. The annual cost of storage in the holding pond is \$0.027/gal. This price is greater than the average price for stormwater runoff reduction (\$0.01/

gallon) assessed in similar studies due primarily to the relatively high cost of land acquisition within this urban center (McPherson and Xiao 2004).

Property Value & Other Benefits

Trees provide a host of aesthetic, social, economic, and health benefits that should be included in any benefit–cost analysis. One of the most frequently cited reasons for planting trees is beautification. Trees add color, texture, line, and form to the landscape softening the hard geometry that dominates built environments. Research on the aesthetic quality of residential streets has shown that street trees are the single strongest positive influence on scenic quality (Schroeder and Cannon 1983). Consumer surveys have shown that preference ratings increase with the presence of trees in a commercial streetscape. In contrast to areas without trees, shoppers indicated that they shopped more often and longer in well-landscaped business districts, and were willing to pay more for goods and services (Wolf 1999). Research in public-housing complexes found that outdoor spaces with trees were used significantly more often than spaces without trees. By facilitating interactions among residents, trees can contribute to reduced levels of violence, as well as foster safer and more sociable neighborhood environments (Sullivan and Kuo 1996).

Well-maintained trees increase the “curb appeal” of properties. Research comparing sales prices of residential properties with different numbers and sizes of trees suggests that people are willing to pay 3–7% more for properties with ample trees versus few or no trees. One of the most comprehensive studies on the influence of trees on residential property values was based on actual sales prices and found that each large front-yard tree was associated with about a 1% increase in sales price (Anderson and Cordell 1988). Depending on average home sale prices, the value of this benefit can contribute significantly to cities’ property tax revenues.

Scientific studies confirm our intuition that trees in cities provide social and psychological benefits. Humans derive substantial pleasure from trees, whether it is inspiration from their beauty, a spiritual connection, or a sense of meaning (Dwyer et al. 1992; Lewis 1996). Following natural disasters, people often report a sense of loss if the urban forest in their community has been damaged (Hull 1992). Views of trees and nature from homes and offices provide restorative experiences that ease mental fatigue and help people to concentrate (Kaplan and Kaplan 1989). Desk-workers with a view of nature report lower rates of sickness and greater satisfaction with their jobs compared to those having no visual connection to nature (Kaplan 1992). Trees provide important settings for recreation and relaxation in and near cities. The act of planting trees can have social value, for community bonds between people and local groups often result.

The presence of trees in cities provides public health benefits and improves the well being of those who live, work and play in cities. Physical and emotional stress has both short-term and long-term effects. Prolonged stress can compromise the human immune system. A series of studies on human stress caused by general urban conditions and city driving showed that views of nature reduce the stress response of both body and mind (Parsons et al. 1998). City nature also appears to have an “immunization effect,” in that people show less stress response if they have had a recent view of trees and vegetation. Hospitalized patients with views of nature and time spent outdoors need less medication, sleep better, have a better outlook, and recover more quickly than patients without connections to nature (Ulrich 1985). Trees reduce exposure to ultraviolet light, thereby lowering the risk of harmful effects from skin cancer and cataracts (Tretheway and Manthe 1999).

Certain environmental benefits from trees are more difficult to quantify than those previously described, but can be just as important. Noise can reach unhealthy levels in cities. Trucks, trains, and planes can produce noise that exceeds 100 decibels, twice the level at which noise becomes a health risk. Thick strips of vegetation in conjunction with landforms or solid barriers can reduce highway noise by 6-15 decibels. Plants absorb more high frequency noise than low frequency, which is advantageous to humans since higher frequencies are most distressing to people (Miller 1997).

Urban forests can be oases, sometimes containing more biological diversity than rural woodlands. Numerous types of wildlife inhabit cities and are generally highly valued by residents. For example, older parks, cemeteries, and botanical gardens often contain a rich assemblage of wildlife. Street-tree corridors can connect a city to surrounding wetlands, parks, and other greenspace resources that provide habitats that conserve biodiversity (Platt et al. 1994).

Urban and community forestry can provide jobs for both skilled and unskilled labor. Public service programs and grassroots-led urban and community forestry programs provide horticultural training to volunteers across the U.S. Also, urban and community forestry provides educational opportunities for residents who want to learn about nature through first-hand experience (McPherson and Mathis 1999). Local nonprofit tree groups, along with municipal volunteer programs, often provide educational materials, work with area schools, and offer hands-on training in the care of trees.

Calculating Changes in Property Values and Other Benefits

In an Athens, GA, study (Anderson and Cordell 1988), a large front-yard tree was found to be associated with an 0.88% increase in average home resale values. In our study, the annual increase in leaf surface area of a typical mature large tree (40-year-old green ash, average leaf surface area 7,930 ft^2) was the basis for valuing the capacity of trees to increase property value.

Assuming the 0.88% increase in property value held true for the City of Minneapolis, each large tree would be worth $1,918 based on the 2004 average single-family-home resale price in Minneapolis ($218,000) (CNN 2004). However, not all trees are as effective as front-yard trees in increasing property values. For example, trees adjacent to multifamily housing units will not increase the property value by the same amount as trees in front of single-family homes. Therefore, a citywide street tree reduction factor (0.923) was applied to prorate trees' value based on the assumption that trees adjacent to different land-uses make different contributions to property sales prices. For this analysis, the street reduction factor reflects the distribution of street trees in Minneapolis by land-use. Reductions factors were single-home residential (100%), multi-home residential (75%), commercial/industrial (50%), vacant (25%), park (50%) and institutional (50%) (McPherson et al. 2001).

Given these assumptions, a typical large street tree was estimated to increase property values by $0.22/$ft^2$ of LSA. For example, it was estimated that a single, street-side red oak added about 100 ft^2 of LSA per year when growing in the DBH range of 12–18 in. Therefore, during this period of growth, red oak trees effectively added $22.33, annually, to the value of an adjacent home, condominium, or business property (100 ft^2 x $0.22/$ft^2$ = $22.32).

Estimating Magnitude Of Benefits

Resource units describe the absolute value of the benefits of Minneapolis's street trees on a per-tree basis. They include kWh of electricity saved per tree, kBtu of natural gas conserved per tree, lbs of atmospheric CO_2 reduced per tree, lbs of NO_2, PM_{10}, and VOCs reduced per tree, ft^3 of stormwater runoff reduced per tree, and ft^2 of leaf area added per tree to increase property values. A dollar value was assigned to each resource unit based on local costs.

Estimating the magnitude of the resource units produced by all street and park trees in Minneapolis required four procedures: (1) categorizing street trees by species and DBH based on the city's street-tree inventory, (2) matching other significant species with those that were modeled, (3) grouping remaining "other" trees by type, and (4) applying resource units to each tree.

Categorizing Trees by DBH Class

The first step in accomplishing this task involved categorizing the total number of street trees by relative age (as a function of DBH class). The inventory was used to group trees into the following classes:

1) 0–3 inches
2) 3–6 inches
3) 6–12 inches
4) 12–18 inches
5) 18–24 inches
6) 24–30 inches
7) 30–36 inches
8) 36–42 inches
9) >42 inches

Next, the median value for each DBH class was determined and subsequently used as a single value to represent all trees in each class. For each DBH value and species, resource units were estimated using linear interpolation.

Applying Resource Units to Each Tree

The interpolated resource-unit values were used to calculate the total magnitude of benefits for each DBH class and species. For example, there were 139 American elms citywide in the 30–36 inch DBH class. The interpolated electricity and natural gas resource unit values for the class midpoint (33 inches) were 348 kWh and 578.1 kBtu per tree, respectively. Therefore, multiplying the resource units for the class by 139 trees equals the magnitude of annual heating and cooling benefits produced by this segment of the population: 54,984 kWh of electricity saved and 91,340 kBtu of natural gas saved.

Matching Significant Species with Modeled Species

To extrapolate from the 17 municipal species modeled for growth to the entire inventoried tree population, each species representing over 1% of the population was matched with the modeled species that it most closely resembled. Less abundant species were then grouped into the "Other" categories described below.

Grouping Remaining "Other" Trees by Type

Species that were represented than 1% of the population were labeled "other" and were categorized into classes based on tree type (one of two life forms and three mature sizes):

- Broadleaf deciduous: large (BDL), medium

(BDM), and small (BDS).

- Coniferous evergreen: large (CEL), medium (CEM), and small (CES).

Large, medium, and small trees were >40 ft, 25–40 ft, and <25 ft in mature height, respectively. A typical tree was chosen to represent each of the above six categories to obtain growth curves for "other" trees falling into each of the categories:

BDL Other = Green ash (*Fraxinus pennsylvanica*)

BDM Other = Norway maple (*Acer platanoides*)

BDS Other = Crabapple (*Malus* spp.)

CEL Other = Ponderosa pine (*Pinus ponderosa*)

CEM Other = Austrian pine (*Pinus nigra*)

CES Other = Bolleana shore pine (*Pinus contorta*)

When local data did not exist for specific categories (CEL and CES), growth data were used from similar-sized species in a different region.

Calculating Net Benefits And Benefit–Cost Ratio

It is impossible to quantify all the benefits and costs produced by trees. For example, owners of property with large street trees can receive benefits from increased property values, but they may also benefit directly from improved health (e.g., reduced exposure to cancer-causing UV radiation) and greater psychological well-being through visual and direct contact with trees. On the cost side, increased health-care costs may be incurred because of nearby trees, due to allergies and respiratory ailments related to pollen. The values of many of these benefits and costs are difficult to determine. We assume that some of these intangible benefits and costs are reflected in what we term "property value and other benefits." Other types of benefits we can only describe, such as the social, educational, and employment/training benefits associated with the city's street tree resource. To some extent connecting people with their city trees reduces costs for health care, welfare, crime prevention, and other social service programs.

Minneapolis residents can obtain additional economic benefits from street trees depending on tree location and condition. For example, street trees can provide energy savings by lowering wind velocities and subsequent building infiltration, thereby reducing heating costs. This benefit can extend to the neighborhood, as the aggregate effect of many street trees reduces wind speed and reduces citywide winter energy use. Neighborhood property values can be influenced by the extent of tree canopy cover on streets. The community benefits from cleaner air and water. Reductions in atmospheric CO_2 concentrations due to trees can have global benefits.

Net Benefits and Costs Methodology

To assess the total value of annual benefits (*B*) for each park and street tree (*i*) in each management area (*j*), benefits were summed:

$$B = \sum_{1}^{n} j\left(\sum_{1}^{n} i\left(e_{ij} + a_{ij} + c_{ij} + h_{ij} + p_{ij}\right)\right)$$

Equation 10

where

e = price of net annual energy savings = annual natural gas savings + annual electricity savings

a = price of annual net air quality improvement = PM_{10} interception + NO_2 and O_3 absorption + avoided power plant emissions – BVOC emissions

c = price of annual carbon dioxide reductions = CO_2 sequestered – releases + CO_2 avoided from reduced energy use

h = price of annual stormwater runoff reductions = effective rainfall interception

p = price of aesthetics = annual increase in property value

Total net expenditures were calculated based on all identifiable internal and external costs associated with the annual management of municipal trees citywide (Koch 2004). Annual costs for the municipality (*C*) were summed:

$C = p + t + r + d + e + s + c + l + a + q$

p = annual planting expenditure

t = annual pruning expenditure

r = annual tree and stump removal and disposal expenditure

d = annual pest and disease control expenditure

e = annual establishment/irrigation expenditure

s = annual price of repair/mitigation of infrastructure damage

c = annual price of litter/storm clean-up

l = average annual litigation and settlements expenditures due to tree-related claims

a = annual expenditure for program administration

q = annual expenditures for inspection/answer service requests

Total citywide annual net benefits as well as the benefit–cost ratio (BCR) were calculated using the sums of benefits and costs:

Citywide Net Benefits = $B – C$ Equation 11

BCR = $B – C$ Equation 12

References

Akbari, H.; Davis, S.; Dorsano, S.; Huang, J.; Winnett, S., eds. 1992. **Cooling Our Communities: A Guidebook on Tree Planting and Light-Colored Surfacing.** Washington, DC: U.S. Environmental Protection Agency. 26 p.

Alden, H.A. 1995. **Hardwoods of North America**. USDA Forest Service, FPL General Technical Report No. 83. Madison, WI. 136 p.

Alden, H.A. 1997. **Softwoods of North America**. USDA Forest Service, FPL Gen. Techn. Report No. 102. Madison, WI.

Anderson, L.M. and H.K. Cordell. 1988. **Residential property values improve by landscaping with trees.** Southern Journal of Applied Forestry 9:162-166.

Benjamin, M.T. and A.M. Winer. 1998. **Estimating the ozone-forming potential of urban trees and shrubs.** Atmos. Environ. 32: 53-68.

Centerpoint Energy. 2004. Accessed via the World Wide Web <http://mn.centerpointenergy.com/for_your_home/energy_your_home/manage/pricing.asp> on Sept 12, 2004.

Chandler, T.J. 1965. **The Climate of London.** London, Hutchinson.

CIMIS. 2004. Accessed via the World Wide Web <http://wwwcimis.water.ca.gov/cimis/data.jsp> on October 27, 2004.

Clark, J.R., N.P. Matheny, G. Cross and V. Wake. 1997. **A model of urban forest sustainability.** J. Arboric. 23(1):17-30.

CNN. 2004. **Median home sales prices, 2nd quarter, 2004**. Accessed via the World Wide Web <http://money.cnn.com/pf/features/lists/q1housing04/state.html#table> on November 13, 2004.

CO2e.com. 2002. **Market Size and Pricing.** Accessed via the World Wide Web. <http://www.co2e.com/stratagies/AdditionalInfo.asp?PageID=273#1613> on October 23, 2002.

Dwyer, J.F., E.G. McPherson, H.W. Schroeder and R.A. Rowntree. 1992. **Assessing the benefits and costs of the urban forest**. Journal of Arboriculture 18(5):227-234.

Hammond, J. J Zanetto and C. Adams. 1980. **Planning Solar Neighborhoods**. California Energy Commission.

Heisler, G.M. 1986. **Energy savings with trees.** Journal of Arboriculture 12(5):113-125.

Heisler, G. M. 1990. **Mean wind speed below building height in residential neighborhoods with different tree densities.** ASHRAE Transactions 96:1:1389-1396.

Hull, R.B. 1992. **How the public values urban forests**. J. Arboric. 18(2):98-101.

Kaplan, R. 1992. Urban Forestry and the Workplace. In P.H. Gobster (Ed). **Managing Urban and High-Use Recreation Settings.** USDA Forest Service, General Technical Report NC-163. Chicago, IL: North Central Forest Exp. Center.

Kaplan, R. and S. Kaplan. 1989. **The Experience of Nature: A Psychological Perspective**. Cambridge University Press, Cambridge, UK.

Lewis, C.A. 1996. **Green Nature/Human Nature: The Meaning of Plants in Our Lives.** University of Illinois Press, Chicago, IL.

Maco, S.E. and E.G. McPherson. 2002. **Assessing canopy cover over streets and sidewalks in street tree populations.** J. Arboric. 28(6):270-276.

Maco, S.E. and E.G. McPherson. 2003. **A practical approach to assessing structure, function, and value of street tree populations in small communities**. J. Arboric. 29(2):84-97.

Maco, S.E., McPherson, E.G., J.R. Simpson, P.J. Peper, Q. Xiao. 2003. **City of San Francisco California Street Tree Resource Analysis**. Center for Urban Forest Research, USDA Forest Service, Pacific Southwest Research Station, CUFR-3.

Maco, S.E., McPherson, E.G., J.R. Simpson, P.J. Peper, Q. Xiao. 2005. **City of Berkeley, California Street Tree Resource Analysis**. Center for Urban Forest Research, USDA Forest Service, Pacific Southwest Research Station

Marion, W. and K. Urban. 1995. **User's manual for TMY2s - typical meteorological years.** National Renewable Energy Laboratory, 1617 Cole Blvd, Golden, Colorado, 80401.

McPherson, E. G. 1984. Planting design for solar control, chapter 8. In **Energy Conserving Site Design**, Am. Soc. Landscape Archit., Washington, D.C., p.141-164.

McPherson, E.G. 1993. **Evaluating the cost effectiveness of shade trees for demand-side management**. The Electricity Journal 6(9): 57-65.

McPherson, E.G. and S. Mathis (Eds.) 1999. **Proceedings of the Best of the West Summit.** Western Chapter, International Society of Arboriculture, Sacramento, CA. 93 p.

McPherson, E.G. and R.A. Rowntree. 1989. **Using structural measures to compare twenty-two U.S. street tree populations.** Landscape Journal 8:13-23.

McPherson, E.G. and J.R. Simpson. 1999. **Guidelines for Calculating Carbon Dioxide Reductions Trough Urban Forestry Programs**. USDA Forest Service, PSW General Technical Report No. 171, Albany, CA.

McPherson, E.G. and J.R. Simpson. 2002. **A comparison of municipal forest benefits and costs in Modesto and Santa Monica, California, USA**. Urban For. Urban Green. 1(2002):61-74.

McPherson, E.G., J.R. Simpson, P.J. Peper, Q. Xiao, D.R. Pettinger and D.R. Hodel. 2001. **Tree Guidelines for Inland Empire Communities**. Local Government Commission, Sacramento, CA. pp. 115.

McPherson, E.G. and Q. Xiao. 2004. **A Storm Runoff Model for the Trust for Public Land's "What is a Park Worth?" Project.** Center for Urban Forest Research, USDA Forest Service, Pacific Southwest Research Station. 12 pp.

Miller, R.W. 1997. **Urban forestry: planning and managing urban greenspaces**. 2nd. ed. Upper Saddle River, Prentice-Hall. 502 p.

Ottinger, R.L.; Wooley, D.R.; Robinson, N.A.; Hodas, D.R.; Babb, S.E. 1990. **Environmental Costs of Electricity.** Pace University Center for Environmental Legal Studies, Oceana Publications. New York.

Parsons, R., L.G. Tassinary, R.S. Ulrich, M.R. Hebl and M. Grossman-Alexander. 1998. **The view from the road: implications for stress recovery and immunization**. Journal of Environmental Psychology 18(2):113-140.

Peper, P.J. and E.G. McPherson. 2003. **Evaluation of four methods for estimating leaf area of isolated trees.** Urban Forestry and Urban Greening 2:19-30.

Pillsbury, N.H., Reimer, J.L., Thompson R.P. 1998. T**ree Volume Equations for Fifteen Urban Species in California**. Tech. Rpt. 7. Urban Forest Ecosystems Institute, California Polytechnic State University, San Luis Obispo, CA. 56 p.

Platt, R.H., R.A Rowntree and P.C. Muick, eds. 1994. **The Ecological City**. Boston, MA, University of Mass. 292 p.

Profaizer, R. 2004. Personal communication on December 9, 2004. Construction and Maintenance Manager, Sewer Dept., City of Minneapolis

Richards, N.A. 1982/83. **Diversity and stability in a street tree population**. Urban Ecology 7: 159-171.

Ritschard, R.L., J.W. Hanford and A.O. Sezgen. 1992. **Single-family heating and cooling requirements: assumptions, methods, and summary results.** Publication GRI-91/0236. Chicago: Gas Research Institute. 97 p.

Schroeder, H.W. and W.N. Cannon. 1983. **The esthetic contribution of trees to residential streets in Ohio towns**. Journal of Arboriculture. 9: 237-243.

Scott, K.I., E.G. McPherson, and J.R. Simpson. 1998. **Air pollutant uptake by Sacramento's urban forest.** Journal of Arboriculture 24(4):224-234.

Sievert, R. and J. Hermann. 2004. Personal communication on September 23, 2004. Director of Forestry and Forestry Section Manager, Minneapolis Parks and Recreations Board.

Simpson, J.R. 1998. **Urban forest impacts on regional space conditioning energy use: Sacramento County case study**. Journal of Arboriculture 24(4): 201-214.

Simpson, J.R. 2002. **Improved estimates of tree shade effects on residential energy use**. Energy and Buildings 34(10): 173-182.

Sullivan, W.C. and E.E. Kuo. 1996. **Do trees strengthen urban communities, reduce domestic violence?** Arborist News. 5(2):33-34.

Ter-Mikaelian, M.T. and M.D. Korzukhin. 1997. **Biomass equations for sixty-five North American tree species.** For. Ecol and Management 97: 1-24.

Thompson, R.P. and J.J. Ahern. 2000. **The State of Urban and Community Forestry in California: Status in 1997 and Trends since 1988**. California Dept. of Forestry and Fire Protection, Technical Report No. 9. Urban Forest Ecosystems Institute, Cal Poly State University, San Luis Obispo, CA. pp. 48.

Tretheway, R. and A. Manthe. 1999. Skin cancer prevention: another good reason to plant trees. In McPherson, E.G. and Mathis, S. **Proceedings of the Best of the West Summit**. University of California, Davis, CA.

Tritton, L.M. and J.W. Hornbeck. 1982. **Biomass Equations for Major Tree Species of the Northeast.** USDA Forest Service, NE General Technical Report No. 69. Broomall, PA. 46 p.

U.S. Environmental Protection Agency. 2003. **E-GRID** (E-GRID2002 Edition).

U.S. Environmental Protection Agency. 2004. **Monitor Values Report for Anoka and Hennepin Co, MN.** Accessed via the World Wide Web <http://www.epa.gov/air/data/reports.html> on Sept 12, 2004.

Ulrich, R. S. 1985. **Human responses to vegetation and landscapes.** Landscape and Urban Planning 13: 29-44.

Wang, M.Q.; Santini, D.J. 1995. **Monetary values of air pollutant emissions in various U.S. regions.** Transportation Research Record 1475.

Wilkinson, D. 1991. **Can photographic methods be used for measuring the light attenuation characteristics of trees in leaf?** Landscape and Urban Planning 20:347-349.

Wolf, K.L. 1999. Nature and commerce: human ecology in business districts. In C. Kollin (Ed), **Building Cities of Green: Proceedings of the 1999 National Urban Forest Conference**. Washington, D.C. American Forests, pp 56-59.

Xcelenergy. 2004. **Minnesota Electric Rate Book - MPUC No. 2.** Accessed via the World Wide Web <http://www.xcelenergy.com/docs/corpcomm/Me_Section_5.pdf> on Sept 12, 2004.

Xiao, Q., E.G. McPherson, J.R. Simpson and S.L Ustin. 1998. **Rainfall interception by Sacramento's urban forest.** Journal of Arboriculture 24(4):235-244.

Xiao, Q., McPherson, E.G., Simpson, J.R., and S.L. Ustin. 2000. **Winter rainfall interception by two mature open grown trees in Davis, California**. Hydrological Processes 14(4):763-784.

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