City of Boulder, Colorado Municipal Tree Resource Analysis

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Technical Report to:
Ellie Bussi-Sottile
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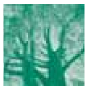
Parks and Recreation Department
City of Boulder, CO

—September 2005—

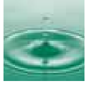
Center for
Urban Forest Research

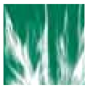
Areas of Research:


Investment Value


Energy Conservation


Air Quality


Water Quality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Mission Statement

We conduct **research** that demonstrates new ways in which **trees add value** to your community, converting results into **financial** terms to assist you in stimulating more **investment in trees.**

CITY OF BOULDER, COLORADO
MUNICIPAL TREE RESOURCE ANALYSIS

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The 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 that have not been subjected to the peer-review process.

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Executive Summary

Boulder is a vibrant city, renowned for its livability and cultural wealth and well known for its Smart Growth policies that protect and restore environmental quality while enhancing economic opportunity. The city 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 Boulder a more enjoyable place to live, work, and play. Over the years, the people of Boulder have invested millions of dollars in their municipal forest. The primary question that this study asks is *whether the accrued benefits from Boulder'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 city's tree inventory, the Urban Forestry Division manages 35,502 trees in Boulder — 10,221 park and 25,281 street trees. These figures do not include most trees in natural areas and other trees in the city's jurisdiction not maintained by the Urban Forestry Division.

- There is approximately one public tree for every three residents, and these municipal trees shade approximately 3% of the city. Assuming that fully stocked streets have two trees every 50 feet, Boulder's streets are stocked at 20% of capacity, with room, theoretically, for an additional 100,000 trees. Not every hypothetical planting space can support a tree; power lines may interfere, planting spaces may not exist or be large enough. A survey is needed to determine the number of planting sites that are actually available for different sizes of trees. Newly developed areas are being designed with planting spaces for large trees in mind.
- The inventory contains 105 tree species with green ash as the dominant tree accounting for almost 14% of all street trees and 14% of all benefits. Siberian elm (8.5% of trees and 21% of total benefits) and silver maple (6% of trees and 11% of benefits) are subdominant species of importance due to their size and numbers.
- The age structure of Boulder's municipal tree population is similar to the "ideal" distribution, indicating that with continued care Boulder's future canopy should be relatively stable and productive. There is a high proportion of young trees (0–6 in diameter at breast height or 4.5 feet [DBH]), which will produce greater benefits as they age (44% compared to the desired 40%). Maturing (6–12 in DBH) and mature (12–24 in) trees account for 27 and 19% of the population, compared to the desired 25% for each class. Nine percent of Boulder's trees are old (>24 in), nearly matching the desired 10%. With this age distribution, Boulder's municipal forest is positioned to produce a steady stream of benefits over the next 50 years.

Resource Function and Value

- The ability of Boulder's municipal trees to intercept rain, thereby reducing stormwater runoff, is substantial, estimated at 6 million ft^3 annually, or $532,311. Citywide, the average tree intercepts 1,271 gallons of stormwater annually, valued at $15 per tree.
- Electricity saved annually in Boulder from shading and climate effects of trees equals

1,826 MWh ($104,074) and annual natural gas saved equals 11,403 MBtu ($72,022) for a total energy savings of $176,095 or $5 per tree.

- Citywide, annual CO_2 sequestration and emission reductions due to energy savings by public trees are 2,535 and 2,017 tons, respectively. CO_2 released during decomposition and tree-care activities is relatively low (325 tons). Net CO_2 reduction is 4,227 tons, valued at $63,409 or $1.79 per tree.
- Net annual air pollutants removed, released, and avoided average 0.47 lb per tree and are valued at $28,215 or $0.79 per tree. Ozone absorption by trees is especially important, totaling 3.5 tons and accounting for a $19,093 annual benefit. Emissions of biogenic volatile organic compounds that are involved in ozone formation were significant, offsetting air quality improvements by $17,189 annually.
- The estimated total annual benefits associated with aesthetics, property value increases, and other less tangible benefits are approximately $1.9 million or $54.67 per tree.
- Annual benefits total $2.7 million and average $77 per tree. Benefits are not evenly distributed among Boulder's neighborhoods; some neighborhoods receive twice the level of benefits of others. Siberian elms produce the greatest benefits among street ($209 per tree, 24% of total benefits) and park trees ($76 per tree, 12%). For street trees, silver maples ($151 per tree; 15%) provide the second highest level of benefits. Among park trees, cottonwoods have a lower per tree value ($35), but contribute the greatest percentage to total benefits (19%).
- Overall, annual benefits are related to tree size and type. Large deciduous trees ($105 per tree) produce nearly twice the annual benefits of large conifers ($63) and three times the benefits of small deciduous trees ($29).
- Boulder spends $752,606 annually, of which about $590,000 comes from the Urban Forestry Division and the remaining $160,000 comes from the budgets of Transportation, Utilities, and the City Attorney. The cost for maintaining Boulder's public trees is $21.20 per tree or $7.29 per capita, slightly more than some cities such as Cheyenne ($19 per tree) and much less than others such as Fort Collins ($32 per tree). Expenditures for tree removal and pruning account for about one-third of total costs.
- Boulder's municipal tree resource is a valuable asset, providing approximately $2 million or $56 per tree ($19 per capita) in net annual benefits to the community. Over the years, Boulder has invested millions in its municipal forest. **Citizens are now receiving a substantial return on their investment: $3.64 in benefits for every $1 spent on tree care.** Boulder's benefit–cost ratio of 3.64 exceeds those reported for Bismarck, ND (3.09), Glendale, AZ (2.41), Fort Collins (2.18), Cheyenne, WY (2.09), and Berkeley, CA (1.37). As Boulder's urban forest matures, continued investment in management is critical to insuring that residents receive a high return on their investment in the future.

Resource Management Needs

Boulder'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 Boulder, but the resource is fragile and needs constant care to maximize and sustain the benefits the trees provide into the future. Management recommendations aimed at increasing resource sustainability include the following:

- Diversify new plantings by developing a list of species that includes trees proven to perform well under most conditions, some trees that are more narrowly adapted, and a small percentage of new introductions for evaluation.
- Increase age diversity in neighborhoods with low diversity by planting trees in empty sites and by replanting on sites where trees have been removed.

- Conduct a windshield survey to count and categorize planting sites. Develop and implement a Street Tree Planting Master Plan to increase street tree stocking with a diverse mix of well-adapted species.

- Develop a list of tree species that cannot be planted because their maintenance costs exceed benefits. Review this list, as well as the list of trees that can be planted, with the Planning department, landscape architects, and developers. Update both lists on a regular basis.

- Continue to insure adequate space for trees in newly developed areas and practice good soil management. Encourage the use of structural soils when appropriate.

- Review and revise parking lot shade guidelines and enforcement to increase canopy cover.

- Develop a strong young-tree care program that includes regular watering, adjustments to initial staking, as well as inspection and pruning on at least a four-year cycle.

- Sustain the current level of inspection and pruning for older trees, as they produce substantial benefits but require intensive care to manage shallow roots, brittle wood, and weediness associated with some species.

- Review the adequacy of current ordinances to preserve and protect large trees from development impacts, and strengthen these ordinances as needed to retain benefits that these heritage trees can produce.

- Identify and implement cost-effective strategies to reduce conflicts between tree roots and hardscape in order to prolong the useful lifespan of mature trees.

These recommendations build on a history of tree management that has put the city on course to provide an urban forest that is both functional and sustainable. As Boulder continues to grow, it should also continue to invest in its tree canopy. This is no easy task, given financial constraints and trends toward higher density development that may put space for trees at a premium. The challenge ahead is to better integrate the green infrastructure with the gray infrastructure by increasing tree planting, 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.

Figure 1—Champion white oak in Boulder's Chautauqua Park.

Chapter One—Introduction

Boulder is a vibrant city, renowned for its livability and cultural wealth and well known for its Smart Growth policies that protect and restore environmental quality while enhancing economic opportunity. The city maintains trees as an integral component of the urban infrastructure (*Figure 1*). Trees improve urban life, making Boulder a more enjoyable place to live, work, and play. Boulder's street and park trees, its municipal forest, account for only about 20% of the city's total tree population. Although most trees in Boulder are on private property and these trees are important to the community, this study focuses on calculating the costs and benefits of the municipal forest.

The people of Boulder have invested millions of dollars to plant and maintain trees as an integral part of the city infrastructure. The Urban Forestry Division of the Boulder Parks and Recreation Department actively manages 25,281 trees along streets, as well as 10,221 park trees. This 35,502 total does not include most trees in natural areas and other trees in the city's jurisdiction not maintained by the Urban Forestry Division. The City believes that the public's investment in stewardship of the urban forest produces benefits that outweigh the costs to the community.

Research indicates that healthy city trees can mitigate impacts associated with urban environs: polluted stormwater runoff, poor air quality, energy for heating and cooling buildings, and heat islands. Healthy public 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.

Boulder's urban forest is a legacy that was largely created by the tree planting and stewardship efforts of previous generations. With the exception of trees native to the streamside corridors that run through town, Boulder's trees were planted and tended by citizens who valued the trees' shade and beauty. According to recent public survey results, today's residents continue to support investing in this legacy.

In an era of dwindling public funds and rising costs, however, there is a need to scrutinize public expenditures that are often 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 Boulder's urban 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 Boulder's urban forest.
2. Provide critical baseline information for evaluating program cost-efficiency and alternative management structures.
3. Highlight the relevance and relationship of Boulder'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—Boulder's Municipal Tree Resource: Describes the current structure of the street tree resource.

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

Chapter Four—Benefits of Boulder'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 and park 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—Boulder's Municipal Tree Resource

Boulder's urban forest has a long and proud history. Landscape architect Frederick Law Olmsted, Jr., wrote in a report to the city Improvement Association in 1910, "Boulder is properly proud among Colorado towns on account of it's numerous and large street trees. They are an example of the immense effect upon a town's appearance that may rapidly result from a popular custom once set agoing. The result is surely pleasing" (*Figure 2*). This tradition continues today. Boulder holds the title for 26 Champion Trees in the state of Colorado, including 73-ft tall chestnut oak (*Quercus muehlenbergii*), a 73-ft tall yellow buckeye (*Aesculus flava*), and a sycamore (*Platanus* spp.) with a trunk over 4 ft in diameter.

Tree Numbers

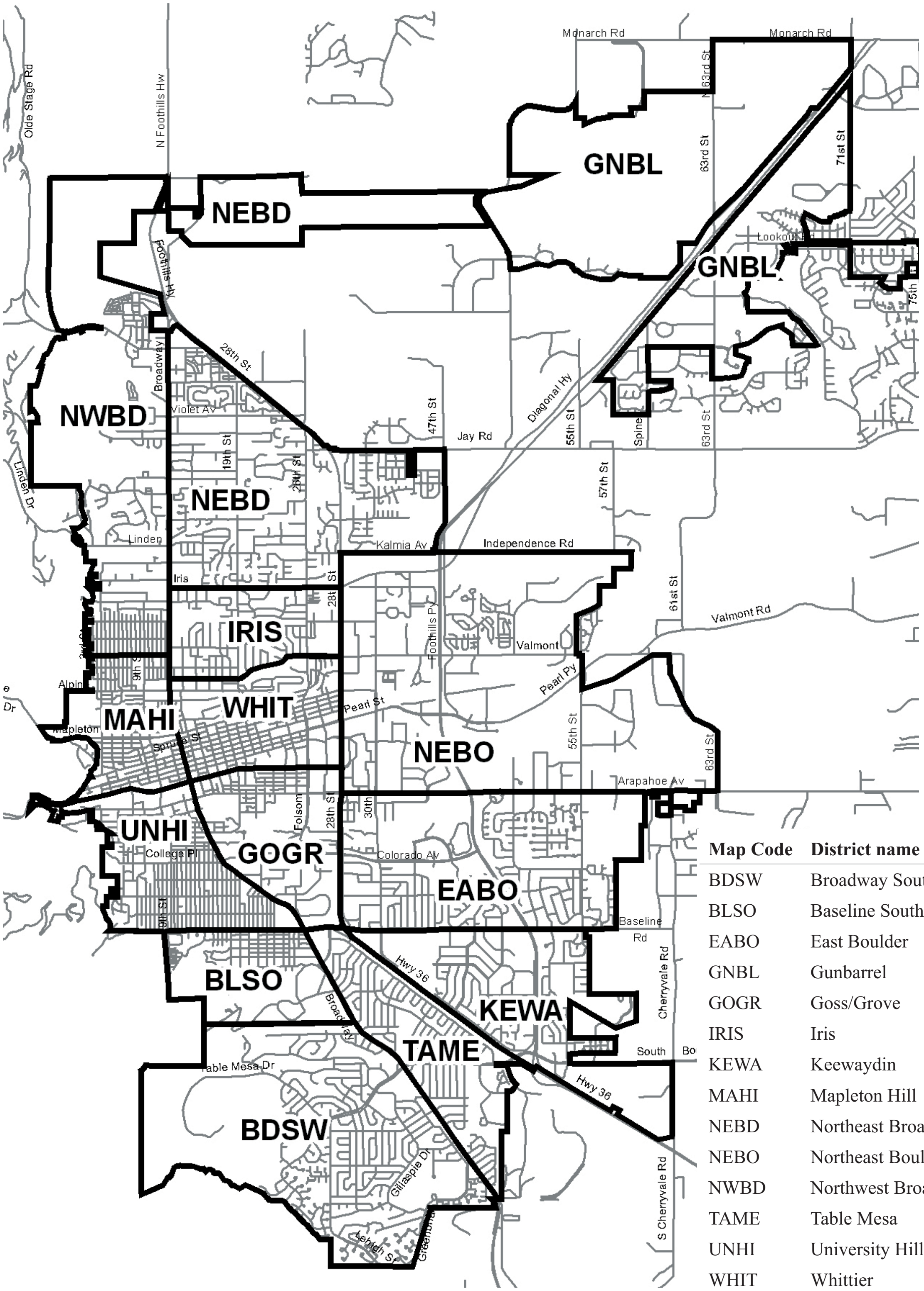
The city of Boulder is divided into 14 neighborhoods (*Figure 3*). For the purpose of this report, street tree data are presented by neighborhood, but all park trees are considered together under one category. The current inventory of street and park trees in Boulder was begun in 1986 and 1988, respectively, and completed in 2002 and 2004. The inventories are now updated on a 7-year rotation, so 1/7 of the trees are reinventoried each year. Currently there are 25,581 street trees and 10,221 park trees (35,502 trees total; *Table 1*) that are actively managed by the Urban Forestry Division.

With a population of 103,216 (Bussi-Sottile and Alexander 2005), Boulder has almost one public tree for every three residents. Calculations of trees per capita are important in determining how well forested a city is. The more residents and greater housing density a city possesses, the more need for trees to provide benefits. Boulder's ratio of street trees per capita is 0.34, slightly below the mean ratio of 0.37 reported for 22 U.S. cities (McPherson and Rowntree 1989).

Park tree density is 21.3 trees per acre, similar to the densities of 22.4 and 18.4 trees per acre report-

Figure 2—Trees planted along Mapleton Avenue in 1895.

Boulder Tree Inventory and Maintenance Districts Map



Map Code	District name
BDSW	Broadway Southwest
BLSO	Baseline South
EABO	East Boulder
GNBL	Gunbarrel
GOGR	Goss/Grove
IRIS	Iris
KEWA	Keewaydin
MAHI	Mapleton Hill
NEBD	Northeast Broadway
NEBO	Northeast Boulder
NWBD	Northwest Broadway
TAME	Table Mesa
UNHI	University Hill
WHIT	Whittier

Figure 3—Boulder’s tree inventory and maintenance districts.

***Table 1**—Street tree numbers by neighborhood and park tree numbers for the entire city.*

Zone	Map code	No. of trees
Broadway Southwest	BDSW	1,284
Baseline South	BLSO	1,261
East Boulder	EABO	1,812
Gunbarrel	GNBL	850
Goss/Grove	GOGR	972
Iris	IRIS	622
Keewaydin	KEWA	1,249
Mapleton Hill	MAHI	2,484
Northeast Broadway	NEBD	2,213
Northeast Boulder	NEBO	1,826
Northwest Broadway	NWBD	3,073
Table Mesa	TAME	744
University Hill	UNHI	4,098
Whittier	WHIT	2,793
Parks		10,221
Citywide total		35,502

ed for Fort Collins and Berkeley, CA (McPherson et al. 2005). Park tree stocking in Boulder is considerably greater than in Cheyenne (8.4/acre) and Glendale, AZ (5.0).

Boulder's street and park tree population is dominated by deciduous trees (84% of the total; *Table 2*). Nearly 75% of the public trees are species that will eventually grow to be large (>40 ft tall). Such a high percentage of large-stature trees is generally good, because big trees provide more shade, pollutant uptake, CO_2 sequestration, and rainfall interception than small trees. There are very few mid-size trees (25–40 ft) in the city (less than 8%).

Species Richness, Composition and Diversity

The tree population in Boulder includes 105 different species—roughly double the mean of 53 species reported by McPherson and Rowntree (1989) in their nationwide survey of street tree populations in 22 U.S. cities. This species richness is especially unusual in a temperate, semi-arid climate. One contributing factor is the acidity of Boulder's soils, which makes them more productive than soils in other Front Range cities, allowing a wider diversity of species to be planted.

The predominant street tree species are green ash (*Fraxinus pennsylvanica*, 13.8%), Siberian elm (*Ulmus pumila*, 8.5%), cottonwood (*Populus* spp., 7.4%), honeylocust *(Gleditsia triacanthos,* 6.5%) and silver maple (*Acer saccharinum*, 6.0%) (*Table 3*). Citywide, only green ash exceeds the general rule that no single species should represent more than 10% of the population (Clark et al. 1997). However, at the neighborhood level, some areas are heavily dominated by just a few species (*Table 4*). In Northeast Boulder, nearly 3 in 10 trees is a green ash (28.5%). In Mapleton Hill, one-quarter (24.5%) of the trees are silver maples and in Northeast Broadway, one-quarter (24.9%) are Siberian elms. Boulder's parks are dominated by cottonwoods (18.8%).

Lack of species diversity of this kind is of concern because of the impact that drought, disease, pests, or other stressors can have on an ecosystem; the urban forest is no different in this respect. Silver maples and green ash, for example, may be particularly vulnerable to loss. The Asian longhorned beetle (*Anoplophora glabripennis*) feeds on maples and other species including poplars, elms, and willows. The emerald ash borer (*Agrilus planipennis*) has decimated ash trees in the Midwest. A catastrophic loss of one or more of these dominant species could leave large structural and functional gaps in Boulder's neighborhoods. In fact, the City

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

Tree type	Large			Medium			Small			Total
	Street	Park	Total	Street	Park	Total	Street	Park	Total	
Deciduous	67.7	66.9	67.4	3.9	1.6	3.3	14.7	10.3	13.4	84.1
Conifer	5.3	8.3	6.2	2.8	8.6	4.5	5.6	4.3	5.2	15.9
Total	73.0	75.2	73.6	6.7	10.2	7.7	20.3	14.6	18.6	100.0

***Table 3**—Most abundant public tree species listed in order of predominance by DBH class (in) and tree type.*

Species	0-3	3-6	6-12	12-18	18-24	24-30	30-36	36-42	>42	Total	% of total
Broadleaf Deciduous Large (BDL)											
Green ash	783	1,393	1,633	577	298	178	35	3	1	4,901	14%
Siberian elm	393	675	869	445	227	241	92	42	20	3,004	8%
Cottonwood	79	179	725	719	320	300	128	87	89	2,626	7%
Honeylocust	344	560	773	383	111	121	22	4	0	2,318	7%
Silver maple	35	199	238	221	392	593	300	117	50	2,145	6%
Norway maple	158	381	380	99	24	10	0	0	0	1,052	3%
Willow	6	44	181	211	91	105	71	57	64	830	2%
Littleleaf linden	175	185	311	44	12	3	0	1	0	731	2%
White ash	130	298	251	17	7	1	0	1	0	705	2%
Boxelder	61	101	250	153	36	17	0	2	0	620	2%
Sugar maple	127	103	87	73	65	25	2	0	1	483	1%
Red oak	103	104	81	52	33	51	13	9	1	447	1%
Hackberry	196	69	118	26	14	11	0	0	0	434	1%
American linden	102	43	117	98	41	23	3	1	0	428	1%
Red maple	227	149	30	5	3	0	0	0	0	414	1%
BDL other	855	515	621	347	180	167	55	45	23	2,808	8%
Total	3,774	4,998	6,665	3,470	1,854	1,846	721	369	249	23,946	67%
Broadleaf Deciduous Medium (BDM)											
Quaking aspen	133	245	98	2	0	0	0	0	0	478	1%
BDM other	267	220	128	40	12	4	6	2	0	679	2%
Total	400	465	226	42	12	4	6	2	0	1,157	3%
Broadleaf Deciduous Small (BDS)											
Crabapple	360	474	580	256	15	8	0	0	0	1,693	5%
Russian olive	93	453	404	132	8	1	0	0	0	1,091	3%
Cockspur hawthorn	351	142	13	2	1	0	0	0	0	509	1%
Amur maple	225	156	25	3	0	0	0	0	0	409	1%
BDS other	527	423	99	9	4	1	0	1	0	1,064	3%
Total	1,556	1,648	1,121	402	28	10	0	1	0	4,766	13%
Broadleaf Evergreen Medium (BEM)											
Total	2	1	2	0	0	0	0	0	0	5	0%
Conifer Evergreen Large (CEL)											
Blue spruce	218	396	421	265	98	20	3	0	0	1,421	4%
CEL other	118	169	279	164	36	10	1	0	0	777	2%
Total	336	565	700	429	134	30	4	0	0	2,198	6%
Conifer Evergreen Medium (CEM)											
Austrian pine	95	419	495	241	51	13	2	1	0	1,317	4%
CEM other	52	44	83	67	19	1	0	0	0	266	1%
Total	147	463	578	308	70	14	2	1	0	1,583	4%
Conifer Evergreen Small (CES)											
Juniper	311	434	268	79	14	6	1	0	0	1,113	3%
Pinyon pine	125	350	158	14	0	0	0	0	0	647	2%
CES other	43	30	13	1	0	0	0	0	0	87	0%
Total	479	814	439	94	14	6	1	0	0	1,847	5%
Citywide Total	6,694	8,954	9,731	4,745	2,112	1,910	734	373	249	35,502	

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

District code	1st (%)	2nd (%)	3rd (%)	4th (%)	5th (%)
BDSW	Green ash (12)	Honeylocust (11.1)	Crabapple (8.6)	Russian olive (8.5)	Austrian pine (6.9)
BLSO	Juniper (13.9)	Blue spruce (8.2)	Norway maple (7.4)	Siberian elm (6.5)	Green ash (6.2)
EABO	Green ash (16.8)	Siberian elm (11.1)	Russian olive (10.5)	Honeylocust (9.2)	Cottonwood (5.5)
GNBL	Green ash (23.2)	Russian olive (9.1)	Littleleaf linden (8.6)	Honeylocust (7.2)	Crabapple (6.8)
GOGR	Green ash (22.5)	Honeylocust (9)	Siberian elm (8.6)	Silver maple (5.6)	Crabapple (4.1)
IRIS	Siberian elm (12.2)	Green ash (10.5)	Russian olive (7.1)	Blue spruce (5.5)	Norway maple (5)
KEWA	Green ash (12.1)	Russian olive (10.6)	Honeylocust (10)	Juniper (8.7)	Siberian elm (6.7)
MAHI	Silver maple (24.5)	Green ash (13.4)	Norway maple (7)	Sugar maple (6.8)	Honeylocust (6.2)
NEBD	Siberian elm (24.9)	Green ash (12.6)	Honeylocust (6.4)	Crabapple (6.2)	Cottonwood (5.1)
NEBO	Green ash (28.5)	Honeylocust (12.7)	Silver maple (10.2)	White ash (8.8)	Cottonwood (6.8)
NWBD	Siberian elm (14.4)	Green ash (12.7)	Silver maple (7.4)	Crabapple (6.3)	Juniper (5.9)
TAME	Siberian elm (14.8)	Green ash (10.2)	Juniper (9)	Honeylocust (7.9)	Russian olive (7.3)
UNHI	Silver maple (12.3)	Green ash (10.6)	Honeylocust (7.8)	Siberian elm (7.8)	Crabapple (6.4)
WHIT	Green ash (21.6)	Honeylocust (12.5)	Siberian elm (9.3)	Silver maple (7.8)	Norway maple (4.7)
Parks	Cottonwood (18.8)	Green ash (10.7)	Austrian pine (7.2)	Willow (7.2)	Siberian elm (5.6)
Total	Green ash (13.8)	Siberian elm (8.5)	Cottonwood (7.4)	Honeylocust (6.5)	Silver maple (6)

of Boulder Design and Construction Standards (City of Boulder 2000) recommend that ash trees be planted sparingly and not in groups. Although the Urban Forestry Division no longer plants green ash, they do get planted in newly developed areas.

Species Importance

Species importance values (IV) can be 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 24 most abundant street and park tree species listed in *Table 5* constitute 84% of the total street tree population, 90% of the total leaf area, 88.5% of total canopy cover, and 87.3% of total IV.

As *Table 5* illustrates, some species are more important than their population numbers suggest. For example, silver maples account for only 6% of all public trees. Because of their relatively large size, however, the amount of leaf area and canopy cover they provide is comparatively great, increasing their importance to 14.3 when all IV components are considered. Other species with high importance values include green ash (12.9), Siberian elm (12.5), and cottonwood (9.5). Some trees have lower IV values than their numbers would suggest. Crabapple, for example, represents almost 5% of the population, but because of its small leaf area, has an IV of only 3.1.

Importance is relatively evenly dispersed among four leading dominants in Boulder. Although these four species have proven to be successful, they are not without their problems. For example, Siberian elm and cottonwood produce large amounts of litter, have invasive roots, and can drop branches during storms. Siberian elms are no longer planted by the Urban Forestry Division because better choices are available. Because no single species is dominant, the continuity of Boulder's canopy is not threatened by the gradual loss of the elms and cottonwoods.

Street tree populations with one major dominant species (IV>25%) may have low maintenance costs

***Table 5**—Importance values (IV) indicate which species dominate the population by virtue of their numbers and size.*

Species	No. of trees	% of total trees	Leaf area (ft^2)	% of total leaf area	Canopy cover (ft^2)	% of total canopy cover	IV
Green ash	4,901	13.8	11,494,500	11.8	2,707,184	13.1	12.9
Siberian elm	3,004	8.5	16,717,420	17.2	2,470,939	12.0	12.5
Cottonwood	2,626	7.4	10,040,710	10.3	2,229,918	10.8	9.5
Honeylocust	2,318	6.5	6,161,348	6.3	1,603,513	7.8	6.9
Silver maple	2,145	6.0	18,858,820	19.4	3,606,471	17.5	14.3
Crabapple	1,693	4.8	1,356,524	1.4	628,580	3.0	3.1
Blue spruce	1,421	4.0	1,870,111	1.9	375,857	1.8	2.6
Austrian pine	1,317	3.7	1,374,887	1.4	336,635	1.6	2.3
Juniper	1,113	3.1	423,684	0.4	120,198	0.6	1.4
Russian olive	1,091	3.1	830,574	0.9	403,715	2.0	2.0
Norway maple	1,052	3.0	1,727,459	1.8	393,909	1.9	2.2
Willow	830	2.3	5,968,116	6.1	1,171,521	5.7	4.7
Littleleaf linden	731	2.1	974,054	1.0	215,424	1.0	1.4
White ash	705	2.0	1,328,841	1.4	248,258	1.2	1.5
Pinyon pine	647	1.8	184,549	0.2	62,389	0.3	0.8
Boxelder	620	1.7	1,747,805	1.8	413,810	2.0	1.9
Cockspur hawthorn	509	1.4	100,602	0.1	40,544	0.2	0.6
Sugar maple	483	1.4	1,477,923	1.5	362,737	1.8	1.5
Quaking aspen	478	1.3	470,618	0.5	91,949	0.4	0.8
Red oak	447	1.3	1,620,053	1.7	335,095	1.6	1.5
Hackberry	434	1.2	691,721	0.7	142,355	0.7	0.9
American linden	428	1.2	1,341,177	1.4	187,760	0.9	1.2
Red maple	414	1.2	198,722	0.2	59,668	0.3	0.6
Amur maple	409	1.2	99,876	0.1	45,643	0.2	0.5
Total	29,816	84.0	87,060,088	89.4	18,254,070	88.5	87.3

due to the efficiency of repetitive work, but may still incur large costs if decline, disease, or senescence of the dominant species results in large numbers of removals and replacements. When IVs are more evenly dispersed among five to ten leading dominant species the risks of a catastrophic loss of a single dominant species are reduced. Of course, suitability of the dominant species is an important consideration. Planting short-lived or poorly adapted species can result in short rotations and increased long-term management costs. Hence, managers can observe the distribution of IVs among species and species suitability to evaluate how the population is likely to change in the future.

Street Tree Stocking Level

Although the inventory used in this study did not sample empty street tree planting sites in Boulder to estimate stocking level, stocking can be estimated based on total street miles. There are 594 linear miles of streets in Boulder (Bussi-Sottile and Alexander 2005) and an average of 42 street trees per street mile. A fully stocked street could hold as many as two trees every 50 feet (211 trees/mile). By this measure, Boulder's street tree stocking level is 20%, and there is room, theoretically, for another 100,000 trees. Boulder's stocking level compares favorably with Fort Collins (18%), Cheyenne (12%), and Glendale, AZ (9%), but is less than Bismarck (37%) and the mean stocking level for 22 U.S. cities (38.4%) (McPherson et al. 2005; McPherson and Rowntree 1989).

The actual number of street tree planting sites may be significantly less than 100,000 due to inadequate planting space, absence of curbs and gutters, presence of privately owned trees, and utility conflicts. Also, stocking levels vary greatly across Boulder depending on factors influencing planting such as land use and time of development. Information needed to estimate stocking levels according to neighborhood was not available.

Age Structure

The distribution of ages within a tree population influences present and future costs as well as the flow of benefits. An unevenly aged population allows managers to allocate annual maintenance costs uniformly over many years and assures 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 of Boulder's municipal tree population is similar to the "ideal" distribution, indicating that with continued care Boulder's future canopy should be relatively stable and productive (*Figure 4*). There is a high proportion (44% compared to desired 40%) of young trees (0–6 in diameter at breast height or 4.5 feet [DBH]) that will produce greater benefits as they age. Maturing (6–12 in DBH) and mature (12–24 in DBH) trees account for 27% and 19% of the population, compared to the desired 25% for each class. The lower number of trees in the mature class may reflect a period of reduced tree planting in the decades after World War II when Boulder grew rapidly. There is no way to make up for this gap that may have resulted from reduced tree planting over a 20-year period. Nine percent of Boulder's trees are old (>24 inch), nearly matching the desired 10%. With this age distribution, Boulder's municipal forest is positioned to produce a steady stream of benefits over the next 50 years.

Age curves for individual tree species help explain their relative importance and suggest how tree management needs may change as these species grow older (*Figure 4*). Cottonwood has a high proportion of maturing trees and a few older ones as well. Silver maple and willow have the highest percentage of trees in the largest DBH classes. Large numbers of Siberian elm, honey locust, and green ash in the smallest size classes indicate that many were planted, or in the case of Siberian elm, volunteered in recent years. Because these are large trees at maturity, they are likely to provide a relatively high level of benefits in the future. Naturally, large percentages of the smaller-stature crabapple and junipers are in the 0–6 and 6–12 in DBH classes, since they rarely grow larger than this.

The populations of street trees in Boulder's neighborhoods are distributed quite differently, reflecting historic development and tree planting patterns (*Figure 5*). Broadway Southwest has no trees in the >30-in class and 86% with a DBH of less than 12 in. In Gunbarrel, 99% of trees have a DBH below

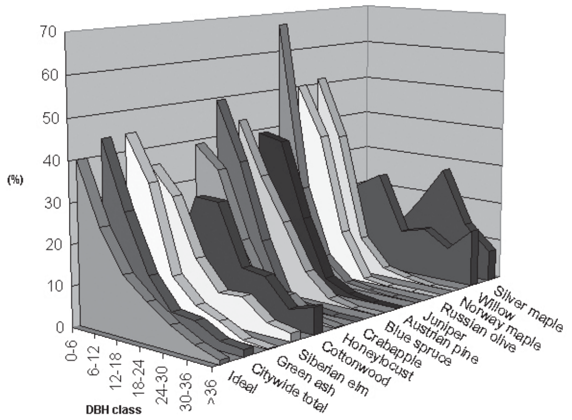


Figure 4—Relative age distribution for Boulder's 12 most abundant street and park trees citywide shown with an ideal distribution.

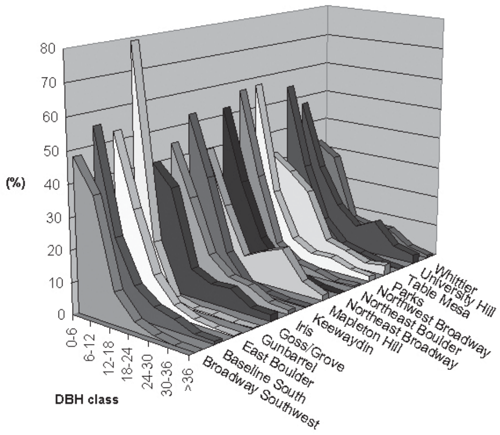


Figure 5—Relative age distribution of all public trees by neighborhood.

18 in. With higher numbers of large, older silver maples and Siberian elms, Mapleton Hill and University Hill have more optimal distributions.

Tree Condition

The Urban Forestry Division does not assess tree condition as a part of their inventory because this information may change frequently in response to severe weather events, development impacts, pests, disease, and other stressors. Condition information was collected, however, for trees in commercial areas during a special project. Because growing conditions are often most harsh in commercial zones, these results underestimate condition citywide. In commercial areas, 57% of trees are in good or excellent condition, 32% are in fair condition, 8% are poor or dead, and 4% are listed as removed (*Table 6*). Large, abundant species with high numbers of trees in good or excellent condition include red oak (*Quercus rubra*) and littleleaf linden (*Tilia cordata*). Cockspur hawthorn (*Crataegus crus-galli*) is a small species that performs well. Poor performers in commercial sites include pin oak (*Quercus palustris*), Norway maple (*Acer platanoides*) and American linden (*Tilia americana*).

Tree Canopy

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. It is important to remember that street and park trees throughout the United States—and those of Boulder—likely represent less than 20% of the entire urban forest (Moll and Kollin 1993). The street and park tree canopy in Boulder is estimated at 473.3 acres and covers 2.9% of the city (total city area is 16,000 acres; Bussi-Sottile 2005). Park trees comprise 32% of the public-tree canopy cover.

Table 6*—Trees (%) by condition class for commercial areas only.*

Species Name	No. of trees	Dead	Poor	Fair	Good	Excellent	Removed
Green ash	594	1.0	10.1	39.7	46.1	0.7	2.4
Honeylocust	306	0.3	5.2	28.8	59.2	4.6	2.0
White ash	125	0.8	7.2	31.2	58.4	0.0	2.4
Littleleaf linden	87	1.2	3.4	21.8	69.0	3.4	1.2
Norway maple	86	3.5	11.6	33.7	33.7	2.3	15.1
Siberian elm	69	0.0	0.0	34.8	56.5	0.0	8.7
Red oak	59	0.0	3.4	20.3	64.4	10.2	1.7
Crabapple	57	0.0	1.8	28.1	68.4	0.0	1.8
Pin oak	53	1.9	22.6	47.2	20.8	5.7	1.9
Silver maple	49	0.0	2.0	26.5	61.2	4.1	6.1
Cockspur hawthorn	47	0.0	0.0	4.3	63.8	29.8	2.1
American linden	37	0.0	13.5	27.0	51.4	8.1	0.0
Blue spruce	29	0.0	10.3	20.7	58.6	10.3	0.0
Red maple	24	4.2	4.2	29.2	62.5	0.0	0.0
Russian olive	23	0.0	4.3	30.4	60.9	4.3	0.0
Austrian pine	22	0.0	0.0	68.2	31.8	0.0	0.0
Cottonwood	22	0.0	0.0	31.8	59.1	0.0	9.1
Plum	22	0.0	4.5	36.4	40.9	0.0	18.2
Tree of heaven	20	0.0	0.0	60.0	40.0	0.0	0.0
European hornbeam	20	0.0	10.0	15.0	70.0	0.0	5.0
Hackberry	20	0.0	10.0	45.0	40.0	5.0	0.0
Citywide total	1771	0.8	6.9	31.8	53.0	3.9	3.7

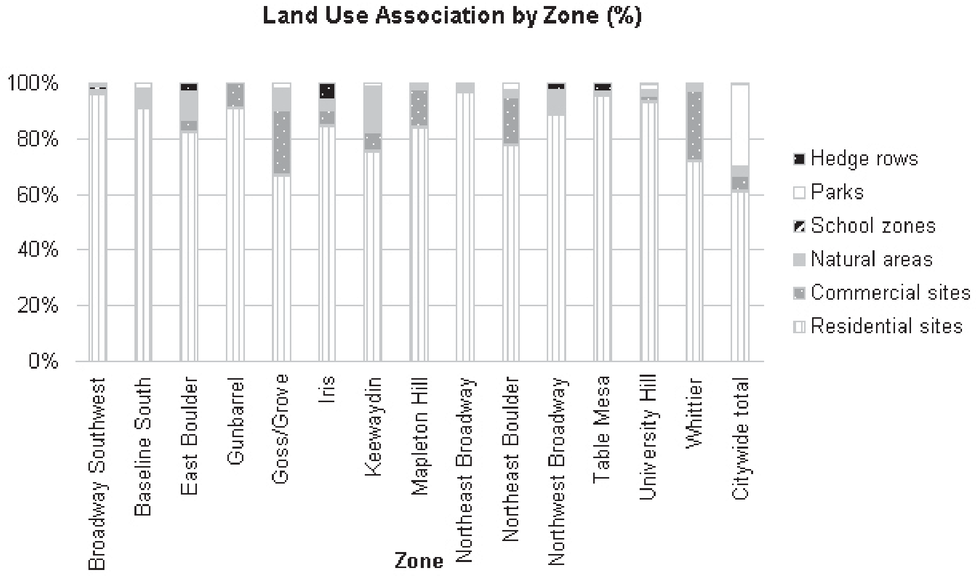


Figure 6—Distribution of trees by adjacent land use.

Land Use

Sixty-one percent of the inventoried public tree population in Boulder is located adjacent to residential property (*Figure 6*). Of the remaining trees, 32% are in parks, 5% are in commercial areas (*Figure 7*), 3% are in natural areas, and the remaining 1% are in school zones or in hedge rows. *Figure 6* shows the distribution of trees in Boulder's 14 neighborhoods, as well as the citywide distribution, which includes park trees. The distribution of trees in Boulder parks is shown in *Table 7*.

Figure 7—Trees line the streets of a commercial area in Boulder.

***Table** 7—Distribution of trees in Boulder's parks.*

Park name	No. of trees
Arapahoe Ridge	104
Arboretum	111
Arrowwood	84
Aurora 7	49
Barker	18
Beach/Harbeck House	100
Bear Creek	139
Bldr Valley Village	280
Boulder Reservoir	205
Burke	98
Campbell Robertson	18
Canyon	93
Canyon Pointe	11
Carnegie Library	2
Catalpa	34
Centennial Tennis	1
Central	91
Chautauqua	275
Christensen	48
Columbia Cemetery	352
Columbine	55
Complex	930
Crestview	65
Eaton	26
Ebcc	281
Eben G. Fine	250
Elks Property	133
Elmers Two Mile	75
Fitzpatrick	10
Flatiron Golf Course	1,418
Foothills Community	327
Fortune	20
Greenleaf	68
Harlow Platts/Sbrc	543
Heuston	268
Hickory Comm Gardens	4
Hiram Fullen	8
Keewaydin	71
Kids Fishing Ponds	32
Knollwood Courts	12
Lovers Hill	14
Mapleton Ballfields	49
Martin	172
Maxwell Lake	182
Meadow Glen	74
Meadows Library	19
Melody	28
Nbrc/ Olmstead/ Iris	59
North Boulder	91
Palo East	27
Palo North	19
Palo South	46
Park East	308
Park Operation/Yards	29
Parkside	64
Pearl St. Mall	115
Pineview	39
Pleasantview	91
Pottery Lab	2
Pp 27th Way/Elm St.	3
Pp 4700 Eisenhower	10
Pp Alpine/17th	8
Pp Athens/18th	54
Pp Grove/18th	6
Pp Grove/19th	6
Pp Grove/20th	6
Pp Walnut/19th	6
Pp Walnut/22nd	3
Reynolds Library	9
Salberg	79
Scott Carpenter	228
Shanahan Ridge	72
Sinton	32
Smith	54
Spruce Pool	16
Stazio Ballfields	56
Tantra	221
Valmont	708
Watson	280
West Highland	20
Whittier	10
Wonderland	197
Total	10,221

Chapter Three—Costs of Managing Boulder's Municipal Trees

Program Expenditures

Costs of Managing Public Trees

Costs are based on a review of expenditures during fiscal year 2004. Annual tree-related expenditures for Boulder's municipal forestry program are $752,606 (*Table 8*) of which about $590,000 comes from the Urban Forestry Division and the remaining $160,000 comes from the budgets of other divisions (Bussi-Sottile and Alexander 2005). This amount represents 0.5% of the City of Boulder's total 2004 operating budget ($182 million) and $7 per person. With 35,502 actively managed street and park trees, the city spends $21 per tree on average during the fiscal year, equal to 1997 mean value of $19 per tree reported for 256 California cities after adjusting for inflation (Thompson and Ahern 2000). However, non-program expenditures (e.g., sidewalk repair, litter clean-up) were not included in the California survey. Boulder's annual expenditure is substantially less than other cities such as Fort Collins ($32) and some California communities such as Santa Monica ($53) and Berkeley ($65) (McPherson et al. 2005). Forestry program expenditures fall into three categories: tree planting and establishment, pruning and general tree care, and administration.

Tree Planting and Establishment

Quality nursery stock, careful planting, and follow-up care are critical to the perpetuation of a healthy urban forest. The city plants about 85 trees annually, most of which are replacements planted after trees are removed. However, the Urban Forestry Division does not replace trees in commercial sites. Costs are typically about $170 per tree, including labor and materials. When administrative and equipment costs are added, tree planting activities account for 4.1% of the total budget or $31,000. Property owners or developers are required to plant trees (and replace them if necessary during the first five years) adjacent to newly developed residential or commercial property.

There are no costs for establishment watering because street trees are only planted adjacent to residential sites where the owner has agreed to water the tree for at least the first five years. Park trees are only planted into irrigated turf areas (Bussi-Sottile and Alexander 2005).

Pruning, Removals, and General Tree Care

Pruning accounts for more than a quarter (27%) of total annual expenditures at $205,000 ($5.77 per tree). About 1,065 street trees and 370 park trees are pruned each year, mostly by contracted labor. Training of new trees with hand pruners or saws is done 5 years after planting. After that, medium and large street trees are pruned on a 10-year cycle and park trees are pruned on an 8-year cycle. In-house seasonal crews prune approximately 200 small street trees per year, which, due to a limited

Table 8*—Boulder's annual municipal forestry-related expenditures (negative numbers indicate revenue.*

Program Expenditures	Total ($)	% of program	$/Tree	$/Capita
Pruning	204,777	27.2	5.77	1.98
Administration	194,289	25.8	4.90	1.69
Infrastructure Repairs	160,961	21.4	4.53	1.56
Tree & Stump Removal	72,809	9.7	2.05	0.71
Inspection/Service	51,777	6.9	1.46	0.50
Pest Management	42,955	5.7	1.21	0.42
Purchasing Trees and Planting	31,041	4.1	0.87	0.30
Storm Damage Clean-up	14,278	1.9	0.40	0.14
Liability/Claim	–20,281	–2.7	–0.57	–0.20
Total Expenditures	752,606	100.0	21.20	7.29

budget, is only a fraction of the number necessary to maintain the program's desired 4-year rotation.

About 250 street trees and 80 park trees are removed each year (based on 5-year average) by in-house or contracted labor. The total annual expenditure for tree and stump removal is approximately $72,000. Due to budget reductions, only about 26% of removed trees are replaced. Almost all (99%) removed wood is salvaged. Sixty percent is used by the Urban Forestry Division as mulch, 39% is sold as firewood and 1% is sold to specialty wood workers. Only wood infected with Dutch elm disease or Ips bark beetles is taken to a landfill. There is a small annual income to the Division from the sale of firewood ($700) and a small cost for landfill dumping ($600). Once administration expenses are added, the salvage program costs about $500 per year.

Annual costs for pest and disease control total approximately $43,000 ($1.21 per tree), most of which is associated with Boulder's Integrated Pest Management (IPM) Program. This program includes monitoring as well as mechanical, cultural and biological controls and an annual citywide tree health survey. There is no program to chemically treat street trees, though the Division will offer guidance to property owners. Historically, park trees were only treated when the life of the tree was threatened and alternative controls were not available. In 2003 a pesticide ban for city property was implemented that built upon the Urban Forestry Division's policy and further limited pesticide use to products on an approved list.

Responding to requests for tree inspection, providing development reviews, and performing tree safety inspections costs the program $52,000 per year. About 85% of service requests are for street trees and the remaining 15% are for park trees.

Administration

Approximately 25% of all program expenditures are for administration, totaling $195,000. This budget item includes dollars not included in any of the above maintenance programs, such as tree inventory, general arboretum maintenance, training, general overhead, and staff time costs. Staff expenses include one city forester and one half-time administrative assistant plus remaining time for the three forestry assistants for tree inventory management (GIS), administration of the Tree Safety Inspection Program, and public education. Also, a seasonal crew is hired each year for planting, pruning, pest management and removals.

External Tree-Related Expenditures

The city has other tree-related expenditures that are not captured in the Urban Forestry Division's budget. Annual costs for storm clean-up are approximately $14,000, of which $5,000 comes from the Urban Forestry Division's budget. It is city policy to clean up only after catastrophic storms (*Figure 8*); however, the Forestry Division staff takes care of trees that are very badly damaged (entire leader or whole tree failures) after less extreme storms. A "spring cleanup" is held to remove organic debris every year.

Annually, about $161,000 is spent by the city on infrastructure repair. Of this, about $13,500 is typically spent by the Forestry Division for tree grate repair and maintenance, however this is presently an unfunded program. The remaining $148,000 comes from other areas of the City's budget and includes approximately $85,000 for sidewalk repair. Shallow roots that heave sidewalks, crack curbs, and damage driveways are an important aspect of mature tree care. The Forestry Division works closely with City Transportation to find solutions to tree/sidewalk conflicts. Once problems occur, the city attempts 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 and root cutting when necessary. When a tree growing in close proximity to the sidewalk causes recurrent problems, the Forestry Division works with Transportation to remove the tree. The Transportation Department spends an additional $9,100 on curb and gutter repair. The Utilities Division spends an estimated $54,000 on sewer and water line repairs and other infrastructure damage each year.

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 Boulder no tree-related liability claims have been paid out since at least 1999 when such records were first kept. In fact, revenue to the City has exceeded costs because of compensatory payments associated with the Tree Protection and Mitigation program. This program generates revenue by charging a fee for damage to city trees or from fees assessed as mitigation for tree removal. Staff costs are only about $7,000, and income has averaged approximately $27,000 annually over the last three years, for a long-term net income of approximately $20,000 per year.

Figure 8—Storm damage to a municipal tree in Boulder.

Chapter Four—Benefits of Boulder's Municipal Trees

Introduction

City trees work ceaselessly, providing ecosystem services that directly improve human health and quality of life. This fact is well recognized by Boulder's citizens. In a 2003 survey, 69% of residents rated the environmental benefits provided by urban trees as "very important" (Urban Forestry Division 2004). In this section the benefits of Boulder'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 economics). 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 of the functional benefits trees provide and their value. Our approach is a general accounting of the benefits produced by municipal trees in Boulder—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 interiors 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) (*Figure 9*). 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.

Trees reduce air movement into buildings and conductive heat loss from buildings. Trees can reduce wind speed and resulting air infiltration by up to

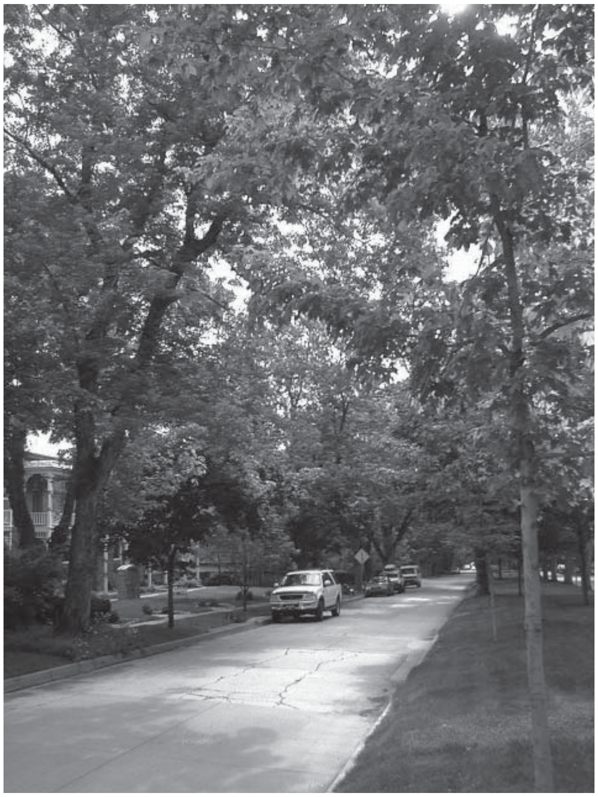


Figure 9—Trees provide shade to a Boulder neighborhood and reduce energy use for cooling.

50%, translating into potential annual heating savings of 25% (Heisler 1986). Decreasing wind speed reduces heat transfer through conductive materials as well. Appendix B provides additional information on specific contributions that trees make toward energy savings.

Electricity and Natural Gas Results

Electricity and natural gas saved annually in Boulder from both shading and climate effects total 1,826 MWh ($104,074) and 11,403 MBtu ($72,022), respectively, for a total retail savings of $176,096 or a citywide average of $4.96 per tree (*Tables 9 and 10*). Silver maple, Siberian elm, and green ash are the primary contributors along streets; cottonwood and willow are the primary contributors in parks. On average, park tree benefits ($6.27 per tree) exceed street tree benefits ($4.44) because trees are relatively larger in parks than streets, especially the conifers. Increased size results in greater winter wind-speed reductions and summer temperature reductions.

Among street trees, silver maples account for only 8.1% of total tree numbers, but they provide 20% of the energy savings. Similarly, Siberian elms represent 9.6% of the street tree population and provide 15% of the energy savings. For both street and park trees, deciduous trees provide significantly greater energy-saving benefits than conifers, except in the medium-stature tree category (*Table 11*). Energy benefits associated with conifers are lower than deciduous tree benefits because of the detrimental effect of their winter shade on heating costs.

Table 9*—Net annual energy savings produced by Boulder street trees.*

Species	Electricity (MWh)	Natural gas (MBtu)	Total ($)	% of trees	% of total $	Avg. $/tree
Green ash	164	773	14,223	15.1	12.7	3.74
Siberian elm	196	902	16,870	9.6	15.0	6.95
Silver maple	286	1,037	22,874	8.1	20.4	11.17
Honeylocust	109	492	9,299	8.0	8.3	4.63
Crabapple	52	438	5,746	5.3	5.1	4.30
Norway maple	32	195	3,082	3.8	2.7	3.25
Russian olive	15	47	1,147	3.6	1.0	1.27
Juniper	8	64	872	3.6	0.8	0.97
Blue spruce	22	138	2,132	3.5	1.9	2.43
Cottonwood	51	208	4,207	2.8	3.8	5.96
Littleleaf linden	14	58	1,146	2.4	1.0	1.89
Austrian pine	17	135	1,797	2.3	1.6	3.12
White ash	20	140	1,998	1.9	1.8	4.21
Quaking aspen	10	66	972	1.9	0.9	2.05
Pinyon pine	4	30	429	1.9	0.4	0.92
Sugar maple	37	260	3,760	1.7	3.4	8.60
Cockspur hawthorn	1	4	95	1.6	0.1	0.24
Red oak	23	111	2,034	1.4	1.8	5.71
Red maple	3	13	274	1.4	0.2	0.78
Hackberry	12	70	1,132	1.4	1.0	3.23
Boxelder	16	77	1,389	1.3	1.2	4.31
Amur maple	1	3	88	1.3	0.1	0.28
Plum	7	47	715	1.1	0.6	2.55
American linden	7	0	411	1.1	0.4	1.50
Other street trees	169	953	15,632	14.4	13.9	4.30
Citywide total	1,277	6,261	112,324	100.0	100.0	4.44

***Table 10**—Net annual energy savings produced by Boulder park trees.*

Species	Electricity (MWh)	Natural gas (MBtu)	Total ($)	% of trees	% of total $	Avg. $/tree
Cottonwood	118	1,111	13,725	18.9	21.5	7.15
Green ash	73	692	8,514	10.8	13.4	7.77
Austrian pine	18	214	2,373	7.3	3.7	3.20
Willow	92	736	9,895	7.2	15.5	13.46
Siberian elm	49	461	5,709	5.7	9.0	9.93
Blue spruce	11	129	1,460	5.4	2.3	2.68
Crabapple	15	165	1,882	3.5	3.0	5.26
Honeylocust	21	197	2,462	3.0	3.9	7.97
Boxelder	20	199	2,406	2.9	3.8	8.07
White ash	9	100	1,128	2.3	1.8	4.88
Juniper	3	37	418	2.1	0.7	1.95
Russian olive	4	41	485	1.8	0.8	2.61
Pinyon pine	1	17	182	1.8	0.3	1.02
White fir	3	37	420	1.5	0.7	2.67
American linden	2	25	292	1.5	0.5	1.88
English oak	2	22	260	1.4	0.4	1.83
White/Silver poplar	22	160	2,237	1.3	3.5	17.61
Littleleaf linden	5	54	655	1.2	1.0	5.32
Bur oak	1	7	85	1.1	0.1	0.75
Cockspur hawthorn	0	4	51	1.1	0.1	0.46
Norway maple	5	52	607	1.0	1.0	5.89
Other park trees	74	683	8,525	17.3	13.4	4.85
Citywide total	549	5,143	63,771	100.0	100.0	6.27

Atmospheric Carbon Dioxide Reductions

Urban forests can reduce 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.

***Table 11**—Annual energy savings produced by Boulder street and park trees by tree type.*

Tree type	Street ($/tree)			Park ($/tree)		
	Large	Med.	Small	Large	Med.	Small
Deciduous	5.55	2.02	2.15	7.98	2.66	2.81
Conifer	2.88	3.04	0.95	2.97	3.32	1.41

Carbon Dioxide Reductions

Citywide, Boulder's municipal forest reduced atmospheric CO_2 by 4,227 tons annually. This benefit was valued at $63,409 or $1.79 per tree. Carbon dioxide released through decomposition and tree care activities totaled 325 tons, or 8% of the net total benefit. Reduction of energy plant CO_2 emissions totaled 2,017 tons, while sequestration by the trees was 2,535 tons. Avoided emissions are important in Colorado because fossil fuels are a critical energy source (80% of energy in Colorado; US EPA 2003). Coal has a relatively high CO_2 emission factor. Shading by trees during hot summers reduces the need for air conditioning, resulting in reduced use of coal for cooling energy production.

Silver maple, green ash, Siberian elm, and cottonwood accounted for the greatest CO_2 benefits (*Tables 12 and 13*). Tree species with the highest per tree benefits were white/silver poplar ($5.61 per tree), silver maple ($5.27 per tree), and willow ($4.31 per tree).

Air Quality Improvement

Urban trees improve air quality in five main ways:

1. Absorbing gaseous pollutants (ozone, nitrogen oxides, sulfur dioxides) 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. At the same time, most trees emit 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.

***Table 12**—CO_2 reductions, releases, and net benefits produced by street trees.*

Species	Sequestered (lb)	Decomp. release(lb)	Maint. release (lb)	Avoided (lb)	Net total (lb)	Total ($)	% of trees	% of total $	Avg. $/tree
Green ash	479,034	45,375	6,316	362,051	789,394	5,920	15.1	13.5	1.56
Siberian elm	509,255	63,113	5,774	433,265	873,633	6,552	9.6	15.0	2.70
Silver maple	980,317	166,155	9,442	632,747	1,437,467	10,781	8.1	24.6	5.27
Honeylocust	251,914	26,098	3,856	239,976	461,936	3,465	8.0	7.9	1.72
Crabapple	100,399	7,801	1,958	115,598	206,237	1,547	5.3	3.5	1.16
Norway maple	91,575	6,967	1,383	71,635	154,860	1,161	3.8	2.7	1.22
Russian olive	68,660	4,695	1,333	33,092	95,724	718	3.6	1.6	0.79
Juniper	12,801	621	667	18,257	29,770	223	3.6	0.5	0.25
Blue spruce	83,015	7,080	1,675	48,750	123,011	923	3.5	2.1	1.05
Cottonwood	129,046	18,591	2,583	112,223	220,095	1,651	2.8	3.8	2.34
Littleleaf linden	36,661	2,165	802	30,126	63,821	479	2.4	1.1	0.79
Austrian pine	26,371	1,770	1,068	36,524	60,057	450	2.3	1.0	0.78
White ash	44,518	2,206	595	43,217	84,934	637	1.9	1.5	1.34
Quaking aspen	29,212	1,229	460	21,569	49,092	368	1.9	0.8	0.78
Pinyon pine	6,161	254	349	9,223	14,780	111	1.9	0.3	0.24
Sugar maple	70,924	8,082	889	82,017	143,970	1,080	1.7	2.5	2.47
Hawthorn	8,752	387	215	2,760	10,910	82	1.6	0.2	0.20
Red oak	63,652	9,173	772	51,736	105,442	791	1.4	1.8	2.22
Red maple	13,871	660	238	7,476	20,448	153	1.4	0.4	0.43
Hackberry	16,701	1,542	458	26,665	41,365	310	1.4	0.7	0.89
Boxelder	45,340	4,371	585	35,106	75,490	566	1.3	1.3	1.76
Amur maple	7,968	319	189	2,605	10,064	75	1.3	0.2	0.24
Plum	5,798	262	88	16,313	21,760	163	1.1	0.4	0.58
American linden	33,121	4,866	673	16,045	43,627	327	1.1	0.8	1.20
Other street trees	381,049	50,617	6,249	372,637	696,821	5,226	14.4	11.9	1.44
Citywide total	3,496,112	434,401	48,617	2,821,613	5,834,707	43,760	100.0	100.0	1.73

Table 13—*CO_2 reductions, releases, and net benefits produced by park trees.*

Species	Sequestered (lb)	Decomp. release (lb)	Maint. release (lb)	Avoided (lb)	Net total (lb)	Total ($)	% of trees	% of total $	Avg. $/tree
Cottonwood	328,929	33,575	6,799	260,047	548,603	4,115	18.9	20.9	2.14
Green ash	228,213	17,275	2,751	160,528	368,715	2,765	10.8	14.1	2.53
Austrian pine	33,579	1,746	1,374	39,510	69,969	525	7.3	2.7	0.71
Willow	255,057	33,192	3,179	203,487	422,172	3,166	7.2	16.1	4.31
Siberian elm	145,424	8,793	1,570	108,435	243,495	1,826	5.7	9.3	3.18
Blue spruce	46,170	3,055	965	25,080	67,230	504	5.4	2.6	0.93
Crabapple	31,813	1,930	617	32,642	61,908	464	3.5	2.4	1.30
Honeylocust	56,336	4,087	810	47,330	98,768	741	3.0	3.8	2.40
Boxelder	63,267	3,763	756	44,455	103,204	774	2.9	3.9	2.60
White ash	22,736	741	300	19,305	41,000	308	2.3	1.6	1.33
Juniper	6,311	368	243	7,038	12,738	96	2.1	0.5	0.44
Russian olive	18,012	1,029	344	8,890	25,528	191	1.8	1.0	1.03
Pinyon pine	2,326	63	125	2,968	5,105	38	1.8	0.2	0.22
White fir	5,497	375	244	7,305	12,183	91	1.5	0.5	0.58
American linden	13,135	991	269	5,301	17,176	129	1.5	0.7	0.83
English oak	8,191	329	121	4,589	12,330	92	1.4	0.5	0.65
White/Silver poplar	57,094	8,875	724	47,558	95,054	713	1.3	3.6	5.61
Littleleaf linden	10,868	652	230	12,089	22,074	166	1.2	0.8	1.35
Bur oak	4,540	221	86	1,635	5,868	44	1.1	0.2	0.39
Hawthorn	2,669	87	65	865	3,382	25	1.1	0.1	0.23
Norway maple	15,322	843	219	10,690	24,950	187	1.0	1.0	1.82
Other park trees	217,940	19,633	3,234	163,352	358,425	2,688	17.3	13.7	1.53
Citywide total	1,573,426	141,621	25,026	1,213,099	2,619,877	19,649	100.0	100.0	1.93

Deposition and Interception

Pollutant uptake of nitrogen dioxide (NO_2), small particulate matter (PM_{10}), ozone (O_3), and sulfur dioxide (SO_2) by trees (pollution deposition and particulate interception) in Boulder is 5.8 tons, or $28,215 for all trees. Boulder trees are most effective at removing ozone (O_3), with an implied annual value of $19,093. Cottonwood, green ash, and silver maple contribute the most to pollutant uptake (*Tables 14* and *15*).

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) (*Tables 14* and *15)*. Together, 5.9 tons of pollutants are avoided annually with an implied value of $19,854. SO_2 and NO_2 are the most significant avoided pollutants.

BVOC Emissions

Biogenic volatile organic compound (BVOC) emissions from trees are significant. At a total of 3.4 tons, these emissions offset air quality improvement by 29% and represent a cost to the city of $17,189. Cottonwood (0.75 lb per tree per year), blue spruce (0.54 lb per tree per year), and silver maple (0.49 lb per tree per year) emit the most BVOCs.

Net Air Quality Improvement

Net air pollutants removed, released, and avoided are valued at $28,215 annually. On average, the benefit per tree is $0.79. Trees vary dramatically in their ability to produce net air-quality benefits. Large-canopied trees with large leaf surface areas produce the greatest benefits, sometimes despite higher than average BVOC emissions. The most valuable trees on a per-tree basis were white/silver poplar ($5.48), willow ($3.79), and Siberian elm

Table 14—*Pollutant deposition, avoided emissions, and emitted BVOCs, and net air-quality benefits produced by street tree species.*

Species	Deposition (lb)				Avoided (lb)				Released BVOCs (lb)	Net total (lb)	Total ($)	% of trees	% of total $	Avg. $/tree
	O_3	NO_2	PM_{10}	SO_2	NO_2	PM_{10}	VOC	SO_2						
Green ash	461	114	121	49	370	84	79	506	0	1,784	2,588	15.1	20.5	0.68
Siberian elm	633	158	173	79	442	100	95	604	0	2,285	3,264	9.6	25.8	1.34
Silver maple	1,504	372	393	175	628	145	138	884	−1,045	3,194	3,106	8.1	24.6	1.52
Honeylocust	354	90	94	39	243	55	52	335	−482	781	573	7.9	4.5	0.29
Crabapple	154	37	41	17	131	27	26	159	−2	591	869	5.3	6.9	0.65
Norway maple	48	12	14	5	76	17	16	99	−80	207	234	3.8	1.9	0.25
Russian olive	89	22	24	10	31	7	7	46	−1	236	314	3.6	2.5	0.35
Juniper	23	7	8	3	20	4	4	25	−85	10	−80	3.6	−0.6	−0.09
Blue spruce	88	25	31	11	51	11	11	67	−491	−196	−842	3.5	−6.7	−0.96
Cottonwood	225	55	60	25	112	26	24	156	−748	−65	−969	2.8	−7.7	−1.37
Littleleaf linden	40	10	11	5	30	7	7	42	−43	108	107	2.4	0.8	0.18
Austrian pine	66	19	23	8	41	9	8	50	−184	40	−152	2.3	−1.2	−0.26
White ash	18	4	5	2	47	10	10	59	0	155	247	1.9	2.0	0.52
Quaking aspen	3	1	1	0	23	5	5	30	−25	44	49	1.9	0.4	0.10
Pinyon pine	10	3	4	1	10	2	2	13	−41	3	−40	1.9	−0.3	−0.08
Sugar maple	114	28	29	12	91	19	18	114	−140	287	266	1.7	2.1	0.61
hawthorn	3	1	1	0	3	1	1	4	−0	12	17	1.6	0.1	0.04
Red oak	96	24	24	10	53	12	11	72	0	303	426	1.4	3.4	1.20
Red maple	4	1	1	0	7	2	2	11	0	28	43	1.4	0.3	0.12
Hackberry	19	5	5	2	28	6	6	37	0	108	165	1.4	1.3	0.47
Boxelder	45	11	12	5	36	8	8	49	0	173	251	1.3	2.0	0.78
Amur maple	2	0	1	0	2	1	1	4	−0	11	16	1.2	0.1	0.05
Plum	11	3	3	1	15	3	3	18	−0	57	87	1.1	0.7	0.31
American linden	46	11	12	5	14	4	3	23	−71	47	−28	1.1	−0.2	−0.10
Other street trees	568	143	154	65	392	87	82	516	−291	1,715	2,133	14.4	16.9	0.59
Citywide total	4,622	1,156	1,246	534	2,898	653	617	3,923	−3,728	11,918	20,733	100.0	100.0	0.50

Table 15—Pollutant deposition, avoided emissions and emitted BVOCs, and net air-quality benefits produced by park tree species.

Species	Deposition (lb)				Avoided (lb)				BVOC (lb)	Net total (lb)	Total ($)	% of tree	% of total $	Avg. $/tree
	O_3	NO_2	PM_{10}	SO_2	NO_2	PM_{10}	VOC	SO_2						
Green ash	275	68	71	30	192	39	36	222	0	933	1,836	10.8	24.5	1.68
Austrian pine	85	25	29	11	50	10	9	54	−236	36	−68	7.3	−0.9	−0.09
Willow	485	120	120	52	232	48	45	280	0	1,383	2,784	7.2	37.2	3.79
Siberian elm	144	36	41	18	129	26	24	149	0	568	1,093	5.7	14.6	1.90
Blue spruce	57	16	19	7	32	6	6	35	−296	−119	−409	5.3	−5.5	−0.75
Crabapple	61	15	16	7	41	8	7	45	−0.53	199	393	3.5	5.3	1.10
Honeylocust	95	24	25	10	56	11	11	65	−107	190	317	3.0	4.2	1.03
Boxelder	63	15	17	7	54	11	10	62	0	238	462	2.9	6.2	1.55
White ash	10	2	3	1	24	5	4	26	0	76	141	2.3	1.9	0.61
Juniper	17	5	6	2	9	2	2	10	−44	8	−10	2.1	−0.1	−0.05
Russian olive	32	8	8	4	11	2	2	12	0	79	162	1.8	2.2	0.87
Pinyon pine	4	1	1	0	4	1	1	4	−15	1	−8	1.8	−0.1	−0.05
White fir	14	4	5	2	9	2	2	10	−48	−1	−32	1.5	−0.4	−0.20
American linden	13	3	4	1	6	1	1	7	−25	13	12	1.5	0.2	0.08
English oak	4	1	1	0	6	1	1	6	0	21	41	1.4	0.5	0.29
White/Silver poplar	127	31	31	14	53	11	11	65	0	343	696	1.2	9.3	5.48
Littleleaf linden	20	5	5	2	15	3	3	17	−15	54	96	1.2	1.3	0.78
Bur oak	5	1	1	1	2	0	0	2	−22	−9	−31	1.1	−0.4	−0.27
Cockspur hawthorn	1	0	0	0	1	0	0	1	0	5	10	1.1	0.1	0.09
Norway maple	9	2	3	1	13	3	2	15	−13	35	58	1.0	0.8	0.56
Other park trees	320	81	86	37	193	39	37	224	−188	829	1,533	17.3	20.5	0.87
Citywide total	2,423	606	646	273	1,440	293	273	1,669	−2,986	4,638	7,482	100.0	100.0	0.74

($1.90). Among street trees, nearly three-quarters of net air-quality improvements are provided by three species (silver maple, Siberian elm, green ash); for park trees, willow provides 37% of total air quality benefits.

Stormwater Runoff Reduction

According to federal Clean Water Act regulations, municipalities must obtain a permit for managing their stormwater discharges into water bodies. Each city's stormwater management program must identify the Best Management Practices it will implement to reduce its pollutant discharge. Trees are mini-reservoirs, controlling runoff at the source (*Figure 10*). 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.

Boulder's municipal trees intercept 6 million ft^3 of stormwater annually, or 1,271 gal per tree on average. The total value of this benefit to the city is $532,311, or $14.99 per tree.

Certain species are much better at reducing stormwater runoff than others (*Tables 16* and *17*). Leaf type and leaf 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. Trees that perform well include Siberian elm ($46.23 per tree), silver/white poplar ($38.23 per tree), and silver maple ($31.23 per tree). Poor performers are species with relatively little leaf and stem surface area, such as hawthorn. Interception by Siberian elm alone accounts for 27% of the total dollar benefit for street trees. Although Siberian elm and poplar currently intercept large amounts of rainfall, they are not the most desirable species for other reasons including their invasiveness, brittle wood, shallow roots, and heavy

Figure 10—Trees in Boulder's University Hill neighborhood reduce stormwater runoff and pollutant loading.

Table 16*—Annual stormwater reduction benefits of Boulder street trees by species.*

Species	Rainfall intercep. (CCF)	Total ($)	% of trees	% of total $	Avg. $/tree
Green ash	3,760	33,190	15.1	9.3	8.72
Siberian elm	10,713	94,562	9.6	26.5	38.93
Silver maple	7,242	63,924	8.1	17.9	31.23
Honeylocust	3,472	30,647	8.0	8.6	15.25
Crabapple	400	3,533	5.3	1.0	2.65
Norway maple	864	7,624	3.8	2.1	8.03
Russian olive	263	2,319	3.6	0.7	2.56
Juniper	571	5,036	3.6	1.4	5.61
Blue spruce	2,198	19,403	3.5	5.4	22.12
Cottonwood	1,662	14,672	2.8	4.1	20.78
Littleleaf linden	451	3,983	2.4	1.1	6.55
Austrian pine	1,152	10,168	2.3	2.9	17.65
White ash	348	3,068	1.9	0.9	6.47
Quaking aspen	238	2,101	1.9	0.6	4.44
Pinyon pine	283	2,496	1.9	0.7	5.32
Sugar maple	715	6,314	1.7	1.8	14.45
Cockspur hawthorn	26	231	1.6	0.1	0.58
Red oak	514	4,536	1.4	1.3	12.74
Red maple	92	809	1.4	0.2	2.29
Hackberry	398	3,515	1.4	1.0	10.04
Boxelder	359	3,164	1.3	0.9	9.83
Amur maple	24	214	1.3	0.1	0.68
Plum	86	760	1.1	0.2	2.72
American linden	396	3,495	1.1	1.0	12.80
Other street trees	4,247	37,489	14.4	10.5	10.32
Citywide total	40,473	357,255	100	100	14.13

litter drop. The Urban Forestry Division is planting other large tree species that will be less costly to maintain and that provide comparable benefits.

Aesthetic, Property Value, Social, Economic 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 (*Figure 11*). 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 with and without trees was used to estimate the contribution 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 Boulder include (1) applying data derived from the southeastern United States to Boulder and (2) extrapolating results from front-yard trees on residential properties to street trees in various locations (e.g., commercial vs. residential) and park trees.

The estimated total annual benefit associated with aesthetic and other benefits is approximately $1.94 million, or $54.67 per tree on average (*Tables 18* and *19*). The magnitude of this benefit is related to the relatively high local median sales price for single family homes ($413,000), as well as tree growth rates.

Table 17*—Annual stormwater reduction benefits of Boulder park trees by species.*

Species	Rainfall intercep. (CCF)	Total ($)	% of trees	% of total $	Avg. $/tree
Cottonwood	4,336	38,270	18.9	21.9	19.93
Green ash	1,824	16,103	10.8	9.2	14.71
Austrian pine	1,439	12,705	7.3	7.3	17.15
Willow	2,331	20,578	7.2	11.8	28.00
Siberian elm	3,012	26,585	5.7	15.2	46.23
Blue spruce	1,271	11,220	5.4	6.4	20.62
Crabapple	135	1,193	3.5	0.7	3.33
Honeylocust	772	6,811	3.0	3.9	22.04
Boxelder	497	4,387	2.9	2.5	14.72
White ash	175	1,545	2.3	0.9	6.69
Juniper	258	2,279	2.1	1.3	10.60
Russian olive	75	660	1.8	0.4	3.55
Pinyon pine	105	929	1.8	0.5	5.22
White fir	241	2,128	1.5	1.2	13.56
American linden	145	1,284	1.5	0.7	8.28
English oak	58	512	1.4	0.3	3.61
White/Silver poplar	550	4,855	1.3	2.8	38.23
Littleleaf linden	148	1,303	1.2	0.7	10.59
Bur oak	30	265	1.1	0.2	2.34
Cockspur hawthorn	9	77	1.1	0.0	0.71
Norway maple	151	1,336	1.0	0.8	12.97
Other park trees	2,269	20,032	17.3	11.4	11.40
Citywide total	19,832	175,057	100	100	17.21

Tree species that produce the highest average annual benefits are Siberian elm ($159 per tree), silver maple ($101 per tree), and white ash (*Fraxinus americana*) ($82), while small conifers such as juniper ($11 per tree) and pinyon pine (*Pinus edulis*) ($10 per tree) are examples of trees that produce the least benefits. The most valuable street trees in terms of aesthetics and other benefits are found in the Northeast Broadway neighborhood ($79 per tree), while benefits from those in the Gunbarrel neighborhood are less than half of that ($37).

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

Total annual benefits produced by Boulder's street trees are estimated to have a value of $2.1 million ($84 per tree, $21 per capita) (*Table 20*). Annual park tree benefits total $620,973 ($61 per tree, $6 per capita) (*Table 20*). Total annual benefits for street and park trees are $2.74 million, or $77 per

Figure 11—Trees beautify a Boulder neighborhood.

***Table 18**—Total annual increases in aesthetic and other benefits produced by street trees ($/tree).*

Species	Total ($)	% of total trees	% of total $	Avg. $/tree
Green ash	237,680	15.1	15.0	62.45
Siberian elm	385,010	9.6	24.3	158.51
Silver maple	206,110	8.1	13.0	100.69
Honeylocust	136,324	8.0	8.6	67.86
Crabapple	34,790	5.3	2.2	26.06
Norway maple	45,932	3.8	2.9	48.40
Russian olive	22,952	3.6	1.5	25.36
Juniper	14,938	3.6	0.9	16.63
Blue spruce	37,782	3.5	2.4	43.08
Cottonwood	42,408	2.8	2.7	60.07
Littleleaf linden	34,782	2.4	2.2	57.21
Austrian pine	20,145	2.3	1.3	34.97
White ash	39,102	1.9	2.5	82.49
Quaking aspen	22,447	1.9	1.4	47.46
Pinyon pine	8,062	1.9	0.5	17.19
Sugar maple	17,602	1.7	1.1	40.28
Cockspur hawthorn	6,879	1.6	0.4	17.20
Red oak	22,056	1.4	1.4	61.96
Red maple	11,809	1.4	0.7	33.45
Hackberry	18,997	1.4	1.2	54.28
Boxelder	21,433	1.3	1.4	66.56
Amur maple	5,485	1.3	0.4	17.41
Plum	7,598	1.1	0.5	27.14
American linden	18,862	1.1	1.2	69.09
Other street trees	166,674	14.4	10.5	45.88
Citywide total	1,585,861	100	100	62.73

tree and $27 per capita. Over the same period, annual tree-related expenditures are estimated to be $752,606 ($21 per tree, $7 per capita).

Net annual benefits (benefits minus costs) are $2 million, or $56 per tree and $19 per capita. The Boulder municipal forest currently returns $3.64 for every $1 spent on management. Boulder's benefit-cost ratio of 3.64 exceeds those reported for Bismarck, ND (3.09), Glendale, AZ (2.41), Fort Collins (2.18), Cheyenne, WY (2.09), and Berkeley, CA (1.37) (McPherson et al. 2005).

Boulder's municipal trees have beneficial effects on the environment. Approximately 29% of the annual benefits are environmental services. Stormwater runoff reduction represents two-thirds of environmental benefits, with energy savings accounting for another 22%. Carbon dioxide reduction (8%) and air quality improvement (4%) provide the remaining environmental benefits. As in most cities and especially in cities with high housing prices, annual increases in aesthetic and other benefits are substantial, accounting for 71% of total annual benefits in Boulder.

Average annual benefits vary among species due to differences in sizes and growth rates. Among street trees, large deciduous trees offer the greatest benefits ($105 per tree), a value nearly twice as high as the next tree-type category (*Figure 12*). Park trees show a similar pattern (data not shown). When considering total benefits, large trees provide the highest average return for the investment dollar. Increased value is primarily due to aesthetic benefits

Table 19—*Total annual increases in aesthetic and other benefits produced by park trees ($/tree).*

Species	Total ($)	% of total trees	% of total $	Avg. $/tree
Cottonwood	66,899	18.9	18.8	34.84
Green ash	52,498	10.8	14.8	47.94
Austrian pine	14,499	7.3	4.1	19.57
Willow	35,619	7.2	10.0	48.46
Siberian elm	43,786	5.7	12.3	76.15
Blue spruce	12,302	5.4	3.5	22.61
Crabapple	6,165	3.5	1.7	17.22
Honeylocust	13,801	3.0	3.9	44.66
Boxelder	15,762	2.9	4.4	52.89
White ash	11,215	2.3	3.2	48.55
Juniper	2,393	2.1	0.7	11.13
Russian olive	3,289	1.8	0.9	17.68
Pinyon pine	1,703	1.8	0.5	9.57
White fir	2,673	1.5	0.8	17.03
American linden	4,838	1.5	1.4	31.21
English oak	3,233	1.4	0.9	22.77
White/Silver poplar	5,798	1.3	1.6	45.65
Littleleaf linden	4,557	1.2	1.3	37.05
Bur oak	1,498	1.1	0.4	13.25
Cockspur hawthorn	1,121	1.1	0.3	10.28
Norway maple	3,008	1.0	0.9	29.20
Other park trees	48,358	17.3	13.6	27.52
Citywide total	355,014	100	100	34.90

and energy savings associated with greater crown volume and leaf area. From an environmental perspective, large deciduous trees provide the highest level of benefits on Boulder's streets and parks.

Tables 21 and *22* show the total annual benefits in dollars for the predominant street tree species in Boulder. Siberian elms produce the greatest benefits among street ($209 per tree, 23% of total benefits) and park trees ($137 per tree, 12%). For street trees, silver maples ($151 per tree; 15%) produce the second highest benefits. Among park trees, cottonwoods have a lower per tree value ($113), but contribute the greatest percent of value (18%).

Table 20—*Benefit–cost summary for all public trees.*

	Street			Park			Total		
Benefits	Total ($)	$/tree	$/capita	Total ($)	$/tree	$/capita	Total ($)	$/tree	$/capita
Energy	112,324	4.44	1.09	63,771	6.27	0.62	176,095	4.96	1.71
CO_2	43,760	1.73	0.42	19,649	1.93	0.19	63,409	1.79	0.61
Air Quality	20,733	0.58	0.20	7,482	0.74	0.07	28,215	0.79	0.27
Stormwater	357,255	14.13	3.46	175,057	17.21	1.70	532,312	14.99	5.16
Aesthetic/Other	1,585,860	62.73	15.36	355,014	34.90	3.44	1,940,874	54.67	18.80
Total benefits	2,119,932	83.62	20.54	620,973	61.05	6.02	2,740,905	77.20	26.56
Total costs							752,606	21.20	7.29
Net benefits							1,988,299	56.01	19.26
Benefit–cost ratio								3.64	

Table 21*—Average annual benefits of street trees by species ($).*

Species	Energy	CO_2	Air quality	Stormwater	Aesthetic/Other	Total
Green ash	3.74	1.56	0.89	8.72	62.45	77.35
Siberian elm	6.95	2.70	1.80	38.93	158.51	208.88
Silver maple	11.17	5.27	2.80	31.23	100.69	151.16
Honeylocust	4.63	1.72	0.59	15.25	67.86	90.06
Crabapple	4.30	1.16	0.85	2.65	26.06	35.02
Norway maple	3.25	1.22	0.34	8.03	48.40	61.24
Russian olive	1.27	0.79	0.52	2.56	25.36	30.50
Juniper	0.97	0.25	−0.04	5.61	16.63	23.42
Blue spruce	2.43	1.05	−0.79	22.12	43.08	67.90
Cottonwood	5.96	2.34	−0.82	20.78	60.07	88.33
Littleleaf linden	1.89	0.79	0.29	6.55	57.21	66.72
Austrian pine	3.12	0.78	−0.06	17.65	34.97	56.46
White ash	4.21	1.34	0.59	6.47	82.49	95.11
Quaking aspen	2.05	0.78	0.12	4.44	47.46	54.85
Pinyon pine	0.92	0.24	−0.05	5.32	17.19	23.62
Sugar maple	8.60	2.47	1.06	14.45	40.28	66.87
Cockspur hawthorn	0.24	0.20	0.05	0.58	17.20	18.27
Red oak	5.71	2.22	1.67	12.74	61.96	84.30
Red maple	0.78	0.43	0.14	2.29	33.45	37.10
Hackberry	3.23	0.89	0.56	10.04	54.28	69.01
Boxelder	4.31	1.76	1.02	9.83	66.56	83.49
Amur maple	0.28	0.24	0.06	0.68	17.41	18.67
Plum	2.55	0.58	0.38	2.72	27.14	33.37
American linden	1.50	1.20	0.19	12.80	69.09	84.79
Other street trees	4.30	1.44	0.86	10.32	45.88	62.80

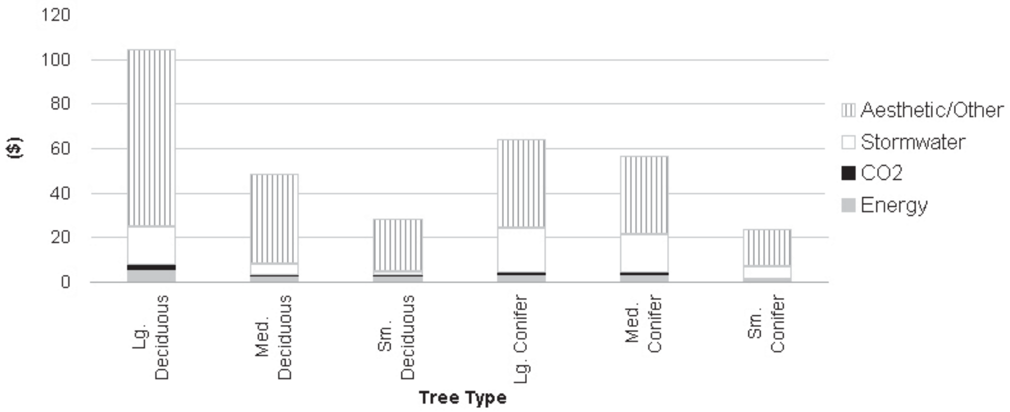


Figure 12—Average annual benefits of street trees by tree type. (Data for air quality not shown. Values range from $−0.58 for large coniferous trees to $1.15 for large deciduous trees.)

Figure 13 illustrates the average annual street tree benefits per tree by neighborhood, and reflects differences in tree types and population ages. Differences across neighborhoods are pronounced: average annual benefits range from $43 per tree in the Gunbarrel neighborhood to $98 per tree in Northeast Broadway.

Table 22*—Average annual benefits of park trees by species ($).*

Species	Energy	CO_2	Air quality	Stormwater	Aesthetic/other	Total
Cottonwood	7.15	2.14	−0.83	19.93	34.84	63.24
Green ash	7.78	2.53	1.68	14.71	47.94	74.63
Austrian pine	3.20	0.71	−0.09	17.15	19.57	40.53
Willow	13.46	4.31	3.79	28.00	48.46	98.02
Siberian elm	9.93	3.18	1.90	46.23	76.15	137.39
Blue spruce	2.68	0.93	−0.75	20.62	22.61	46.10
Crabapple	5.26	1.30	1.10	3.33	17.22	28.21
Honeylocust	7.97	2.40	1.03	22.04	44.66	78.10
Boxelder	8.08	2.60	1.55	14.72	52.89	79.84
White ash	4.88	1.33	0.61	6.69	48.55	62.06
Juniper	1.95	0.44	−0.05	10.60	11.13	24.07
Russian olive	2.61	1.03	0.87	3.55	17.68	25.74
Pinyon pine	1.02	0.22	−0.05	5.22	9.57	15.98
White fir	2.67	0.58	−0.20	13.56	17.03	33.64
American linden	1.88	0.83	0.08	8.29	31.21	42.29
English oak	1.83	0.65	0.29	3.61	22.77	29.14
White/Silver poplar	17.61	5.61	5.48	38.23	45.65	112.59
Littleleaf linden	5.32	1.35	0.78	10.59	37.05	55.09
Bur oak	0.75	0.39	−0.27	2.34	13.25	16.47
Cockspur hawthorn	0.46	0.23	0.09	0.71	10.28	11.78
Norway maple	5.90	1.82	0.56	12.97	29.20	50.44
Other park trees	4.85	1.53	0.87	11.40	27.52	46.18

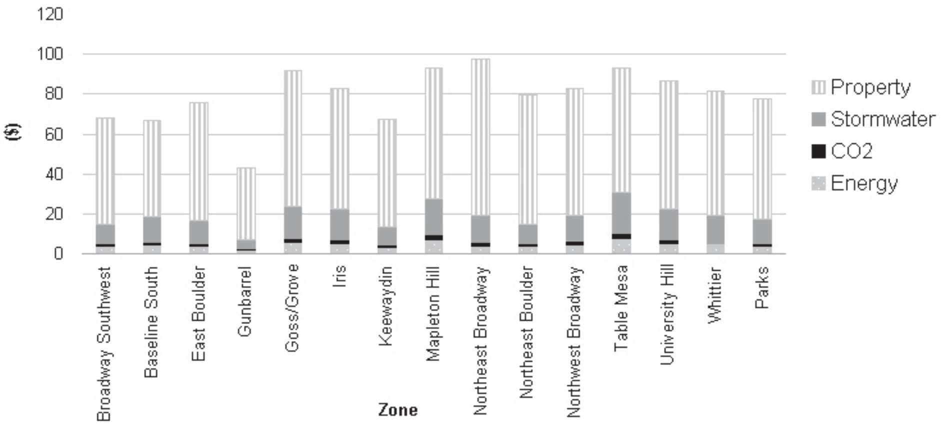


Figure 13—Average annual street tree benefits per tree by neighborhood.

Figure 14—New trees will grow to provide substantial benefits to the citizens of Boulder.

Chapter Five—Management Implications

Boulder's urban forest reflects the values, lifestyles, preferences, and aspirations of current and past residents. It is a dynamic legacy, currently dominated by older trees planted several generations ago, but with a future to be determined by young trees whose character will change greatly over the next decades (*Figure 14*). Drought during the past few years has left its mark in the form of increased tree mortality rates.

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 Boulder's street and park 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 management costs. The structural features of a sustainable urban forest include adequate complexity (species and age diversity), well-adapted, healthy trees, appropriate tree size distribution and cost-efficient management. Focusing on these components—resource complexity, resource extent, and maintenance—will help refine broader municipal tree management goals.

Resource Complexity

Though Boulder has a rich mix of species with 105 species of street trees, a heavy emphasis is placed on green ash, which makes up 14% of the population. Green ash provides a high level of benefits at approximately $75 per tree and this number will increase as the trees age and grow larger (currently nearly half of green ash trees are under 6 in in DBH). However, a disease or pest infestation, of the emerald ash borer, for example, could result in a severe loss to the city. For this reason, a more diverse mix of species should be planted: some proven performers, some species that are more narrowly adapted, and a small percentage of new introductions for evaluation. Proven performers include the American linden (*Tilia americana*), red oak (*Quercus rubra*), bur oak (*Quercus macrocarpa*), swamp white oak (*Quercus bicolor*), catalpa (*Catalpa speciosa*), hackberry (*Celtis occidentalis*), and horsechestnut (*Aesculus hippocastanum*). Species that merit planting and evaluation include Shumard (*Quercus shumardii*) and chinquapin (*Q. muehlenbergii*) oaks, hornbeam (*Carpinus betulus*), dawn redwood (*Metasequoia glyptostroboides*), and new cultivars of disease-resistant elms such as 'Frontier' and 'Pioneer' (*Ulmus* hybrids).

Figure 15 displays trees in the smallest DBH size classes, indicating trends in new and replacement trees. Green ash, Siberian elm, honeylocust, and crabapple are most common. Most of the species shown are large trees that have potential to be functionally productive. Only crabapple, Amur maple, cockspur hawthorn, and juniper are smaller trees. New introductions include white ash, red maple, and littleleaf linden. Hence, it appears that a diverse mix of large tree species is being planted, though green ash has been planted at twice the rate of the next most common tree. This species is not planted by the Urban Forestry Division, but they have been planted in newly developed areas. Siberian elms are also not planted by the Division; trees of this species in the smallest DBH class represent volunteers.

Boulder's municipal forest has a diverse age structure that should provide a steady stream of future benefits from continuous canopy cover. Although some neighborhoods lack age diversity, such as Gunbarrel, where almost 80% of trees are in the youngest class, most of the trees will be large at maturity, and if properly cared for, will provide a high level of benefits in the future.

In summary, to improve Boulder's urban forest resource complexity we recommend:

- Diversify new plantings by developing a list of species that includes species proven to perform well in most conditions, some species that are

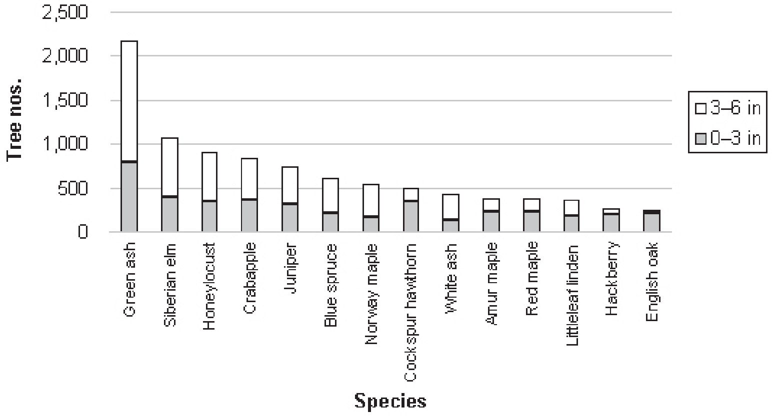


Figure 15—Municipal trees being planted in the highest numbers by the Urban Forestry Division and in areas of new development. Siberian elms are no longer being planted; those shown here are volunteers.

more narrowly adapted, and a small percentage of new introductions for evaluation.

- Increase age diversity in neighborhoods with low diversity by planting empty sites and by replanting in sites where trees have been removed.

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 quality and extent of Boulder's canopy cover.

Increasing street tree canopy cover is a goal outlined in the Boulder Valley Comprehensive Plan. Currently the stocking rate for street trees is only 20% and street and public trees cover only 3% of the city. Canopy cover will increase as young trees mature, but there is room along Boulder's streets for many more trees. We recommend that the city undertake a windshield survey to determine the number of planting sites that are actually available for different sizes of trees. To provide the greatest level of benefits in the future, sites for large trees should be planted first wherever possible, followed by those for medium and then small trees. Focusing planting efforts in zones where stocking levels are lowest will improve the distribution of benefits across neighborhoods.

The city should continue to insure that adequate space is provided for trees planted in new developments. Increased tree planting in parking lots to provide shade is another strategy to that could be applied to new and existing development. In summary, to improve the extent of Boulder's urban forest we recommend that the City:

- Conduct a windshield survey to count and categorize planting sites, then develop and implement a Street Tree Planting Master Plan to increase street tree stocking with a diverse mix of well-adapted species.

- Develop a list of tree species that cannot be planted because their maintenance costs exceed benefits. Review this list, as well as the list of trees that can be planted, with the Planning department, landscape architects, and developers. Update both lists on a regular basis.

- Continue to insure adequate space for trees in new developments and encourage soil management. Encourage the use of structural soils when appropriate.

- Review and revise parking lot shade guidelines and enforcement to increase canopy cover.

Maintenance

Boulder's maintenance challenge in the coming years will be to care properly for the large number of trees in the smallest size classes. Currently, newly planted trees are only trained once, after five years, and then pruning is done on an 8- or 10-year rotation (for park and street trees, respectively) after the tree reaches a DBH of 9 in. Small street trees are pruned even less frequently—only about 300 of 12,000 trees each year. Ideally, young trees should be pruned for structure and form at least every four years after planting.

Developing a strong young-tree care program is imperative to insure that the trees survive the establishment period and make the transition into well-structured, healthy mature trees that require minimal pruning. An effective program will provide regular watering and tree basin inspection during the first several years. Staking should be adjusted and removed once it is no longer needed. Young trees should be pruned for structure and form as needed. Investing in the young-tree-care program will improve survival rates and reduce future costs for routine care as trees mature. Also, well-trained trees are less likely to be damaged during storms than trees that have not developed a strong structure.

Cottonwood, silver maple, and willow have a large proportion of their populations in the larger size classes. These mature trees are responsible for a relatively large proportion of the current benefits due to their size. However, these species develop invasive roots and brittle wood with age. Therefore, continued regular inspection and pruning of these trees is essential to sustaining safe conditions and the current high level of benefits in the short term.

As Boulder implements Smart Growth policies there will be increased pressure to remove large, old trees for infill development, and other trees will be adversely impacted by construction practices. Ordinances to preserve and protect large trees should be scrutinized and strengthened if needed. The community's heritage trees represent a substantial investment and produce benefits far greater than their maintenance costs.

Reducing sidewalk and sewer line repair expenditures is a cost-savings strategy for Boulder, which spends about $161,000 ($4.90 per tree) annually on infrastructure repairs. Most conflicts between tree roots and sidewalks occur where trees are located in cutouts and narrow planting strips less than 4-ft wide. Expanding cutouts, meandering sidewalks around trees, and avoiding shallow-rooting species are strategies that may be cost-effective when functional benefits associated with increased longevity are considered (Costello and Jones 2003).

In summary, we recommend that the City:

- Develop a strong young-tree care program that includes regular watering, staking adjustment, and inspection and pruning on at least a four-year cycle.
- Sustain the current level of inspection and pruning for older trees, as they produce substantial benefits but require intensive care to manage the shallow roots and brittle wood with some species.
- Review the adequacy of current ordinances to preserve and protect large trees from development impacts, and strengthen the ordinances as needed to retain benefits that these heritage tree can produce.
- Identify and implement cost-effective strategies to reduce conflicts between tree roots and hardscape that will prolong the useful lifespan of mature trees.

Figure 16—Trees shade the pedestrian area of the Pearl Street Mall, providing Boulder's residents with cleaner air, reduced atmospheric CO_2, cooler summer temperatures, and a more beautiful, economically viable environment.

Chapter Six—Conclusion

This analysis describes structural characteristics of the street tree population and uses tree growth and geographic data for Boulder to model 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 and park trees in Boulder that can be utilized to make informed management and planning decisions.

Boulder's 35,500 street and park trees are a valuable asset (*Figure 16*), providing approximately $2.7 million ($77 per tree) in annual gross benefits. Benefits to the community are most pronounced for increased local property values, which enhance property tax revenue for the city. Less tangible, but perhaps just as important are the effects of Boulder's tree-lined streets on attracting and retaining businesses and increasing commercial activity in shopping areas. Stormwater runoff reduction and energy savings are also significant benefits. Thus, street and park trees are found to play a particularly important role in maintaining the environmental, economic, and aesthetic qualities of the city.

Boulder spends approximately $750,000 maintaining its trees or $21 per tree. Expenditures for pruning and tree removal account for about one-third of total costs, and infrastructure repair associated with tree roots costs the City approximately $160,000 per year.

After costs are taken into account, Boulder's municipal tree resource provides approximately $2 million, or $56 per tree ($19 per capita) in net annual benefits to the community. Over the years, Boulder has invested millions of dollars in its municipal forest. **Citizens are seeing a return on their investment—receiving $3.64 in benefits for every $1 spent on tree care.** The fact that Boulder's benefit–cost ratio of 3.64 exceeds ratios reported for five comparable cities (3.09 in Bismarck to 1.37 in Berkeley) indicates that the program is not only operationally efficient, but capitalizing on the functional services its trees can produce. As the resource matures, continued investment in management is critical to insuring that residents will receive this level of return on investment in the future.

Boulder's municipal trees are a dynamic resource. Managers of this resource and the community alike can delight in knowing that street and park 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 increase the city's canopy cover as the tree population structure changes and the city continues to grow, putting space for trees at a premium.

Management recommendations derived from this analysis include the following:

- Diversify new plantings by developing a list of species that includes trees proven to perform well in most conditions, some species that are more narrowly adapted, and a small percentage of new introductions for evaluation.
- Increase age diversity in neighborhoods with low diversity by planting empty sites and replanting in sites where trees have been removed.
- Conduct a windshield survey to count and categorize planting sites, then develop and implement a Street Tree Planting Master Plan to increase street tree stocking with a diverse mix of well-adapted species.
- Develop a list of tree species that cannot be planted because their maintenance costs exceed benefits. Review this list, as well as the list of trees that can be planted, with the Planning Department, landscape architects, and developers. Update both lists on a regular basis.

- Continue to insure adequate space for trees in newly developed areas. Encourage the use of structural soils when appropriate.

- Review and revise parking lot shade guidelines and enforcement to increase canopy cover.

- Develop a strong young-tree care program that includes regular watering, early adjustment of stakes, and inspection and pruning on at least a four-year cycle.

- Sustain the current level of inspection and pruning for older trees, as they produce substantial benefits but require intensive care to manage shallow roots, brittle wood, and weediness associated with some species.

- Review the adequacy of current ordinances to preserve and protect large trees from development impacts, and strengthen as needed to retain the benefits that these heritage trees can produce.

- Identify and implement cost-effective strategies to reduce conflicts between tree roots and hardscape in order to prolong the useful lifespan of mature trees.

Figure 17—Trees line the median of Mapleton Avenue in the historic Mapleton neighborhood in the 21st century. For a comparison with the late 19th century, see Figure 1 on page 11.

Appendix A—Tree Distribution

Table A1*—Tree numbers by size class (DBH in inches) for all street and park trees.*

Species	0-3	3-6	6-12	12-18	18-24	24-30	30-36	36-42	>42	Total
Broadleaf deciduous large (BDL)										
Green ash	783	1,393	1,633	577	298	178	35	3	1	4,901
Siberian elm	393	675	869	445	227	241	92	42	20	3,004
Populus species	79	179	725	719	320	300	128	87	89	2,626
Honeylocust	344	560	773	383	111	121	22	4	0	2,318
Silver maple	35	199	238	221	392	593	300	117	50	2,145
Norway maple	158	381	380	99	24	10	0	0	0	1,052
Willow	6	44	181	211	91	105	71	57	64	830
Littleleaf linden	175	185	311	44	12	3	0	1	0	731
White ash	130	298	251	17	7	1	0	1	0	705
Boxelder	61	101	250	153	36	17	0	2	0	620
Sugar maple	127	103	87	73	65	25	2	0	1	483
Red oak	103	104	81	52	33	51	13	9	1	447
Hackberry	196	69	118	26	14	11	0	0	0	434
American linden	102	43	117	98	41	23	3	1	0	428
Red maple	227	149	30	5	3	0	0	0	0	414
American elm	20	43	69	56	26	63	27	10	3	317
English oak	207	36	32	11	4	0	0	0	0	290
Tree of heaven	44	84	94	36	16	9	3	0	0	286
Black walnut	21	33	90	68	37	16	0	0	0	265
Catalpa	119	52	26	21	19	17	3	3	0	260
Bur oak	148	54	24	11	1	2	0	0	1	241
Pin oak	4	23	122	45	22	15	1	0	0	232
Black locust	23	28	75	48	18	8	2	2	2	206
Swamp white oak	139	47	5	5	0	2	0	0	0	198
White/Silver poplar	4	3	15	26	23	22	16	25	14	148
Kentucky coffeetree	36	25	18	4	3	1	0	0	0	87
Autumn blaze maple	21	20	1	0	0	0	0	0	0	42
Baldcypress	6	9	17	7	0	0	0	0	0	39
Lombardy poplar	8	11	9	2	1	0	0	0	0	31
White oak	3	11	6	2	1	3	0	2	1	29
Upright English oak	14	9	1	0	0	0	0	0	0	24
Gambel oak	9	11	3	0	0	0	0	0	0	23
Sycamore	0	1	1	1	6	6	1	1	1	18
Japanese pagoda tree	7	0	1	2	0	0	0	0	0	10
Manchurian ash	6	1	0	0	0	0	0	0	0	7
Ginkgo	3	4	0	0	0	0	0	0	0	7
Shumard oak	2	0	0	0	0	2	1	1	1	7
Yellow buckeye	4	0	0	0	0	0	0	0	0	4
Pecan	1	1	0	1	1	0	0	0	0	4
Beech	3	0	0	1	0	0	0	0	0	4
Tulip tree	0	3	0	0	1	0	0	0	0	4
Shingle oak	0	0	4	0	0	0	0	0	0	4

Species	0-3	3-6	6-12	12-18	18-24	24-30	30-36	36-42	>42	Total
Chestnut oak	0	0	2	0	0	0	1	1	0	4
Elm	0	3	1	0	0	0	0	0	0	4
Rocky Mtn. maple	2	1	0	0	0	0	0	0	0	3
Black maple	1	0	1	0	0	0	0	0	0	2
European ash	0	0	1	0	1	0	0	0	0	2
Willow oak	0	1	0	0	0	1	0	0	0	2
Redcedar	0	1	1	0	0	0	0	0	0	2
American chestnut	0	0	1	0	0	0	0	0	0	1
Camperdown elm	0	0	1	0	0	0	0	0	0	1
Total	3,774	4,998	6,665	3,470	1,854	1,846	721	369	249	23,946
Broadleaf deciduous medium (BDM)										
Quaking aspen	133	245	98	2	0	0	0	0	0	478
Pear	118	117	47	5	0	0	0	0	0	287
Mountain ash	26	39	26	10	0	0	0	0	0	101
Goldenrain tree	39	21	10	5	0	0	0	0	0	75
Birch	20	11	6	1	0	0	0	0	0	38
European hornbeam	27	9	0	1	0	0	0	0	0	37
Mulberry	5	2	6	7	7	4	4	0	0	35
Turkish hazelnut	10	7	14	3	0	0	0	0	0	34
Ohio buckeye	8	10	9	4	0	0	0	0	0	31
Horsechestnut	8	1	9	3	4	0	1	1	0	27
English elm	2	1	1	0	0	0	1	1	0	6
Sycamore maple	1	0	0	1	1	0	0	0	0	3
Weeping white mulberry	1	2	0	0	0	0	0	0	0	3
Paulownia	2	0	0	0	0	0	0	0	0	2
Total	400	465	226	42	12	4	6	2	0	1,157
Broadleaf deciduous small (BDS)										
Crabapple	360	474	580	256	15	8	0	0	0	1,693
Russian olive	93	453	404	132	8	1	0	0	0	1,091
Cockspur hawthorn	351	142	13	2	1	0	0	0	0	509
Amur maple	225	156	25	3	0	0	0	0	0	409
Plum	180	135	18	3	0	0	0	0	0	336
Chokecherry	148	112	18	0	0	0	0	0	0	278
Cherry plum	32	58	40	4	1	0	0	1	0	136
Washington hawthorn	15	42	4	1	0	0	0	0	0	62
Japanese tree lilac	55	6	1	0	0	0	0	0	0	62
Redbud	22	10	7	0	0	0	0	0	0	39
Peach	8	21	1	0	0	0	0	0	0	30
Downy hawthorn	22	4	2	0	0	0	0	0	0	28
Apricot	0	16	3	0	0	1	0	0	0	20
Hedge maple	6	8	5	0	0	0	0	0	0	19
Serviceberry	17	2	0	0	0	0	0	0	0	19
Alder	3	4	0	1	3	0	0	0	0	11
Russian hawthorn	6	4	0	0	0	0	0	0	0	10
Buckthorn	10	0	0	0	0	0	0	0	0	10
Smoketree	2	1	0	0	0	0	0	0	0	3

Species	0-3	3-6	6-12	12-18	18-24	24-30	30-36	36-42	>42	Total
Sumac	1	0	0	0	0	0	0	0	0	1
Total	1,556	1,648	1,121	402	28	10	0	1	0	4,766
Broadleaf evergreen medium (BEM)										
Magnolia	2	1	2	0	0	0	0	0	0	5
Total	2	1	2	0	0	0	0	0	0	5
Conifer evergreen large (CEL)										
Blue spruce	218	396	421	265	98	20	3	0	0	1,421
Ponderosa pine	13	73	129	85	13	6	1	0	0	320
White fir	56	47	44	31	13	4	0	0	0	195
Douglas fir	4	25	80	41	10	0	0	0	0	160
White spruce	9	6	18	5	0	0	0	0	0	38
Western white pine	18	3	3	2	0	0	0	0	0	26
Arborvitae	15	4	0	0	0	0	0	0	0	19
Norway spruce	0	8	3	0	0	0	0	0	0	11
Subalpine fir	3	3	2	0	0	0	0	0	0	8
Total	336	565	700	429	134	30	4	0	0	2,198
Conifer evergreen medium (CEM)										
Austrian pine	95	419	495	241	51	13	2	1	0	1,317
Scotch pine	17	28	64	54	18	1	0	0	0	182
Limber pine	32	5	5	8	1	0	0	0	0	51
Lodgepole pine	2	11	14	5	0	0	0	0	0	32
Yew	1	0	0	0	0	0	0	0	0	1
Total	147	463	578	308	70	14	2	1	0	1,583
Conifer evergreen small (CES)										
Juniper	311	434	268	79	14	6	1	0	0	1,113
Pinyon pine	125	350	158	14	0	0	0	0	0	647
Bristlecone pine	25	27	8	1	0	0	0	0	0	61
Dwarf Alberta spruce	18	0	0	0	0	0	0	0	0	18
Mugo pine	0	3	5	0	0	0	0	0	0	8
Total	479	814	439	94	14	6	1	0	0	1,847

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.

Growth Modeling

Tree growth models for the Northern Mountain and Prairie region were developed from data (McPherson et al. 2003) collected in Fort Collins, CO. Fort Collins serves as the reference city for this region, which includes other areas of the central and northern United States that share similar tree species, tree growth patterns, and environmental conditions. For the regional modeling, a stratified random sample of 847 street trees belonging to the 20 most abundant tree species in Fort Collins was measured to establish relations between tree age, size, leaf area and biomass.

Information spanning the life cycle of predominant tree species was collected. The inventory was stratified into nine DBH classes for sampling:

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

Thirty-five to 70 trees of each species were randomly selected to survey, 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 using historical planting records. Fieldwork in Fort Collins was conducted in June and July 2002.

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).

Nonlinear regression was used to fit predictive models—with DBH as a function of age—for each of the 20 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).

The public trees of Boulder were fitted to the growth models for the Northern Mountain and Prairie climate region. The information used is based on the city's tree inventory which began in 1986 for street trees and in 1988 for park trees; a reinventory was completed in 2002 and 2004 for street and park trees, respectively.

Identifying and Calculating Benefits

Annual benefits for Boulder'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 CO_2 released due to decomposition of wood from removed trees do consider average annual mortality.) This approach directly connects benefits with tree-size variables such DBH and LSA (leaf surface area). 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 economics). 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 Boulder, 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 stormwater 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 two to three 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 20 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 Boulder'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 Fort Collins (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 the 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, multi-family 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 (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 thermostat settings were 78°F (25°C); winter settings were 68°F (20°C) during the day and 60°F (16°C) 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 B1*).

Weather data for a typical meteorological year (TMY2) from Denver International Airport were used (Marion and Urban 1995). Dollar values for energy savings were based on Boulder prices for the 2004 for electricity and natural gas prices of \$0.057/kWh and \$0.6312/therm, respectively.

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 for cooling and 1.0 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 (Fadjacent 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 B1*) or heating (*Table B2*) 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 (Fequipment). Building vintage distribution was combined with adjusted saturations to compute combined vintage/saturation factors for air conditioning (*Table B3*). Heating loads

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**		**Instit./ Trans-porta-tion**
	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	38	56	72	38	56	72	38	56	72	38	56	72	38	56	72	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	37	23	25	37	23	25	37	25	26	37	23	25	37	23	25	9	9	9
None	25	21	3	25	21	3	25	21	3	25	21	3	25	21	3	5	5	5
Adjusted cooling saturation	47	62	78	47	62	78	47	62	78	47	62	78	47	62	78	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	6.8	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	2.4	10.9	21.4	2.4	10.9	21.4	2.4	10.9	21.4	2.4	10.9	21.4	2.4	10.9	21.4	4.9	4.9	4.9
Heat pump	0.4	1.8	3.6	0.4	1.8	3.6	0.4	1.8	3.6	0.4	1.8	3.6	0.4	1.8	3.6	5.4	5.4	5.4
Adjusted electric heat saturations	0.4	1.7	2.9	0.4	1.7	2.9	0.4	1.7	3.9	0.4	1.7	2.9	0.4	1.7	2.9	0.4	1.7	2.9
Natural gas and other heating saturations																		
Natural gas	69	61	50	69	61	50	69	61	50	69	61	50	69	61	50	69	61	50
Oil	18	19	0	18	19	0	18	19	0	18	19	0	18	19	0	0	0	0
Other	10	8	25	10	8	25	10	8	25	10	8	25	10	8	25	0	0	0
NG heat saturations	97	87	75	97	87	75	97	87	75	97	87	75	97	87	75	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	37	41	22	37	41	22	37	41	22	37	41	22	37	41	22	100	100	100
Tree distribution by vintage and building type	18.3	20.4	11.2	2.01	2.24	1.23	1.41	1.57	0.86	1.81	2.01	1.10	2.09	2.33	1.28	11.6	6.8	11.7
Combined vintage, equipment saturation factors for cooling																		
Cooling factor: shade	8.46	12..4	8.56	0.93	1.36	0.94	0.57	0.84	0.58	0.62	0.90	0.62	0.40	0.58	0.40	3.6	1.0	0.0
Cooling factor: climate	8.65	12.7	8.75	0.96	1.40	0.97	0.42	0.61	0.42	0.43	0.62	0.43	0.48	0.70	0.48	9.7	19.0	0.0
Combined vintage, equipment saturation for heating																		
Heating factor, natural gas: shade	17.4	17.4	8.22	1.91	1.91	0.90	1.18	1.18	0.56	1.27	1.27	0.60	0.82	0.82	0.38	3.6	1.1	0.0
Heating factor, electric: shade	0.06	0.33	0.32	0.01	0.04	0.03	0.00	0.02	0.02	0.00	0.02	0.02	0.00	0.02	0.01	0.07	0.02	0.00
Heating factor, natural gas: climate	17.8	17.8	8.40	0.87	0.87	0.41	1.02	1.02	0.48	0.74	0.74	0.35	0.54	0.54	0.25	8.2	16.1	0.0
Heating factor, electric: climate	0.07	0.34	0.33	0.00	0.02	0.02	0.00	0.02	0.02	0.00	0.01	0.01	0.00	0.01	0.01	0.16	0.31	0.0

were converted to fuel use based on efficiencies in *Table B2*. 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 B3*).

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 roof 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) 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. A point is reached, however, at which no additional area is shaded as surface area increases. 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 9* did not change for C/I and I/T land uses.

Atmospheric Carbon Dioxide Reduction

Sequestration (net rate of CO_2 storage 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 to calculate 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 Boulder was 5.0% per year for the first five years after planting for street trees and 2.0% per year for the first five years for park trees and 0.85% every year thereafter for street trees and 0.57% for park trees (Bussi-Sottile and Alexander 2005). Finally, CO_2 released during tree maintenance was estimated to be 0.21 lb CO_2/in DBH based on annual fuel consumption of gasoline (3,020 gal) and diesel fuel (1,040 gal) (Bussi-Sottile and Alexander 2005).

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 Boulder. The fuel mix for electrical generation included natural gas (14%) and coal (80%) (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 B4*).

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. Environmental Protection Agency 2002). 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 (*Table B4*) were obtained from U.S. EPA (2004), and a population estimate of 103,216.

Calculating Deposition and Interception

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

	Emission factor		Implied value[1] (\$/lb)
	Electricity (lb/MWh)	Natural gas (lb/MBtu)	
CO_2	2,210	118.0	0.0075
NO_2	3.650	0.0922	2.54
SO_2	5.650	0.0006	0.90
PM_{10}	0.903	0.0075	0.45
VOCs	0.861	0.0054	2.39

[1] \$15/ton for CO_2 from CO2e.com (2001), values for all other pollutants are based on methods of Wang and Santini (1995) using emissions concentrations from U.S. EPA (1998) and population estimates from the U.S. Census Bureau (2003).

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 Boulder were obtained from the Colorado Department of Public Health and Environment (Hague 2003). The year 1999 was chosen because data were available and it closely approximated long-term, regional climate records.

Deposition was determined for deciduous species only when trees were in-leaf. A 50% re-suspension rate was applied to PM_{10} deposition. Methods described in the section "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 Fort Collins, CO, during summer 2002. 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 1999 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 $4.99/lb for Boulder (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 rainwater 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 and stem surface or 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 1998 from the Colorado Agricultural Meteorological Network (COAGMET) (Station: Fort Lupton; latitude 40°00′25″N, longitude 104°50′57″W) and from Boulder, Colorado NOAA station (ID: 05048) were used for this simulation. Annual precipitation during 1998 was 18.1 in (459.74 mm), close to the recent 50-year average annual precipitation of 19.1 in (485.14 mm). Storm events less than 0.1 in (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).

Boulder has constructed a number of detention ponds for stormwater retention/detention. Data on the construction and maintenance for nine ponds were analyzed to derive average costs citywide.

For a typical 6.5-acre basin, land costs total $1.78 million ($274,000/acre) and construction costs are $1.6 million ($253,000/acre) (Hunter 2005). The annual cost for operation and maintenance is $3,000. Assuming a 20-year life before dredging and reconstruction, the total life-cycle cost is $3.46 million. Assuming the pond adds one foot of depth due to runoff seven times a year, it will store 45 acre-ft of runoff annually over the course of a year. The annual cost of storage in the holding pond is $0.0118/gal. This price is comparable to the average price for stormwater runoff reduction ($0.01/gallon) reported in similar studies (McPherson and Xiao 2004).

Aesthetic, Property Value, Social, Economic and 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 the 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 quicker 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, 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 United States. 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 Aesthetic, Property Value, Social, Economic 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 hackberry, average leaf surface area 7,266 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 Boulder, each large tree would be worth $3,634 based on the 2004 median single-family-home resale price in Boulder ($413,000) (Boulder County Assessor 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 at the same rate as trees in front of single-family homes. Therefore, a citywide street tree reduction factor (0.85) was applied to prorate trees' value based on the assumption that trees adjacent to different land-uses make different contributions to property sales prices. Reductions factors were based on distribution of trees by land use in Fort Collins: single-home residential (59%), multi-home residential (8%), commercial/industrial (12%), vacant/other (6%). The park tree reduction factor was 50% (McPherson et al. 2001).

Given these assumptions, a typical large street tree was estimated to increase property values by $0.50/ft^2 of LSA. For example, assuming a single, street tree adds 100 ft^2 of LSA per year when growing in the DBH range of 12–18 inches, during this period of growth, it effectively adds $50, annually, to the value of an adjacent home (100 ft^2 × $0.50/ft^2 = $50).

Estimating Magnitude of Benefits

Resource units describe the absolute value of the benefits of Boulder'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 Boulder 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 in
2) 3–6 in
3) 6–12 in
4) 12–18 in
5) 18–24 in
6) 24–30 in
7) 30–36 in
8) 36–42 in
9) >42 in

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, assume that there are 300 silver maples citywide in the 30–36 in DBH class. The interpolated electricity and natural gas resource unit values for the class midpoint (33 in) were 348 kWh and 578.1 kBtu per tree, respectively. Therefore, multiplying the resource units for the class by 300 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 20 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 that were not matched were then grouped into the "Other" categories described below.

Grouping Remaining "Other" Trees by Type

The species that were less than 1% of the population were labeled "other" and were categorized according into classes based on tree type (one of four 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 15 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 = Blue spruce (*Picea pungens*)
CEM Other = Austrian pine (*Pinus nigra*)
CES Other = Bolleana shore pine (*Pinus contorta*)

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

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.

Boulder 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

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