City of Charleston, South Carolina Municipal Forest Resource Analysis

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Center for Urban Forest Research
USDA Forest Service, Pacific Southwest Research Station

Technical Report to:
Danny Burbage, Urban Forestry Superintendent
Urban Forestry Division, Department of Parks
Charleston, South Carolina

—July 2006—

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MUNICIPAL FOREST RESOURCE ANALYSIS

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Executive Summary

Charleston, a charming Southern city appreciated for its rich history and culture, maintains trees as an integral component of the urban infrastructure (*Figure 1*). Research indicates that healthy trees can lessen impacts associated with the built environment by reducing stormwater runoff, energy consumption, and air pollutants. Trees improve urban life, making Charleston a more enjoyable place to live, work, and play, while mitigating the city's environmental impact. Over the years, the people of Charleston have invested millions of dollars in their municipal forest. The primary question that this study asks is whether the accrued benefits from Charleston'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 on the tree resource:

- Structure (species composition, diversity, age distribution, condition, etc.)
- Function (magnitude of annual environmental and esthetic benefits)
- Value (dollar value of benefits minus management costs)
- Management needs (sustainability, planting, maintenance)

Resource Structure

The city's tree inventory includes 15,244 publicly managed trees along the streets in Charleston. The inventory does not include and estimated 35,000 other trees located in parks, traffic medians, wooded buffers and drainage areas. This assessment focuses on the 15,244 trees that have been inventoried and may therefore understate the full extent and benefit of Charleston's entire municipal forest.

Figure 1—Trees shade a historic home in Charleston, South Carolina. Public trees in Charleston provide great benefits, improving air quality, sequestering carbon dioxide, reducing stormwater runoff and beautifying the city. The trees of Charleston return $1.34 in benefits for every $1 spent on tree care.

There is approximately one public tree for every seven residents, and these public trees shade approximately 0.24% of the city. Charleston's streets are planted at near capacity, with 80% of possible planting spaces filled.

The inventory contains 136 tree species with Southern live oak (*Quercus virginiana*), crapemyrtle (*Lagerstroemia indica*) and sabal palmetto (*Sabal palmetto*) as the dominant species. These three species represent 64% of all street trees in Charleston and provide 51% of benefits.

The age structure of Charleston's municipal tree population appears fairly close to "ideal." A recent emphasis on new plantings means that there are many trees (nearly 50%) in the smallest size class (0–6 inch diameter at breast height or 4.5 ft above the ground [DBH]). The larger size classes are also well represented, while the 6–12 inch DBH class shows a marked dip with only 15% of trees in this class. Closer inspection at the management zone and species level shows a less desirable picture. Some areas have a high proportion of trees in the largest size classes, while others are represented almost entirely by small trees. As well, some species have a desirable age distribution while others include only young or only old trees.

Resource Function and Value

The ability of Charleston's municipal trees to intercept rain—thereby reducing stormwater runoff—is substantial, estimated at 3.98 million cubic ft annually, or $171,406. Citywide, the average tree intercepts 1,858 gallons of stormwater each year, valued at $11 per tree.

Electricity saved annually in Charleston from both shading and climate effects of trees totals 1,039 MWh ($97,020) and annual natural gas saved totals 2,002 Mbtu ($23,971) for a total energy cost savings of $120,991 or $8 per tree.

Citywide, annual carbon dioxide (CO_2) sequestration and emission reductions due to energy savings by public trees are 944 tons and 711 tons, respectively. CO_2 released during decomposition and tree-care activities is relatively low (91 tons). Net CO_2 reduction is 1,563 tons, valued at $23,452 or $1.54 per tree.

Net annual air pollutants removed, released, and avoided average 0.46 lb per tree and are valued at $36,270 or $0.43 per tree. Ozone is the most significant pollutant intercepted by trees, with 6,104 lbs per year removed from the air, while sulfur dioxide is the most important air pollutant whose production is avoided at the power plant, due to reduced energy needs (8,104 lbs per year).

The estimated total annual benefits associated with aesthetics, property value increases, and other less tangible improvements are approximately $395,000 or $26 per tree on average.

Annual benefits total $717,034 and average $47 per tree. The 3,632 live oaks produce the highest total level of benefits among street trees ($84 per tree, 43% of total benefits). On a per tree basis, water oaks and laurel oaks are most important, providing an average of $156 and $133 per tree, respectively. Although together these two species make up less than 10% of the population, because of their great size and leaf area, they provide 27.6% of the total benefits. Nonetheless, despite the water oak's high level of benefits, the species is not well suited as a street tree as it is short-lived, shallow-rooted and prone to failure. Species providing the least benefits on an individual tree basis include crapemyrtle ($8) and dogwood ($10).

Charleston spends approximately $700,000 annually maintaining its public trees. For the purposes of this study, it was assumed that 75% of the budget ($531,200) is spent on the 15,244 trees in the inventory, or $35 per tree. Expenditures for pruning account for about one-half of total costs. Planting represents another one-fifth.

Charleston's municipal trees are a valuable asset, providing approximately $185,834 or $12 per tree ($2/capita) in net annual benefits to the community. Over the years, Charleston has invested millions in its urban forest. Citizens are now receiving a return on that investment—trees are providing

$1.35 in benefits for every $1 spent on tree care. Charleston's benefit–cost ratio of 1.35 is similar to that reported for Berkeley, CA (1.37), and exceeds that of San Francisco (1.00), but is lower than other cities, including Charlotte, NC (3.25), Glendale, AZ (2.41), Fort Collins, CO (2.18), Cheyenne, WY (2.09), and Minneapolis, MN (1.57) (McPherson et al. 2003, 2004b, 2005a–f).

The mild climate and clean air of the Charleston area are a partial explanation for the lower benefits of trees. Another possible factor is the predominance of crapemyrtles and sabal palmettos. These species, which make up 40% of the population, have smaller leaf areas and return far fewer benefits on a per tree basis. Of course, in a historic city like Charleston, high building density and narrow streets mean smaller species are sometimes the best or only choice.

Continued investment in management and careful consideration of the future structure of the urban forest are critical to insuring that residents receive a high return on their investment.

Resource Management Needs

Charleston's municipal trees are a dynamic resource. Managers of the urban forest and the community alike can take pride in knowing that municipal trees do improve the quality of life in Charleston; the resource, however, is fragile and needs constant care to maximize and sustain the benefits through the foreseeable future. Achieving resource sustainability requires that Charleston:

- Continue to diversify the mix of tree species planted to guard against catastrophic losses due to storms, pests or disease.
- Sustain an annual planting program over the long-term to increase age diversity.
- Sustain benefits by investing in intensive maintenance of mature trees to prolong the functional life spans of these heritage trees.
- Develop a strong young-tree-care program that includes inspection and pruning on a two-year cycle.
- Plant large species where conditions are suitable to maximize benefits.
- Insure adequate space for large trees in new developments by revising street design standards. Encourage the use of structural soils where appropriate. Where possible, locate power lines belowground.
- Review and revise parking lot shade guidelines and the adequacy of current ordinances to preserve and protect large trees from development impacts.

These recommendations build on a history of civic commitment to tree management that has put Charleston on course to provide an urban forest resource that is both functional and sustainable. As the city continues to grow, it must also continue to invest in its tree canopy. This is no easy task, given financial constraints and trends toward increased development that put trees at risk.

The challenge ahead is to better integrate the green infrastructure with the gray infrastructure. This can be achieved by including green space and trees in the planning phase of development projects, providing adequate space for trees, and designing and maintaining plantings to maximize net benefits over the long term. By acting now to implement these recommendations, Charleston will benefit from a more functional and sustainable urban forest in the future.

Figure 2—Stately oaks shade a park gazebo in Charleston.

Chapter One—Introduction

Charleston is a charming, vibrant Southern city, appreciated for its rich history and cultural wealth. Trees are maintained as an integral component of the urban infrastructure (*Figure 2*) and have long been beloved and cared for by the city's residents. The city's Urban Forestry Division of the Department of Parks actively manages more than 50,000 trees along streets, in parks, in wooded buffers and drainage easements. The City believes that the public's investment in stewardship of the urban forest produces benefits that far outweigh the costs to the community. Investing in Charleston's green infrastructure makes sense economically, environmentally, and socially.

Research indicates that healthy city trees can mitigate impacts associated with urban environs: polluted stormwater runoff, poor air quality, high requirements for 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, social, and physical health. Street and park trees are associated with other intangibles, too, such as increasing community attractiveness for tourism and business and providing wildlife habitat and corridors. The urban forest makes Charleston a more enjoyable place to live, work and play, while mitigating the city's environmental impact (*Figure 3*).

In an era of decreasing public funds and rising costs, however, there is a need to scrutinize public expenditures that are often viewed as "nonessential," 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 Charleston's urban trees justify the annual expenditures*?

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

- Assist decision-makers to assess and justify the degree of funding and type of management program appropriate for Charleston's urban forest.
- Provide critical baseline information for evaluating program cost-efficiency and alternative management structures.

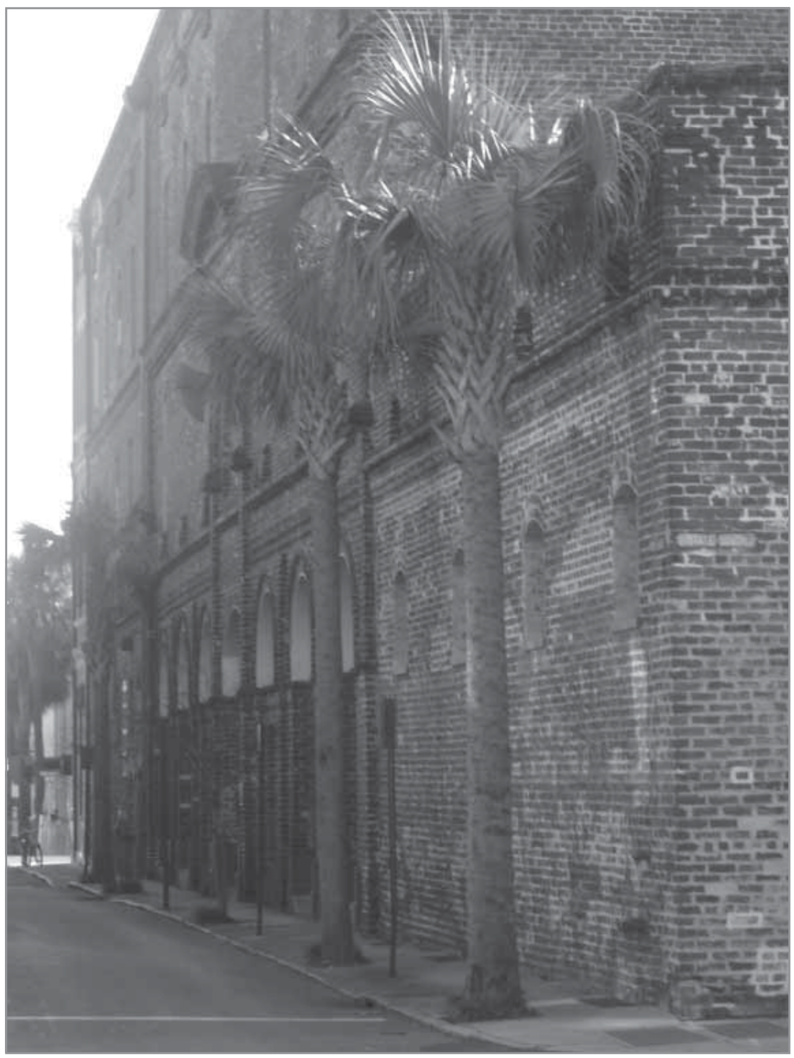

Figure 3—Sabal palmettos, the State Tree of South Carolina, enliven Charleston's historic Queen Street.

- Highlight the relevance and relationship of Charleston's municipal tree resource to local quality of life issues such as environmental health, economic development, and psychological health.

- 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 six chapters and three appendices:

Chapter One—Introduction: Describes the purpose of the study.

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

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

Chapter Four—Benefits of Charleston's Municipal Trees: Quantifies the estimated value of tangible benefits and calculates net benefits and a benefit–cost ratio.

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

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

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

Appendix B—Replacement Values: Lists replacement values for the entire street tree population.

Appendix C—Describes procedures and methodology for calculating structure, function, and value of the urban tree resource.

References—Lists publications cited in the study.

Chapter Two—Charleston's Municipal Tree Resource

As might be expected in a city that includes the oldest landscaped gardens in the United States, the citizens of Charleston are passionate about their trees, believing that they add character, beauty, and serenity to the city. Sabal palmettos (*Sabal palmetto*), the state tree, line the brick streets of the historic district and are renowned in Charleston's history for helping to defeat the British during the Revolutionary War—the spongy logs of the make-shift fort on Sullivan's Island absorbed the impact of cannonballs without splintering and breaking. Southern live oaks, draped with Spanish moss, form a living canopy over the streets of the city. Charleston is also home to the Angel Oak, a Southern live oak (*Quercus virginiana*) estimated to be more than 1,400 years old (*Figure 4*). The Angel Oak has cast its 17,000 square feet of shade over performances by the Charleston Ballet Theatre, the Charleston Symphony Orchestra and over countless more-humble picnics.

Tree Numbers

The Charleston street tree inventory was begun in 1992 and included 15,244 trees at the time of this study. Charleston's Urban Forestry Division is also responsible for an additional estimated 35,000 trees, most of which are located in drainage easements and wooded buffers.

The street tree population is dominated by broadleaf trees (75% of the total; *Table 1*). Because broadleaf trees are usually larger than coniferous trees or palms and most of the benefits provided by

***Table 1**—Street tree percentages by tree type.*

Tree type	Number	% of total
Broadleaf deciduous	7,047	46.2
Broadleaf evergreen	4,355	28.6
Coniferous	597	3.9
Palm	3,245	21.3
Total	15,244	

Figure 4—Charleston's Angel Oak, a Southern live oak estimated to be 1,400 years old.

Table 2—*Most abundant street tree species in order of predominance by DBH class and tree type.*

Species	0–3	3–6	6–12	12–18	18–24	24–30	30–36	36–42	>42	Total	% of total
Broadleaf deciduous large (BDL)											
Water oak	11	19	53	161	278	200	51	8	1	782	5.1
Laurel oak	8	33	37	118	177	136	57	23	9	598	3.9
Red maple	43	92	12	4	4	-	-	-	-	155	1.0
BDL other	158	456	164	88	70	41	21	19	6	1,023	6.7
Total	220	600	266	371	529	377	129	50	16	2,558	16.8
Broadleaf deciduous medium (BDM)											
BDM other	182	323	78	43	20	9	2	-	-	657	4.3
Total	182	323	78	43	20	9	2	-	-	657	4.3
Broadleaf deciduous small (BDS)											
Crapemyrtle	1,568	1,025	418	45	2	-	-	-	-	3,058	20.1
Flowering dogwood	138	122	86	7	-	-	-	-	-	353	2.3
BDS other	283	114	20	3	-	1	-	-	-	421	2.8
Total	1,989	1,261	524	55	2	1	-	-	-	3,832	25.1
Broadleaf evergreen large (BEL)											
Live oak	809	1,235	542	260	223	233	163	111	56	3,632	23.8
BEL other	-	1	-	-	-	-	-	-	-	1	-
Total	809	1,236	542	260	223	233	163	111	56	3,633	23.8
Broadleaf evergreen medium (BEM)											
BEM other	106	51	50	41	13	2	1	1	-	265	1.7
Total	106	51	50	41	13	2	1	1	-	265	1.7
Broadleaf evergreen small (BES)											
BES other	265	134	49	9	-	-	-	-	-	457	3.0
Total	265	134	49	9	-	-	-	-	-	457	3.0
Conifer evergreen large (CEL)											
Loblolly pine	9	15	60	99	63	24	3	1	-	274	1.8
CEL other	26	22	40	36	19	10	1	-	1	155	1.0
Total	35	37	100	135	82	34	4	1	1	429	2.8
Conifer evergreen medium (CEM)											
CEM other	64	67	15	13	7	2	-	-	-	168	1.1
Total	64	67	15	13	7	2	-	-	-	168	1.1
Conifer evergreen small (CES)											
CES other	-	-	-	-	-	-	-	-	-	-	-
Total	-	-	-	-	-	-	-	-	-	-	-
Palm evergreen large (PEL)											
PEL other	2	2	-	-	-	-	-	-	-	4	-
Total	2	2	-	-	-	-	-	-	-	4	-
Palm evergreen medium (PEM)											
Sabal palmetto	3	49	558	2,324	54	-	-	-	-	2,988	19.6
PEM other	2	4	2	-	-	-	-	-	-	8	0.1
Total	5	53	560	2,324	54	-	-	-	-	2,996	19.7
Palm evergreen small (PES)											
Jelly palm	4	11	39	92	74	3	-	-	-	223	1.5
PES other	9	5	1	7	-	-	-	-	-	22	0.1
Total	13	16	40	99	74	3	-	-	-	245	1.6
Citywide total	3,690	3,780	2,224	3,350	1,004	661	299	163	73	15,244	

trees are related to leaf surface area, broadleaf trees usually provide the highest level of benefits. Of the broadleaf trees, approximately 40% are evergreen. The presence of leaves on the trees year-round adds to their value in terms of stormwater interception, air pollutant uptake, and carbon dioxide sequestration. Palms make up one-fifth of the street tree population and conifers, the remaining 4%.

Species Richness, Composition And Diversity

The tree population in Charleston includes a rich mix 136 different species—more than twice the mean of 53 species reported by McPherson and Rowntree (1989) in their nationwide survey of street tree populations in 22 U.S. cities. The mild climate of the Coastal Plain and the city's long history of lush, carefully tended gardens, some dating back to the late 17th century, play a role in this species richness.

The predominant street tree species are live oak (23.8%), crapemyrtle (*Lagerstroemia* spp., 20.1%), and sabal palmetto (19.6%) (*Table 2*). Taken together, these three species represent 64% of the street trees in Charleston, and all exceed the general rule that no single species should represent more than 10% of the population and no genus more than 20% (Clark et al. 1997).

Dominance of this kind is of concern because of the impact that drought, disease, pests, or other stressors can have on the urban forest. Although live oaks, crapemyrtles, and sabal palmettos are generally not susceptible to pests and disease, nonnative fungi and insects have caused serious unexpected damage to other species in the past. On the other hand, live oaks and sabal palmettos are among the most hurricane-resistant of all trees, withstanding the winds of the worst hurricanes to hit the southeastern United States (Duryea et al. 1996; Duryea 1997; Touliatos and Roth 1971).

At the management zone level, the problem of overly dominant species is exacerbated (*Table 3*). In James Island, for instance, nearly half of all street trees are crapemyrtles. In the Broad-Calhoun and South of Broad areas, sabal palmettos represent one-third of street tree plantings. In these cases, in addition to the dangers of catastrophic loss due to pests or disease, there should be concern over lost benefits, as small trees and palms have less leaf surface area and provide fewer benefits than large trees. In historic cities, of course, space for trees is at a premium, and small trees and palms are sometimes the only option.

Species Importance

Importance values (IV) are particularly meaningful to managers because they indicate a community's reliance on the functional capacity of particular species. For this study, IV takes into account not only total tree numbers, but canopy cover and leaf

Table 3—Most abundant tree species listed by management zone with percentage of totals in parenthesis.

Zone	1st (%)	2nd (%)	3rd (%)	4th (%)	5th (%)
Broad - Calhoun	Sabal palmetto (34.7)	Live oak (18.6)	Crapemyrtle (17.6)	Water oak (2.9)	Laurel oak (2.7)
Calhoun - Crosstown	Live oak (26.5)	Sabal palmetto (22.3)	Crapemyrtle (22.1)	Water oak (3.3)	Dogwood (2.3)
Crosstown - City limits	Live oak (30)	Crapemyrtle (18)	Sabal palmetto (16.5)	Water oak (8)	Laurel oak (4.8)
Daniel Island	Live oak (27.4)	Crapemyrtle (13.2)	London plane (8.3)	Chinese pistache (7.9)	Sabal palmetto (6.9)
Hampton Park Terrace	Live oak (27.3)	Crapemyrtle (23.9)	Laurel oak (8.5)	Sabal palmetto (7.9)	Water oak (7.3)
Hwy 17 - Hwy 61	Live oak (34)	Crapemyrtle (20.3)	Sabal palmetto (11.5)	Water oak (4.3)	Laurel oak (4.1)
James Island	Crapemyrtle (47.6)	Live oak (29.2)	Sabal palmetto (3.3)	Dogwood (2.6)	Jelly palm (2.2)
N of Hwy 61	Crapemyrtle (20.2)	Live oak (15.9)	Sabal palmetto (12.3)	Loblolly pine (9)	Jelly palm (6.3)
S of Hwy 61	Live oak (25.6)	Crapemyrtle (19.1)	Sabal palmetto (11.9)	Water oak (8.4)	Laurel oak (8.1)
South of Broad	Sabal palmetto (33.4)	Crapemyrtle (19.5)	Live oak (15.7)	Water oak (3.9)	Laurel oak (3.3)
Wagener Terrace	Live oak (23)	Crapemyrtle (22.8)	Water oak (9.5)	Sabal palmetto (9.5)	Laurel oak (6.4)
Citywide total	Live oak (23.8)	Crapemyrtle (20.1)	Sabal palmetto (19.6)	Water oak (5.1)	Laurel oak (3.9)

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

The nine most abundant street tree species listed in Table 4 constitute 79% of the total street tree population, 85% of the total leaf area, and 86% of total canopy cover, for an IV of 83.4. As Table 4 illustrates, Charleston is relying on the functional capacity of live oaks even more than their population numbers suggest. Though the species accounts for 23.8% of all public trees, because of the trees' relatively large size, the amount of leaf area and canopy cover they provide is even greater, increasing their importance value to 33 when all components are considered. This makes them 2.5 times more significant than the next species. In contrast, small trees tend to have lower importance values than their population numbers would suggest. Although crapemyrtles make up 20% of the population, their IV is only 8.4.

Street Tree Stocking Level

The stocking level, or the ratio of planted trees to possible planting spaces, is an important way of measuring how well-forested a city is. It also serves as a helpful baseline for setting future goals. The stocking level in Charleston is not easy to estimate. The inventory used for this project includes some sites identified as available planting spaces for small species (106 sites) and existing stumps (89); both represent opportunities for planting, but there are certainly far more empty sites than these. A recent management plan for the city (Davey Resource Group 2000) stated that there were 3,764 potential planting spaces. By this measure, Charleston's street tree stocking level is 80%, a very high percentage.

Street Trees Per Capita

Calculation of street trees per capita is another way of describing how well-forested a city is. Assuming a human population of 104,883 and a tree population of 15,244 (Burbage 2005), Charleston's number of street trees per capita is 0.15—approximately one tree for every seven people—significantly below the mean ratio of 0.37 reported for 22 U.S. cities (McPherson and Rowntree 1989).

Table 4*—Importance values (IV) indicate which species dominate the population due to 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	I V
Live oak	3,632	23.8	5,390,199	38.3	2,633,361	37.7	33.3
Crapemyrtle	3,058	20.1	135,581	1.0	291,091	4.2	8.4
Sabal palmetto	2,988	19.6	1,205,900	8.6	732,614	10.5	12.9
Water oak	782	5.1	2,648,985	18.8	1,125,728	16.1	13.4
Laurel oak	598	3.9	2,134,941	15.2	902,394	12.9	10.7
Flowering dogwood	353	2.3	20,587	0.1	58,810	0.8	1.1
Loblolly pine	274	1.8	317,560	2.3	203,621	2.9	2.3
Jelly palm	223	1.5	57,088	0.4	39,969	0.6	0.8
Red maple	155	1.0	31,146	0.2	27,382	0.4	0.5
Total most abundant	12,063	79.1	11,941,987	85	6,014,970	86	83.4

Age Structure

The distribution of ages within a tree population influences present and future costs as well as the flow of benefits. An uneven-aged population allows managers to allocate annual maintenance costs uniformly over many years and 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 overall age structure, represented here in terms of DBH, for street trees in Charleston appears quite similar to the ideal (*Figure 5*). Closer examination, however, shows that the results differ greatly by species. Live oak shows a desirable distribution across DBH classes. Other large-growing species are heavily represented in the smaller DBH classes, suggesting that the city has begun to plant some new large- and medium-growing species recently, including red maple (*Acer rubrum*) and Chinese pistache (*Pistacia chinensis*) (87.1 and 100% in the 0–6 inch DBH class, respectively). In contrast, other species, such as laurel oak (*Quercus laurifolia*) and water oak (*Quercus nigra*), seem to have fallen out of favor with only 6.8 and 3.8% of their populations, respectively, in the smallest DBH class.

A closer look at age distribution by management zone also presents an interesting picture (*Figure 6*). Some areas, such as Wagener Terrace and Hampton Park Terrace, have a large proportion of trees in the largest size classes. James Island and Daniel Island, in contrast, have most of their trees in the smallest size classes. In James Island, this can be partly explained by the fact that nearly half of their trees are crapemyrtles, which rarely grow beyond the 0–6 inch DBH class. The predominant species mix in Daniel Island, however, includes live oak, London plane (*Platanus* x *acerifolia*) and Chinese pistache. The age distribution therefore indicates increased planting efforts in recent years.

For many neighborhoods and for the city overall, there is a dip in the number of trees in the 6–12 inch DBH class. This may reflect reduced planting rates in the 1990s, increased mortality levels, such as following Hurricane Hugo, or both.

Tree Condition

Tree condition indicates both how well trees are managed and how well they perform given site-specific conditions. Overall, the condition of trees in Charleston is very good, with 89% in good or fair shape (*Figure 7*).

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

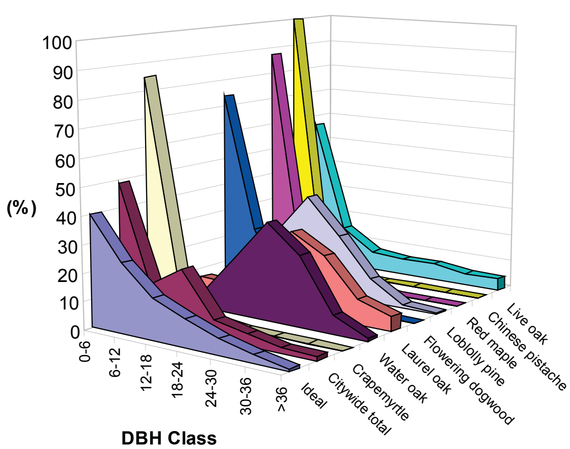

Figure 5—Relative age distribution for Charleston's 8 most abundant street tree species citywide shown with an ideal distribution.

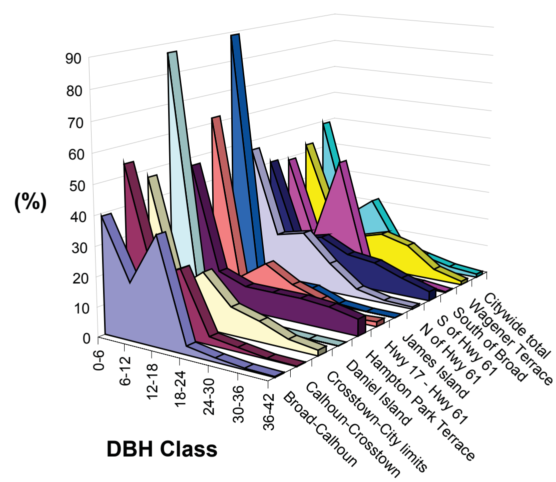

Figure 6—Relative age distribution of all street trees by management zone.

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 Charleston—likely represent less than 20% of the entire urban forest (Moll and Kollin 1993). The street tree canopy in Charleston is estimated at 120 acres and covers 0.24% of the city, given a city area of 65,920 acres (103 miles) (Burbage 2005). Publicly maintained street trees shade approximately 2% of streets and sidewalks.

Maintenance Needs

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

The city's inventory included an assessment of maintenance needs, with the most urgent task identified for each tree (*Table 5*). The most common priority task was routine pruning to promote continued good health and performance: 43% of the population are larger trees (>6 inch DBH) and 9.8% are smaller trees that need routine pruning, and 46% are young trees in need of training. Trees requiring removal (0.2%) have severe problems, although these are not necessarily related to safety hazards. They may be dead or dying trees that were planted recently, or they may contain unmanageable defects and hazards. The small percentages of trees requiring urgent attention in terms of priority pruning or removal reflect the outstanding management and maintenance of the Urban Forestry Division.

Data in *Table 5* can be used with tree-care cost estimates to calculate the amount of funding required to address current management needs.

Conflicts

The Charleston inventory includes information about conflicts with overhead utility lines; clearance problems with signs, lights and overhead in traffic corridors; and sidewalk damage caused by trees. Keeping records on these types of conflicts is

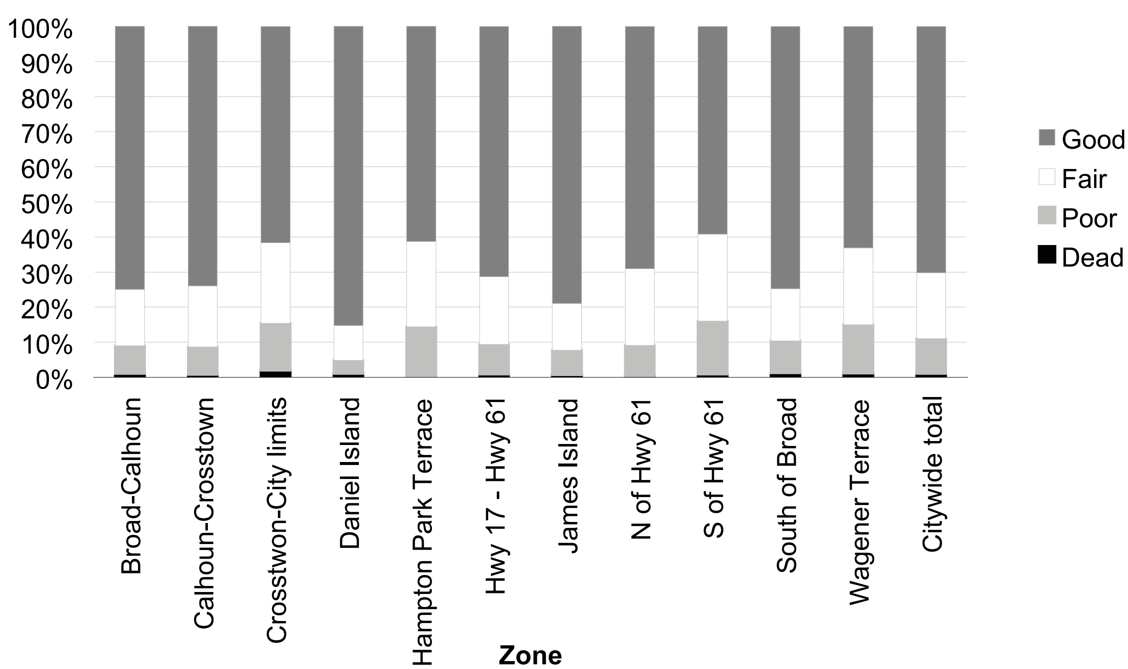

Figure 7—Condition of street trees in Charleston by management zone.

helpful in planning future maintenance and can be very useful in understanding which species are best suited to certain sites. *Table 6* describes conflicts for the most predominant species.

Replacement Value

Replacement value is a way of describing the current value of trees, reflecting their current number, stature, placement, and condition. There are several methods that arborists employ to develop a fair and reasonable perception of a tree's value (CTLA 1992, Watson 2002). The cost approach is widely used today and assumes that value equals the cost of production, or in other words, the cost of replacing a tree in its current state (Cullen 2002).

Replacing Charleston's 15,244 street trees with trees of similar size, species, and condition if, for example, all were destroyed by a catastrophic storm, would cost approximately $42.5 million (*Table 7*). The average replacement value per tree is $2,788. Live oaks account for almost 50% of the population's total replacement value, with most of this value in the older and larger trees. Charleston's street trees are a valuable legacy. As a central component of the city's green infrastructure, these street trees are an asset valued at $42.5 million.

Replacement value should be distinguished from the value of annual benefits produced by the urban forest. The latter will be described in Chapter 4, as a "snapshot" of benefits during one year, while the former accounts for the historical investment in trees over their lifetimes. Hence, the replacement value of Charleston's street tree population is many times greater than the value of annual benefits it produces.

Table 5—*Maintenance needs by DBH class.*

Maintenance type	0–3	3–6	6–12	12–18	18–24	24–30	30–36	36–42	>42	Total	% of pop'n
Priority 1	-	-	-	2	8	6	3	-	-	19	0.1
Priority 2	-	-	4	7	2	2	1	-	-	16	0.1
Removal 1	-	1	1	3	2	-	-	-	-	7	0.0
Removal 2	4	5	1	8	3	1	1	-	-	23	0.2
Routine prune	3	67	1,303	3,129	895	633	286	161	71	6,548	43.0
Routine small prune	12	627	602	166	78	4	-	-	-	1,489	9.8
Train	3,670	3,059	291	3	-	-	-	-	-	7,023	46.1
Stump	1	21	21	29	16	14	8	2	2	114	0.7
Boom	-	-	1	3	-	1	-	-	-	5	0.0
Citywide total	3,690	3,780	2,224	3,350	1,004	661	299	163	73	15,244	100.0

Table 6—Number of conflicts between trees and power lines, overhead communication lines, sidewalks, lights, and signs for the most common species in Charleston.

Species	Power lines	Comm. lines	Power and comm. lines	Sidewalk heave	Lights	Signs
Live oak	349	186	1,084	2,822	21	395
Crapemyrtle	150	146	1,117	2,722	13	215
Sabal palmetto	151	127	737	2,661	2	9
Water oak	56	27	331	630	1	48
Laurel oak	48	29	295	523	0	58
Flowering dogwood	21	23	165	289	0	18
Jelly palm	40	0	38	36	0	6
Other trees	232	129	944	2,667	37	178
Citywide total	1,047	667	4,711	12,350	74	927

***Table** 7—Replacement values, summed by DBH class, for the 40 most valuable species of street trees in Charleston. See Appendix B for complete listing.*

Species	0-3	3-6	6-12	12-18	18-24	24-30	30-36	36-42	>42	Total
Live oak	79,588	666,396	1,122,699	1,527,439	2,506,392	4,337,350	4,478,524	3,954,465	2,214,472	20,887,324
Water oak	1,739	8,860	82,594	596,516	2,069,399	2,521,279	911,086	156,486	3,844	6,351,803
Laurel oak	990	17,330	64,328	534,686	1,560,200	1,935,157	1,177,804	655,900	311,583	6,257,978
Crapemyrtle	172,835	542,299	820,276	243,048	20,260	-	-	-	-	1,798,718
Loblolly pine	1,130	7,602	115,127	476,936	560,072	341,236	70,205	28,696	-	1,601,002
Southern red oak	-	28,126	-	9,284	76,474	88,053	118,907	146,040	30,882	497,767
American sycamore	1,580	10,869	16,083	22,060	52,277	122,693	47,031	143,397	24,121	440,111
Southern magnolia	2,546	8,932	81,633	197,778	81,765	28,646	20,880	-	-	422,181
Willow oak	466	32,814	57,744	36,291	60,207	69,266	85,363	31,184	34,859	408,193
Hackberry	946	1,151	40,066	113,370	116,366	77,825	24,703	-	25,788	400,215
Sweetgum	5,611	1,884	30,451	66,100	117,280	109,389	48,501	-	-	379,215
Flowering dogwood	15,256	65,368	163,810	33,025	-	-	-	-	-	277,459
Pecan	377	2,022	13,530	53,103	87,753	47,837	21,682	28,696	-	255,000
Northern red oak	-	58	1,174	429	23,383	8,056	39,971	74,705	54,677	202,452
Eastern red cedar	4,182	13,559	22,428	50,349	56,124	22,379	-	-	-	169,022
Sabal palmetto	60	1,203	21,117	132,186	4,177	-	-	-	-	158,743
Honeylocust	2,033	11,789	83,220	53,581	-	-	-	-	-	150,622
American holly	2,200	27,350	70,068	42,673	-	-	-	-	-	142,291
Red maple	4,922	48,022	22,728	23,355	39,905	-	-	-	-	138,933
Callery pear	4,248	13,201	15,822	42,064	7,388	-	-	-	-	82,724
American elm	-	-	-	6,340	22,086	23,006	9,304	9,857	-	70,593
Chinese elm	368	488	3,444	5,642	45,167	12,756	-	-	-	67,866
Darlington oak	-	-	-	-	25,810	-	-	28,696	-	54,505
Baldcypress	550	8,637	29,388	15,585	-	-	-	-	-	54,160
Chinese pistache	5,763	46,133	-	-	-	-	-	-	-	51,896
Jelly palm	601	2,550	9,090	21,227	17,005	695	-	-	-	51,168
Tallowtree	3,184	8,412	20,086	19,184	-	-	-	-	-	50,866
Oct glory red maple	1,904	46,679	-	-	-	-	-	-	-	48,584
London planetree	2,813	44,685	-	-	-	-	-	-	-	47,498
Japanese zelkova	2,461	27,931	13,776	-	-	-	-	-	-	44,168
Muskogee crapemyrtle	8,920	23,364	11,429	-	-	-	-	-	-	43,713
Winged elm	-	-	-	13,292	9,846	16,113	-	-	-	39,250
Shumard oak	4,179	32,462	-	-	-	-	-	-	-	36,641
Black oak	-	-	-	-	7,743	-	-	28,696	-	36,439
White oak	-	-	-	5,305	10,349	20,735	-	-	-	36,389
River birch	718	15,099	14,022	5,642	-	-	-	-	-	35,481
Carolina laurelcherry	3,182	7,266	7,945	10,903	5,863	-	-	-	-	35,160
Siberian elm	-	-	-	4,589	11,593	10,583	7,353	-	-	34,118
Red mulberry	-	943	8,349	5,065	8,906	10,303	-	-	-	33,565
Slash pine	-	-	-	11,362	8,196	13,314	-	-	-	32,872
Other trees	92,046	153,321	121,831	105,075	82,339	15,535	-	-	-	570,147
Citywide total	427,399	1,926,806	3,084,259	4,483,482	7,694,324	9,832,209	7,061,316	5,286,815	2,700,224	42,496,834

Chapter Three—Costs of Managing Charleston's Municipal Trees

The benefits that Charleston's trees provide come, of course, at a cost. This chapter presents a breakdown of annual expenditures for fiscal year 2004. Total annual tree-related expenditures for Charleston's municipal forestry program are approximately $700,000 (*Table 8*) (Burbage 2005). This amount represents 0.6% of Charleston's total 2004 operating budget ($115 million) and $6/capita. The tree budget funds the care of more than the 15,244 trees included in the inventory; it includes an additional estimated 35,000 trees in parks, traffic medians, wooded buffers and drainage easements. This study will only determine benefits for the inventoried trees, therefore we consider only the portion of the budget that applies to trees in the inventory. Because the other 35,000 trees are in parks and other more "naturalized" areas, they require less maintenance than the street trees, and we therefore estimate that the inventoried trees consume about 75% of the tree care budget, or $531,200 (Burbage 2005). The numbers in the following sections represent this proportion of the municipal tree care budget.

The city spends about $35 per tree on average during the fiscal year, significantly greater than the 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. Charleston's annual expenditure is approximately equal to that of Fort Collins, CO ($32), and far less than some California communities such as Santa Monica ($53) and Berkeley ($65) (McPherson et al. 2002, 2003, 2005f).

Forestry program expenditures fall into three general 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 perpetuation of a healthy urban forest. By planting new trees that are relatively large, with DBH of 2.5–3 inches, the city of Charleston is giving its urban forest a healthy start. The Urban Forestry Division plants about 500 trees annually, with three trees planted for every one removed. Tree planting activities, including materials, labor, administration, and equipment costs, account for 20.5% of the program budget or approximately $110,000.

An innovative tree planting program that brings together the Urban Forestry Division and residents is partly responsible for the high number of new plantings. On request, residents receive a 2½–3 inch DBH tree at wholesale prices. The tree is planted by the city and the homeowner agrees to water it for the first year. The effectiveness of this collaboration is also evident in the low establishment-related mortality of newly planted trees: less than 1% annually (Burbage 2005).

Pruning, Removals, and General Tree Care

Pruning accounts for nearly half of the annual expenditures at $243,750 ($16 per tree). This is partly

Table 8—*Charleston's annual municipal forestry-related expenditures.*

Expenditures	Total ($)	$/Tree	$/Capita	% of total
Purchasing trees and planting	109,125	7.16	1.04	20.5
Contract pruning	243,750	15.99	2.32	45.9
Tree & stump removal	23,625	1.55	0.23	4.4
Irrigation	4,700	0.31	0.04	0.9
Administration	60,000	3.94	0.57	11.3
Litter clean-up	45,000	2.95	0.43	8.5
Infrastructure repairs	45,000	2.95	0.43	8.5
Total expenditures	531,200	34.85	5.06	100

a reflection of the amount of care the sabal palmetto trees require for safety and aesthetics purposes. The tree maintenance crews spend nearly one-third of the year pruning the city's 3,000 palmettos (Davey Resource Group 2000).

On average, new trees are trained once every three years. Small trees are pruned every six years and large trees every ten. The quality of the Urban Forestry Division's pruning program is reflected in the low number of trees requiring priority pruning (0.2%). Careful pruning is particularly important in such a hurricane-prone area.

Tree and stump removal accounts for only 4.4% of tree-related expenses ($23,625). About 70 street trees are removed each year. Most of the removed wood (85%) is disposed of in a landfill in order to control the spread of Formosan termites. Formosan termites are an invasive, nonnative species that first appeared in the United States in Charleston in 1957. They eat more than 50 species of plants as well as lumber, mulch, asphalt, plastic and thin sheets of metal and can cause severe structural damage to a house in less than two years (Forschler 2002). For these reasons, the Urban Forestry Division is careful to dispose of all potentially infested woody material.

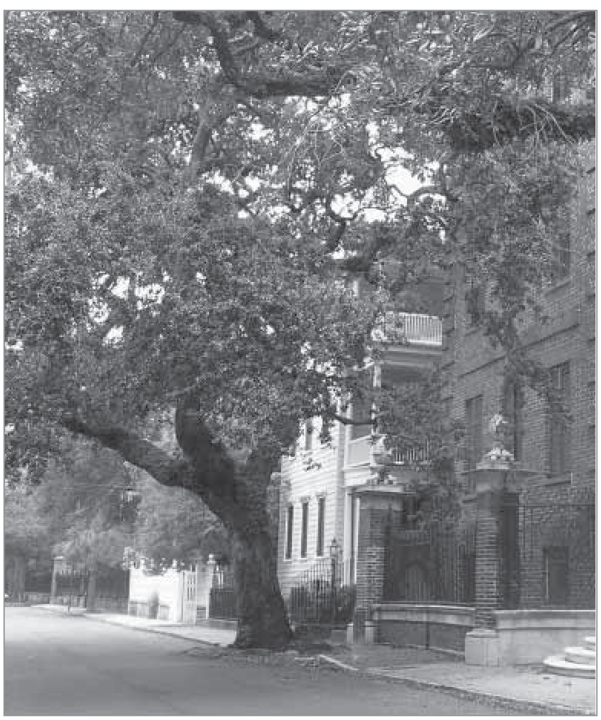

Figure 8—Conflicts between older trees and old infrastructure can be costly and difficult to repair, but the benefits provided by trees such as this one make the effort worthwhile.

Irrigation accounts for less than 1% of the budget ($4,700). New trees that are not planted in front of homes are irrigated for the first year using a water truck. The city does not have any budgeted funds for pest and disease management.

Administration

An additional $60,000 is spent on administration expenses including supplies, travel, training, insurance and workers' compensation. Salaries for managers and clerical staff and overtime costs for hourly workers have been included in other cost categories.

Other Tree-Related Expenditures

In a typical year, Charleston spends about $45,000 on litter clean-up. This number includes overtime salaries for clean-up crews. In years with heavy storms, this number may be significantly higher.

Annually, about $45,000 is spent by the city on infrastructure repair related to tree roots. Shallow roots that heave sidewalks, crack curbs, and damage driveways are an important aspect of mature tree care (*Figure 8*). The Division works closely with other departments to find solutions to tree/sidewalk conflicts. Once problems occur, the city attempts to resolve them without removing the tree. Strategies include ramping the sidewalk over the root or moving the sidewalk around the tree, grinding concrete to level surfaces, removing and replacing concrete, and pruning roots only when necessary. Not all curb and sidewalk damage is due to tree roots, especially in historic parts of the city where infrastructure is old. However, infill and higher density development will increase tree root–hardscape conflicts unless structural soils, careful species selection, and other practices are used.

Chapter Four—Benefits of Charleston's Municipal Trees

City trees work ceaselessly, providing ecosystem services that directly improve human health and quality of life. In this section, the benefits of Charleston'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 and physical health, crime, and violence). Also, our limited knowledge about the physical processes at work and their interactions makes these estimates imprecise (e.g., fate of air pollutants trapped by trees and then washed to the ground by rainfall). Tree growth and mortality rates are highly variable. A true and full accounting of benefits and costs must consider variability among sites throughout the city (e.g., tree species, growing conditions, maintenance practices), as well as variability in tree growth.

Therefore, these estimates provide first-order approximations of tree value. Our approach is a general accounting of the benefits produced by municipal trees in Charleston—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 C*.

Energy Savings

Trees modify climate and conserve energy in three principal ways:

- Shading reduces the amount of radiant energy absorbed and stored by built surfaces.
- Transpiration converts moisture to water vapor and thus cools the air by using solar energy that would otherwise result in heating of the air.
- Wind-speed reduction reduces the movement of outside air into interior spaces and conductive heat loss where thermal conductivity is relatively high (e.g., glass windows) (Simpson 1998).

Trees and other vegetation within building sites may lower air temperatures 5°F (3°C) compared to outside the greenspace (Chandler 1965) (*Figure 9*). At the larger scale of city-wide 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 50%, translating into potential annual heating sav-

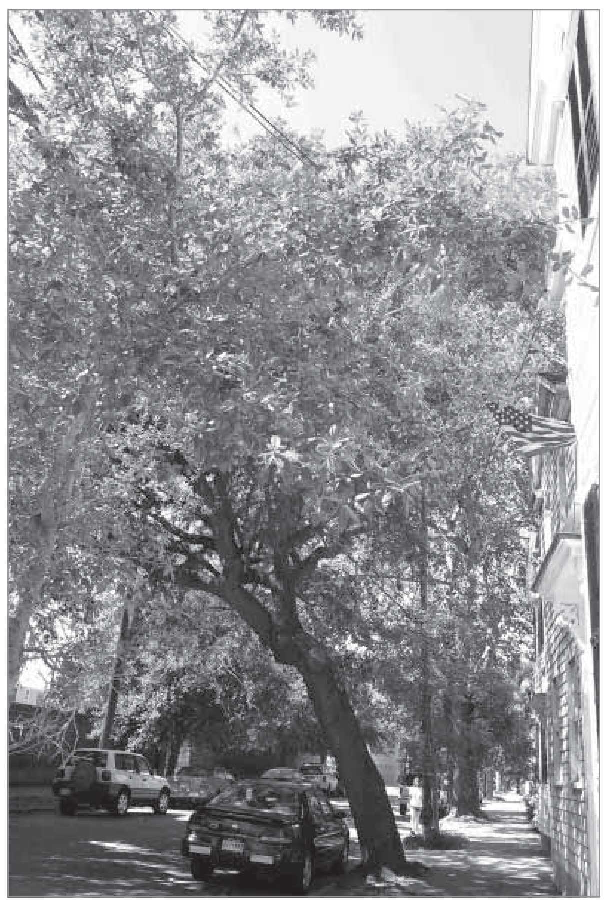

Figure 9—Trees shade a Charleston neighborhood, reducing energy use for cooling and cleaning the air.

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

Species	Electricity (MWh)	Electricity ($)	Natural gas (MBtu)	Natural gas ($)	Total ($)	% of total trees	% of total $	Avg. $/tree
Live oak	376	35,105	565	6,766	41,871	23.8	34.6	11.53
Crapemyrtle	45	4,177	125	1,493	5,670	20.1	4.7	1.85
Sabal palmetto	117	10,885	291	3,481	14,367	19.6	11.9	4.81
Water oak	167	15,595	348	4,170	19,766	5	16.3	25.28
Laurel oak	131	12,249	267	3,201	15,449	3.9	12.8	25.83
Flowering dogwood	9	851	24	286	1,137	2.3	0.9	3.22
Loblolly pine	32	3,015	63	749	3,764	1.8	3.1	13.74
Jelly palm	6	595	13	162	756	1.5	0.6	3.39
Red maple	6	523	10	124	647	1.0	0.5	4.18
Other street trees	150	14,025	296	3,540	17,565	20.9	14.5	5.52
Citywide total	1,039	97,020	2,002	23,971	120,991	100.0	100.0	7.94

ings of 25% (Heisler 1986). Decreasing wind speed reduces heat transfer through conductive materials as well. *Appendix C* provides additional information on specific contributions that trees make toward energy savings.

Electricity and Natural Gas Results

Electricity and natural gas saved annually in Charleston from both shading and climate effects total 1,039 MWh ($97,020) and 2,002 Mbtu ($23,971), respectively, for a total retail savings of $120,991 (*Table 9*) or a citywide average of $7.94 per tree. Water, laurel, and live oaks are the primary contributors to energy savings on a per tree basis.

Live oaks account for 23.8% of total tree numbers, but provide 34.6% of the energy savings, as expected for a tree species with such a high Importance Value (IV). Water oaks and laurel oaks provide even greater energy savings on a per tree basis. One reason their contribution is greater than live oaks is because, as semi-deciduous trees, they block less of the winter sun's warming rays and therefore do not have a negative effect on heating costs, as live oaks, planted injudiciously, can. Crapemyrtles, in contrast, make up 20.1% of the population and provide less than 5% of energy savings, consistent with their smaller IV.

Atmospheric Carbon Dioxide Reductions

Urban forests can reduce atmospheric carbon dioxide in two ways:

- Trees directly sequester CO_2 as woody and foliar biomass while they grow.
- 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.

At the same time, however, 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 as they decompose unless recycled. These factors must be taken into consideration when calculating the carbon dioxide benefits of trees.

Carbon Dioxide Reductions

Citywide, Charleston's municipal forest reduced atmospheric CO_2 by a net of 1,563 tons annually (*Table 10*). This benefit was valued at $23,452 or $1.54 per tree. Avoided CO_2 emissions from power plants due to cooling energy savings totaled 711 tons, while CO_2 sequestered by trees was 944 tons. CO_2 released through decomposition and tree care activities totaled 91 tons, or 5.5% of the net total benefit. Avoided emissions are important in Charleston because coal, which has a relatively high CO_2 emissions factor, accounts for 66% of the fuel used in power plants that generate electricity there (US EPA 2003). Shading by trees during summer reduces the need for air conditioning, resulting in reduced use of coal for electricity generation.

On a per tree basis, water, laurel, and live oaks, and loblolly pine provide the greatest CO_2 benefits (*Table 10*). Because of its great numbers, live oak also provides the greatest total CO_2 benefits, accounting for nearly 40% of citywide CO_2 reduction. Crapemyrtle represents only 3.2% of the benefits, although it makes up 20.1% of the population.

Air Quality Improvement

Urban trees improve air quality in five main ways:

- Absorbing gaseous pollutants (ozone, nitrogen oxides) through leaf surfaces
- Intercepting particulate matter (e.g., dust, ash, dirt, pollen, smoke)
- Reducing emissions from power generation by reducing energy consumption
- Releasing oxygen through photosynthesis
- 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 temperatures contribute to ozone formation. On the other hand, most trees emit various biogenic volatile organic compounds (BVOCs) such as isoprenes and monoterpenes that can also 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.

Deposition and Interception

An average of 3.5 tons or $7,075 worth of nitrogen dioxide (NO_2), small particulate matter (PM_{10}), ozone (O_3), and sulfur dioxide (SO_2) are intercepted by trees (pollution deposition and particulate interception) in Charleston each year (*Table 11*). Charleston's trees are most effective at removing O_3 and PM_{10}, with an implied annual value of $5,841. Again, due to its great numbers and large leaf area, live oaks contribute the most to pollutant uptake, removing nearly 3,000 lbs each year.

Avoided Pollutants

Energy savings result in reduced air pollutant emissions of NO_2, PM_{10}, volatile organic compounds (VOCs), and SO_2 (*Table 11*). Together, 7.3 tons of pollutants are avoided annually with an implied value of $14,676. In terms of amount and dollar value, avoided emissions of SO_2 are greatest (8,104 lb, $10,373). Live oaks have the greatest impact on reducing energy needs and thereby account for 4,370 lbs of pollutants whose production is avoided in power plants each year.

***Table 10**—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
Live oak	817,144	-83,677	-708	514,305	1,247,064	9,353	23.8	39.9	2.58
Crapemyrtle	40,139	-1,153	-596	61,190	99,580	747	20.1	3.2	0.24
Sabal palmetto	34,519	-5,119	-583	159,476	188,293	1,412	19.6	6.0	0.47
Water oak	358,278	-34,638	-152	228,474	551,962	4,140	5.1	17.6	5.29
Laurel oak	321,280	-30,844	-117	179,448	469,768	3,523	3.9	15.0	5.89
Flowering dogwood	10,689	-561	-69	12,472	22,532	169	2.3	0.7	0.48
Loblolly pine	59,056	-3,578	-53	44,167	99,592	747	1.8	3.2	2.73
Jelly palm	75	-105	-43	8,714	8,642	65	1.5	0.3	0.29
Red maple	12,971	-366	-30	7,666	20,241	152	1.0	0.6	0.98
Other street trees	233,341	-18,888	-620	205,465	419,298	3,145	20.9	13.4	0.99
Citywide total	1,887,493	-178,927	-2,973	1,421,377	3,126,970	23,452	100.0	100.0	1.54

Table 11—*Pollutant deposition, avoided and BVOC emissions, and net air-quality benefits produced by predominant street tree species.*

Species	Deposition					Avoided					BVOC emissions		Net total		% of trees	Avg. $/tree
	O_3 (lb)	NO_2 (lb)	PM_{10} (lb)	SO_2 (lb)	($)	NO_2 (lb)	PM_{10} (lb)	VOC (lb)	SO_2 (lb)	($)	(lb)	($)	(lb)	($)		
Live oak	1,700	301	790	201	2,939	968	238	236	2,928	5,286	−6,825	−10,100	538	−1,876	23.8	−0.52
Crapemyrtle	147	15	52	8	219	120	29	28	349	636	0	0	750	855	20.1	0.28
Sabal palmetto	473	84	220	56	818	311	75	74	910	1,654	−1,369	−2,026	833	446	19.6	0.15
Water oak	687	91	254	59	1,077	440	107	106	1,304	2,365	−2,120	−3,138	927	304	5.1	0.39
Laurel oak	551	73	204	47	863	345	84	83	1,024	1,856	−694	−1,027	1,716	1,692	3.9	2.83
Flowering dogwood	30	3	11	2	44	24	6	6	71	129	0	0	152	174	2.3	0.49
Loblolly pine	131	23	61	16	227	85	21	20	252	457	−553	−818	56	−134	1.8	−0.49
Jelly palm	26	5	12	3	45	17	4	4	50	90	−71	−105	49	30	1.5	0.13
Red maple	17	2	6	1	25	15	4	4	44	80	−3	−5	88	100	1.0	0.64
Other street trees	535	63	198	36	818	394	96	95	1,172	2,124	−699	−1,034	1,890	1,908	20.9	0.60
Citywide total	4,296	659	1,808	428	7,075	2,720	661	657	8,104	14,676	−12,333	−18,253	6,999	3,498	100.0	0.23

BVOC Emissions

Biogenic volatile organic compound (BVOC) emissions from trees are significant. At a total of 6.2 tons, these emissions offset about 60% of air quality improvements and are valued as a cost to the city of $18,253. Oak species are often fairly heavy emitters of BVOCs and this can be seen in Charleston as well. The live oaks are especially high with total annual BVOC emissions of 6,825 lbs.

Net Air Quality Improvement

Net air pollutants removed, released, and avoided are valued at $3,498 annually. The average benefit per tree is $0.23. Trees vary dramatically in their ability to produce net air-quality benefits. Large-canopied trees with large leaf surface areas that are not high emitters, such as the laurel oak, produce the greatest benefits. Laurel oak was the most valuable tree, by far, on a per-tree basis ($2.83). Some species had levels of BVOC emissions that were high enough to offset their contributions to air quality improvement, including the live oak ($−0.52) and the loblolly pine ($−0.49).

Stormwater Runoff Reductions

According to federal Clean Water Act regulations, municipalities must obtain a permit for managing their stormwater discharges into water bodies. Each city's program must identify the Best Management Practices (BMPs) it will implement to reduce its pollutant discharge. Trees are mini-reservoirs, controlling runoff at the source. Healthy urban trees can reduce the amount of runoff and pollutant loading in receiving waters in three primary ways:

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

Charleston's municipal trees intercept 3,787,400 cubic ft (28.3 million gal) of stormwater annually, or 1,858 gal per tree on average. The total value of this benefit to the city is $171,406, or $11.24 per tree.

Certain species are much better at reducing stormwater runoff than others (*Table 12*). Leaf type and area, branching pattern and bark, as well as tree size and shape all affect the amount of precipitation trees can intercept and hold to reduce runoff. Trees that perform well include laurel oak ($38 per tree), water oak ($36 per tree), and live oak ($19 per tree). Interception by live oak alone accounts for 41% of the total dollar benefit for street trees. Poor performers are species with relatively small leaf and stem surface areas, such as dogwood and crapemyrtle.

Table 12*—Annual stormwater reduction benefits of Charleston's public trees by species.*

Species	Rainfall interception (CCF)	Total ($)	% of trees	% of Total $	Avg. $/tree
Live oak	15,627	70,723	23.8	41.3	19.47
Crapemyrtle	862	3,901	20.1	2.3	1.28
Sabal palmetto	3,912	17,705	19.6	10.3	5.93
Water oak	6,185	27,991	5.1	16.3	35.79
Laurel oak	4,962	22,456	3.9	13.1	37.55
Flowering dogwood	166	749	2.3	0.4	2.12
Loblolly pine	1,056	4,781	1.8	2.8	17.45
Jelly palm	199	902	1.5	0.5	4.05
Red maple	105	477	1.0	0.3	3.08
Other street trees	4,799	21,720	20.9	12.7	6.83
Citywide total	37,874	171,406	100.0	100.0	11.24

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 difficult to price (*Figure 10*). 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" intangible benefits, research that compares differences in sales prices of houses was used to estimate the contribution associated with trees. The difference in sales price reflects the willingness of buyers to pay for the benefits and costs associated with trees. This approach has the virtue of capturing what buyers perceive as both the benefits and costs of trees in the sales price. One limitation of using this approach is the difficulty associated with extrapolating results from front-yard trees on residential properties to street trees in other locations (e.g., commercial vs. residential) (see *Appendix C* for more details).

The estimated total annual benefit associated with property value increases and other less tangible benefits is $395,000, or $26 per tree on average (*Table 13*). Tree species that produce the highest average annual benefits include laurel oak ($83 per tree), water oak ($66 per tree), and live oak ($51), while small trees and palms such as the jelly palm ($1 per tree) and sabal palmetto ($1 per tree) are examples of trees that produce the least benefits.

Figure 10—Trees add value to residential property.

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

Total annual benefits produced by Charleston's street trees are estimated at $717,034 ($47 per tree, $7 per capita) (*Table 14*). Over the same period, tree-related expenditures are estimated to be $531,200 ($35 per tree, $5 per capita). Net annual benefits (benefits minus costs) are $185,834, or $12 per tree and $2 per capita. The Charleston municipal forest currently returns $1.35 to the community for every $1 spent on management. Charleston's benefit–cost ratio of 1.35 is similar to that reported for Berkeley, CA (1.37), exceeds that reported for San Francisco (1.00) but is below those reported

Table 13*—Total annual increases in property value produced by street trees.*

Species	Total ($)	% of trees	% of total $	Avg. $/tree
Live oak	185,389	23.8	46.6	51.04
Crapemyrtle	12,545	20.1	3.2	4.10
Sabal palmetto	4,371	19.6	1.1	1.46
Water oak	52,130	5.1	13.1	66.66
Laurel oak	50,306	3.9	12.6	84.12
Flowering dogwood	1,160	2.3	0.3	3.29
Loblolly pine	12,925	1.8	3.3	47.17
Jelly palm	268	1.5	0.1	1.20
Red maple	3,556	1.0	0.9	22.94
Other street trees	75,037	20.9	18.9	23.59
Citywide total	397,687	100.0	100.0	26.09

Table 14—Benefit–cost summary for all public trees.

Benefits	**Total ($)**	**$/tree**	**$/capita**
Energy	120,991	7.94	1.15
CO2	23,452	1.54	0.22
Air quality	3,498	0.23	0.03
Stormwater	171,406	11.24	1.63
Aesthetic / other	397,687	26.09	3.79
Total benefits	717,034	47.04	6.84
Costs			
Planting	109,125	7.16	1.04
Contract pruning	243,750	15.99	2.32
Tree & stump removal	23,625	1.55	0.23
Irrigation	4,700	0.31	0.04
Administration	60,000	3.94	0.57
Litter clean-up	45,000	2.95	0.43
Infrastructure repairs	45,000	2.95	0.43
Total costs	531,200	34.85	5.06
Net benefits	185,834	12.19	1.77
Benefit-cost ratio		1.35	

for Charlotte, NC (3.25), Glendale, AZ (2.41), Fort Collins, CO (2.18), Cheyenne, WY (2.09), and Minneapolis, MN (1.57) (McPherson et al. 2003, 2004b, 2005a–f). The lower benefit–cost ratio of Charleston's street trees compared to other areas is due in part to lower air quality and energy benefits because of a more salubrious climate and cleaner air, and in part, to slightly higher costs.

Charleston's municipal trees have beneficial effects on the environment. Almost half (45%) of the annual benefits provided to residents of the city are environmental services. Stormwater runoff reduction represents 54% of environmental benefits, with energy savings accounting for another 38%. Carbon dioxide reduction (7%) and air quality improvement (1%) provide the remaining environmental benefits. Annual increases in property value are very valuable, accounting for 55% of total annual benefits in Charleston.

Table 15 shows the distribution of total annual benefits in dollars for the predominant street tree species in Charleston. Live oaks are most valuable to the city overall (43% of total benefits, $84 per tree). On a per tree basis, water oak ($156 per tree) and laurel oak ($133 per tree) also produce significant benefits. Nonetheless, despite the water oak's high level of benefits, the species is not well suited as a street tree as it is short-lived, shallow-rooted and

Table 15—Average annual benefits ($ per tree) of street trees by species.

Species	**Energy**	**CO_2**	**Air quality**	**Stormwater**	**Aesthetic / other**	**Total**	**% of Total $**
Live oak	11.53	2.58	-0.52	19.47	51.04	84.10	42.6
Crapemyrtle	1.85	0.24	0.28	1.28	4.10	7.76	3.3
Sabal palmetto	4.81	0.47	0.15	5.93	1.46	12.82	5.3
Water oak	25.28	5.29	0.39	35.79	66.66	133.41	14.6
Laurel oak	25.83	5.89	2.83	37.55	84.12	156.23	13.0
Flowering dogwood	3.22	0.48	0.49	2.12	3.29	9.60	0.5
Loblolly pine	13.74	2.73	-0.49	17.45	47.17	80.59	3.1
Jelly palm	3.39	0.29	0.13	4.05	1.20	9.07	0.3
Red maple	4.18	0.98	0.64	3.08	22.94	31.81	0.7
Other street trees	5.52	0.99	0.60	6.83	23.59	37.53	16.6

prone to failure. As trees grow their ability to provide environmental services increases dramatically, hence, the substantial difference between the average annual benefits of the oaks and the crapemyrtle ($8) or dogwood ($10).

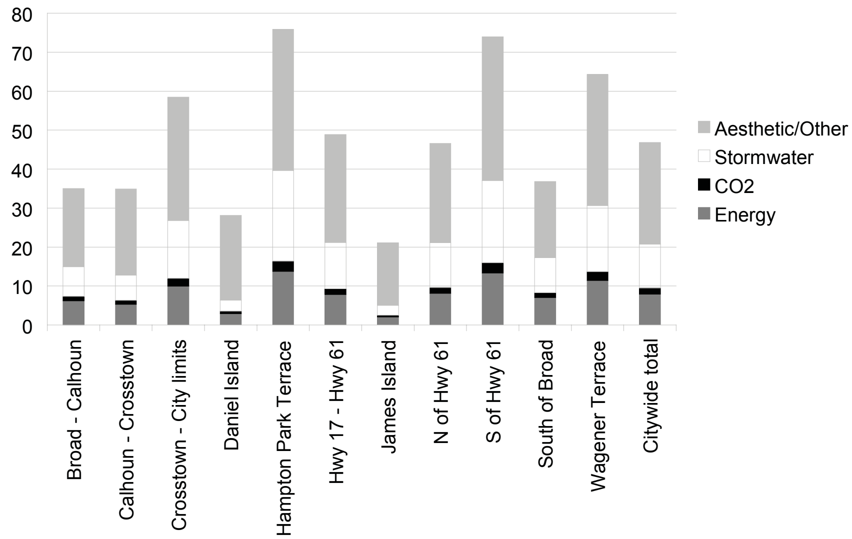

Figure 12—Average annual street tree benefits per tree by management zone.

In historic cities like Charleston, small species may be the only option in many areas, where high building density has left little room for trees. Regional pruning techniques, however, play a large factor in the relatively small benefits afforded by crapemyrtles. The small leaf area of the trees is not inherent in the species: crapemyrtles in Claremont, CA, have 11 times more leaf surface area than those in Charleston (3,080 vs. 270ft^2; McPherson et al. 2001) (*Figure 11*). Changing the way crapemyrtles are pruned may be an easy way to increase benefits.

Figure 12 illustrates the average annual street tree benefits per tree by management zone and reflects differences in tree types and population ages.

Differences across neighborhoods are pronounced: average annual benefits range from $21 in James Island, where half of the trees are crapemyrtles to $76 in Hampton Park Terrace where a large proportion of the trees are in the largest size classes.

Figure 11—Crapemyrtles grow large enough nearly to meet over a wide street in Claremont, CA. On average, the crapemyrtles in Claremont have 11 times the leaf surface area of those in Charleston. Changing pruning techniques may be an easy way to increase benefits.

Chapter Five—Management Implications

Charleston's urban forest reflects the values, lifestyles, preferences, and aspirations of current and past residents. It is a dynamic legacy whose character will change greatly over the next decades. 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 Charleston's street tree population, what future trends are likely and what management challenges will need to be met to sustain or increase this level of benefits?

Focusing on three components—resource complexity, resource extent, and maintenance—will help refine broader municipal tree management goals. Achieving resource sustainability will produce long-term net benefits to the community while reducing the associated costs incurred in managing the resource.

Resource Complexity

Although Charleston's urban forest has a rich mix of 136 species of street trees, three—live oak, crapemyrtle, and sabal palmetto—clearly dominate. Together they represent 64% of all street trees and provide more than half of all benefits (51%). A disease or pest infestation that targeted one or more of these species could result in a severe loss to the city. At the same time, however, these trees are well-suited to the hurricanes and other difficult conditions of the location, and their aesthetic qualities and character make them beloved representatives of the charms of an old Southern city.

Nonetheless, a more diverse mix should be considered to provide some protection against potential catastrophes due to pests or disease; it should include some proven performers, some species that are more narrowly adapted and a small percentage of new introductions for evaluation.

In recent years the Urban Forestry Division has begun to experiment with planting a broader selection of large-growing species. *Figure 13* displays large- and medium-growing trees in the smallest DBH size classes, indicating trends in new and replacement trees. Live oaks still vastly outnumber all other species, but an interesting mix of native (Shumard oak [*Q. shumardii*], Southern red oak [*Q. falcata*], red maple [*Acer rubrum*], and river birch [*Betula nigra*]) and nonnative, but good urban performers (London plane [*Platanus* x *acerifo-*

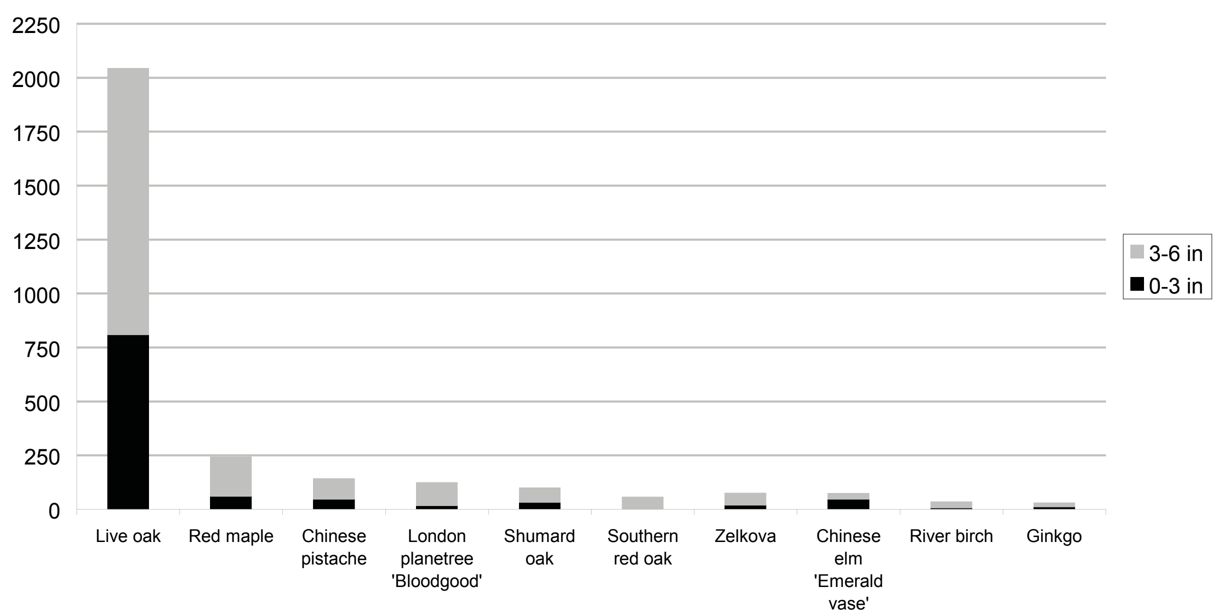

Figure 13—Municipal trees being planted in the highest numbers.

lia], Chinese pistache [*Pistacia chinensis*], zelkova [*Zelkova serrata*], Chinese elm [*Ulmus parvifolia*] and ginkgo [*Ginkgo biloba*]) species has been planted.

Although native species may not be appropriate in all urban settings, they should be considered, as they have adapted over centuries to withstand hurricanes and other local pressures. Possibilities include bald and pond cypress (*Taxodium distichum* and *T. ascendens*), sweetbay magnolia (*Magnolia virginiana*), sassafras (*Sassafras albidum*), and longleaf pine (*Pinus palustris*).

Among small trees, crapemyrtles are still overwhelmingly dominant among new plantings, with more than 10 times as many crapemyrtles (1,568) in the 0–3 inch DBH class as the next most common species, the flowering dogwood (138). Small native flowering trees to consider include the ti-ti tree (*Cyrilla racemiflora*), silverbells (*Halesia diptera* and *H. carolina*), snowbells (*Styrax grandifolius* and *S. americanus*) and the fringe tree (*Chionanthus virginicus*).

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 the number of trees, and therefore, 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 Charleston's canopy cover.

The stocking level of Charleston is reported to be 80% (Davey Resource Group 2000). This very impressive number, a tribute to the management and dedication of the Urban Forestry Division, will continue to improve as the city plants 400–500 new trees each year and removes only 120.

As Charleston approaches full stocking of street trees, other areas warrant attention. Increased tree planting in parking lots to provide shade and improve air quality is another strategy to increase tree canopy cover that could be applied to new and existing development. Similarly, Charleston should 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 trees can produce.

Maintenance

Charleston's maintenance challenges in the coming years will be to care properly for the many new trees that have been planted and for the large trees as they age. Live, water and laurel oaks have a sizable proportion of their populations in the larger size classes. These mature trees are responsible for a relatively large proportion of current benefits. Therefore, regular inspection and pruning of these trees is essential to sustaining the current high level of benefits in the short term.

The Urban Forestry Division is making a concerted effort to increase the number of new trees planted. With 400–500 new trees planted each year, a strong young-tree-care program is imperative to insure that the trees transition into well-structured, healthy mature trees requiring minimal pruning. Investing in the young-tree-care program will reduce costs for routine care as they mature. Also, well-trained trees are less likely to be damaged during storms than trees that have not developed a strong structure. The Urban Forestry Division should work to increase the rate of young tree pruning from every three years to every two years for the first six years.

Chapter Six—Conclusion

This analysis describes structural characteristics of the street tree population and uses tree growth and geographic data for Charleston to model the ecosystem services trees provide the city and its residents. In addition, the benefit–cost ratio has been calculated and management needs are identified. The approach is based on established tree sampling, numerical modeling, and statistical methods and provides a general accounting of the benefits produced by street trees in Charleston that can be used to make informed decisions.

Charleston's 15,244 street trees are a valuable asset, providing approximately $717,034 ($47 per tree) in annual gross benefits. Benefits to the community are most pronounced for stormwater reduction and aesthetic benefits. Thus, street trees play a particularly important role in maintaining the environmental and aesthetic qualities of the city (*Figure 14*).

Charleston spends approximately $531,200 maintaining its inventoried trees or $35 per tree. Expenditures for pruning account for about one-half of total costs.

After costs are taken into account, Charleston's municipal tree resource provides approximately $185,834, or $12 per tree ($2/capita) in net annual benefits to the community. Over the years, Charleston has invested millions of dollars in its municipal forest. **Citizens are seeing a return on that investment—receiving $1.35 in benefits for every $1 spent on tree care**. The fact that Charleston's benefit–cost ratio exceeds 1 indicates that the program is not only operationally efficient, but is capitalizing on the functional services its trees can produce. As the resource grows, continued investment in management is critical to insuring that residents will receive a high return on investment in the future.

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

Management recommendations derived from this analysis are sevenfold:

1. Continue to diversify the mix of tree species planted to guard against catastrophic losses due to storms, pests or disease.

2. Sustain an annual planting program over the long-term to increase age diversity.

3. Sustain benefits by investing in intensive maintenance of mature trees to prolong the functional life spans of these heritage trees.

4. Develop a strong young-tree-care program that includes inspection and pruning on a two-year cycle.

5. Plant large species where conditions are suitable to maximize benefits.

6. Insure adequate space for large trees in new developments by revising street design standards. Encourage the use of structural soils where appropriate. Where possible, locate power lines belowground.

7. Review and revise parking lot shade guidelines and the adequacy of current ordinances to preserve and protect large trees from development impacts.

These recommendations build on a history of dedicated management that has put Charleston on course to provide an urban forest resource that is both functional and sustainable.

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)										
Quercus nigra	11	19	53	161	278	200	51	8	1	782
Quercus laurifolia	8	33	37	118	177	136	57	23	9	598
Acer rubrum	43	92	12	4	4	-	-	-	-	155
Platanus acerifolia 'Bloodgood'	17	107	-	-	-	-	-	-	-	124
Gleditsia triacanthos	11	28	62	18	-	-	-	-	-	119
Quercus phellos	4	63	29	7	6	4	4	1	1	119
Liquidambar styraciflua	35	4	22	19	16	10	3	-	-	109
Quercus shumardii	32	68	-	-	-	-	-	-	-	100
Quercus falcata	0	58	-	2	8	6	6	5	1	86
Zelkova serrata	20	56	8	-	-	-	-	-	-	84
Platanus occidentalis	10	25	12	6	8	10	3	6	1	81
Carya illinoensis	3	5	8	11	10	3	1	1	-	42
Ginkgo biloba	11	19	4	-	-	-	-	-	-	34
Quercus rubra	0	1	1	1	4	1	3	4	3	18
Ulmus americana	0	-	-	3	8	5	1	1	-	18
Prunus serotina	2	7	2	3	2	-	-	-	-	16
Acer saccharinum	3	4	3	2	-	1	-	-	-	13
Liriodendron tulipifera	7	4	1	1	-	-	-	-	-	13
Acer saccharum	0	1	2	4	2	-	-	-	-	9
Nyssa sylvatica	1	-	3	-	2	-	-	-	-	6
Quercus coccinea	0	3	1	1	-	-	-	-	-	5
Quercus palustris	0	1	2	1	-	-	-	-	-	4
Carya cordiformis	0	-	-	3	-	-	-	-	-	3
Populus deltoides	0	1	2	-	-	-	-	-	-	3
Quercus alba	0	-	-	1	1	1	-	-	-	3
Fraxinus americana	1	1	-	-	-	-	-	-	-	2
Populus alba	1	-	1	-	-	-	-	-	-	2
Quercus stellata	0	-	-	1	1	-	-	-	-	2
Quercus velutina	0	-	-	-	1	-	-	1	-	2
Ulmus rubra	0	-	-	2	-	-	-	-	-	2
Carya glabra	0	-	-	1	-	-	-	-	-	1
Juglans nigra	0	-	-	1	-	-	-	-	-	1
Quercus michauxii	0	-	1	-	-	-	-	-	-	1
Tilia americana	0	-	-	-	1	-	-	-	-	1
Total	220	600	266	371	529	377	129	50	16	2,558
Broadleaf deciduous medium (BDM)										
Pistacia chinensis	47	96	-	-	-	-	-	-	-	143
Acer rubrum 'October glory'	17	91	-	-	-	-	-	-	-	108
Pyrus calleryana	28	29	11	12	1	-	-	-	-	81
Sapium sebiferum	15	24	25	11	-	-	-	-	-	75
Ulmus parvifolia 'Emer II'	46	28	-	-	-	-	-	-	-	74
Betula nigra	6	29	9	1	-	-	-	-	-	45
Ulmus pumila	0	-	-	5	8	5	2	-	-	20

Species	0–3	3–6	6–12	12–18	18–24	24–30	30–36	36–42	>42	Total
Pyrus calleryana 'Bradford'	1	7	11	-	-	-	-	-	-	19
Morus rubra	0	2	7	2	2	1	-	-	-	14
Ulmus parvifolia	3	1	2	1	5	1	-	-	-	13
Melia azedarach	2	4	2	2	2	-	-	-	-	12
Ulmus parvifolia 'Drake'	5	3	2	1	-	-	-	-	-	11
Carpinus caroliniana	0	4	5	-	-	-	-	-	-	9
Ulmus alata	0	-	-	4	2	2	-	-	-	8
Tilia cordata	1	-	2	2	-	-	-	-	-	5
Salix matsudana 'Tortuosa'	4	-	-	-	-	-	-	-	-	4
Diospyros virginiana	2	1	-	-	-	-	-	-	-	3
Salix babylonica	2	-	-	1	-	-	-	-	-	3
Broussonetia papyrifera	2	-	-	-	-	-	-	-	-	2
Quercus acutissima	0	2	-	-	-	-	-	-	-	2
Acer buergeranum	0	-	1	-	-	-	-	-	-	1
Cladrastis kentukea	0	1	-	-	-	-	-	-	-	1
Firmiana simplex	0	-	-	1	-	-	-	-	-	1
Koelreuteria bipinnata	1	-	-	-	-	-	-	-	-	1
Robinia pseudoacacia	0	-	1	-	-	-	-	-	-	1
Salix nigra	0	1	-	-	-	-	-	-	-	1
Total	182	323	78	43	20	9	2	-	-	657
Broadleaf deciduous small (BDS)										
Lagerstroemia indica	1568	1,025	418	45	2	-	-	-	-	3,058
Cornus florida	138	122	86	7	-	-	-	-	-	353
Lagerstroemia x 'Muskogee'	83	45	6	-	-	-	-	-	-	134
Hibiscus syriacus	60	2	-	-	-	-	-	-	-	62
Lagerstroemia x 'Tuskegee'	23	29	-	-	-	-	-	-	-	52
Malus angustifolia	11	10	2	1	-	-	-	-	-	24
Albizia julibrissin	9	10	3	-	-	-	-	-	-	22
Lagerstroemia x 'Tuscarora'	21	1	-	-	-	-	-	-	-	22
Magnolia x soulangiana	17	4	1	-	-	-	-	-	-	22
Cercis canadensis	18	-	1	-	-	-	-	-	-	19
Vitex agnus-castus	3	5	3	1	-	1	-	-	-	13
Prunus americana	5	-	3	-	-	-	-	-	-	8
Hibiscus mutabilis	7	-	-	-	-	-	-	-	-	7
Acer palmatum	4	1	-	1	-	-	-	-	-	6
Parkinsonia aculeata	6	-	-	-	-	-	-	-	-	6
Prunus cerasifera	4	-	-	-	-	-	-	-	-	4
Prunus serrulata	0	4	-	-	-	-	-	-	-	4
Prunus species	3	-	-	-	-	-	-	-	-	3
Prunus persica	2	1	-	-	-	-	-	-	-	3
Forsythia x intermedia	2	-	-	-	-	-	-	-	-	2
Magnolia stellata	1	1	-	-	-	-	-	-	-	2
Acer ginnala	1	-	-	-	-	-	-	-	-	1
Cornus kousa	1	-	-	-	-	-	-	-	-	1
Magnolia tripetala	0	-	1	-	-	-	-	-	-	1
Cassia bicapsularis	1	-	-	-	-	-	-	-	-	1
Viburnum prunifolium	0	1	-	-	-	-	-	-	-	1

Species	0–3	3–6	6–12	12–18	18–24	24–30	30–36	36–42	>42	Total
Wisteria floribunda	1	-	-	-	-	-	-	-	-	1
Total	1989	1,261	524	55	2	1	-	-	-	3,832
Broadleaf evergreen large (BEL)										
Quercus virginiana	809	1,235	542	260	223	233	163	111	56	3,632
Eucalyptus saligna	0	1	-	-	-	-	-	-	-	1
Total	809	1,236	542	260	223	233	163	111	56	3,633
Broadleaf evergreen medium (BEM)										
Magnolia grandiflora	24	17	40	37	8	2	1	-	-	129
Magnolia grandiflora 'Little Gem'	46	2	-	-	-	-	-	-	-	48
Prunus caroliniana	19	16	6	3	1	-	-	-	-	45
Ilex opaca x attenuata 'Savannah'	14	14	2	-	-	-	-	-	-	30
Cinnamomum camphora	1	-	2	1	1	-	-	-	-	5
Quercus hemisphaerica	0	-	-	-	3	-	-	1	-	4
Podocarpus macrophyllus	1	2	-	-	-	-	-	-	-	3
Eucalyptus cinerea	1	-	-	-	-	-	-	-	-	1
Total	106	51	50	41	13	2	1	1	-	265
Broadleaf evergreen small (BES)										
Ilex opaca	20	51	35	8	-	-	-	-	-	114
Photinia spp.	100	5	-	-	-	-	-	-	-	105
Myrica cerifera	51	11	1	-	-	-	-	-	-	63
Ilex species	18	18	6	1	-	-	-	-	-	43
Ligustrum japonicum	21	15	5	-	-	-	-	-	-	41
Nerium oleander	14	20	-	-	-	-	-	-	-	34
Eriobotrya japonica	20	7	2	-	-	-	-	-	-	29
Ilex vomitoria	5	4	-	-	-	-	-	-	-	9
Ligustrum sinense	6	2	-	-	-	-	-	-	-	8
Camellia sasanqua	5	-	-	-	-	-	-	-	-	5
Ilex cornuta	1	1	-	-	-	-	-	-	-	2
Osmanthus fragrans	2	-	-	-	-	-	-	-	-	2
Citrus aurantium	1	-	-	-	-	-	-	-	-	1
Pyracantha coccinea	1	-	-	-	-	-	-	-	-	1
Total	265	134	49	9	-	-	-	-	-	457
Conifer evergreen large (CEL)										
Pinus taeda	9	15	60	99	63	24	3	1	-	274
Celtis laevigata	8	2	24	28	15	8	1	-	1	87
Taxodium distichum[a]	5	18	15	3	-	-	-	-	-	41
Pinus elliottii	0	-	-	5	2	2	-	-	-	9
x Cupressocyparis leylandii	7	-	-	-	-	-	-	-	-	7
Metasequoia glyptostroboides[a]	5	-	-	-	-	-	-	-	-	5
Chamaecyparis thyoides	1	2	-	-	-	-	-	-	-	3
Pinus palustris	0	-	1	-	2	-	-	-	-	3
Total	35	37	100	135	82	34	4	1	1	429
Conifer evergreen medium (CEM)										
Juniperus virginiana	27	29	13	13	7	2	-	-	-	91
Thuja occidentalis	25	34	2	-	-	-	-	-	-	61
Cupressus sempervirens	10	4	-	-	-	-	-	-	-	14
Pinus virginiana	2	-	-	-	-	-	-	-	-	2
Total	64	67	15	13	7	2	-	-	-	168

Species	0–3	3–6	6–12	12–18	18–24	24–30	30–36	36–42	>42	Total
Palm evergreen large (PEL)										
Phoenix canariensis	2	2	-	-	-	-	-	-	-	4
Total	2	2	-	-	-	-	-	-	-	4
Palm evergreen medium (PEM)										
Sabal palmetto	3	49	558	2,324	54	-	-	-	-	2,988
Trachycarpus fortunei	2	4	2	-	-	-	-	-	-	8
Total	5	53	560	2,324	54	-	-	-	-	2,996
Palm evergreen small (PES)										
Butia capitata	4	11	39	92	74	3	-	-	-	223
Washingtonia robusta	2	5	-	5	-	-	-	-	-	12
Cycas revoluta	6	-	1	2	-	-	-	-	-	9
Yucca gloriosa[a]	1	-	-	-	-	-	-	-	-	1
Total	13	16	40	99	74	3	-	-	-	245
Citywide total	3690	3,780	2,224	3,350	1,004	661	299	163	73	15,244

[a]*Taxodium distichum* and *Metasequoia glyptostroboides* are not evergreen trees, but have been grouped into this category as it most closely approximates the level of benefits they provide. Yucca gloriosa is not actually a tree, but may grow large enough to provide the benefits of a tree and is categorized here in the most appropriate category.

Appendix B—Replacement Values

Species	0–3	3–6	6–12	12–18	18–24	24–30	30–36	36–42	>42	Total
Live oak	79,588	666,396	1,122,699	1,527,439	2,506,392	4,337,350	4,478,524	3,954,465	2,214,472	20,887,324
Crapemyrtle	172,835	542,299	820,276	243,048	20,260	-	-	-	-	1,798,718
Sabal palmetto	60	1,203	21,117	132,186	4,177	-	-	-	-	158,743
Water oak	1,739	8,860	82,594	596,516	2,069,399	2,521,279	911,086	156,486	3,844	6,351,803
Laurel oak	990	17,330	64,328	534,686	1,560,200	1,935,157	1,177,804	655,900	311,583	6,257,978
Flowering dogwood	15,256	65,368	163,810	33,025	-	-	-	-	-	277,459
Loblolly pine	1,130	7,602	115,127	476,936	560,072	341,236	70,205	28,696	-	1,601,002
Jelly palm	601	2,550	9,090	21,227	17,005	695	-	-	-	51,168
Red maple	4,922	48,022	22,728	23,355	39,905	-	-	-	-	138,933
Chinese pistache	5,763	46,133	-	-	-	-	-	-	-	51,896
Muskogee crapemyrtle	8,920	23,364	11,429	-	-	-	-	-	-	43,713
Southern magnolia	2,546	8,932	81,633	197,778	81,765	28,646	20,880	-	-	422,181
London planetree	2,813	44,685	-	-	-	-	-	-	-	47,498
Honeylocust	2,033	11,789	83,220	53,581	-	-	-	-	-	150,622
Willow oak	466	32,814	57,744	36,291	60,207	69,266	85,363	31,184	34,859	408,193
American holly	2,200	27,350	70,068	42,673	-	-	-	-	-	142,291
Sweetgum	5,611	1,884	30,451	66,100	117,280	109,389	48,501	-	-	379,215
October glory red maple	1,904	46,679	-	-	-	-	-	-	-	48,584
Photinia	10,962	2,694	-	-	-	-	-	-	-	13,656
Shumard oak	4,179	32,462	-	-	-	-	-	-	-	36,641
Eastern red cedar	4,182	13,559	22,428	50,349	56,124	22,379	-	-	-	169,022
Hackberry	946	1,151	40,066	113,370	116,366	77,825	24,703	-	25,788	400,215
Southern red oak	-	28,126	-	9,284	76,474	88,053	118,907	146,040	30,882	497,767
Japanese zelkova	2,461	27,931	13,776	-	-	-	-	-	-	44,168
American sycamore	1,580	10,869	16,083	22,060	52,277	122,693	47,031	143,397	24,121	440,111
Callery pear	4,248	13,201	15,822	42,064	7,388	-	-	-	-	82,724
Tallowtree	3,184	8,412	20,086	19,184	-	-	-	-	-	50,866
Emerald Vase Chinese elm	6,822	12,470	-	-	-	-	-	-	-	19,292
Wax myrtle	5,379	5,795	1,905	-	-	-	-	-	-	13,079
Rose-of-sharon	6,539	1,033	-	-	-	-	-	-	-	7,573
Northern white cedar	3,673	15,923	2,089	-	-	-	-	-	-	21,685
Tuskegee crapemyrtle	2,426	14,986	-	-	-	-	-	-	-	17,411
Little gem southern magnolia	4,852	1,033	-	-	-	-	-	-	-	5,885
River birch	718	15,099	14,022	5,642	-	-	-	-	-	35,481
Carolina laurelcherry	3,182	7,266	7,945	10,903	5,863	-	-	-	-	35,160
Holly	2,347	8,892	11,808	4,647	-	-	-	-	-	27,693
Pecan	377	2,022	13,530	53,103	87,753	47,837	21,682	28,696	-	255,000
Japanese privet	2,358	8,231	9,524	-	-	-	-	-	-	20,113
Baldcypress	550	8,637	29,388	15,585	-	-	-	-	-	54,160
Ginkgo	1,305	10,008	7,626	-	-	-	-	-	-	18,939
Oleander	1,477	10,335	-	-	-	-	-	-	-	11,811
Savannah holly	1,477	7,161	3,810	-	-	-	-	-	-	12,447
Loquat tree	2,855	2,955	3,408	-	-	-	-	-	-	9,218
Southern crabapple	1,527	4,662	3,188	3,513	-	-	-	-	-	12,890
Mimosa	1,722	4,076	3,479	-	-	-	-	-	-	9,276
Tuscarora crapemyrtle	2,215	517	-	-	-	-	-	-	-	2,732
Chinese magnolia	2,023	2,057	1,476	-	-	-	-	-	-	5,556
Siberian elm	-	-	-	4,589	11,593	10,583	7,353	-	-	34,118

Species	0–3	3–6	6–12	12–18	18–24	24–30	30–36	36–42	>42	Total
Eastern redbud	2,695	-	1,539	-	-	-	-	-	-	4,234
Bradford pear	148	2,736	16,236	-	-	-	-	-	-	19,120
Northern red oak	-	58	1,174	429	23,383	8,056	39,971	74,705	54,677	202,452
American elm	-	-	-	6,340	22,086	23,006	9,304	9,857	-	70,593
Black cherry	387	2,714	1,385	4,898	7,353	-	-	-	-	16,737
Italian cypress	1,278	1,838	-	-	-	-	-	-	-	3,116
Red mulberry	-	943	8,349	5,065	8,906	10,303	-	-	-	33,565
Silver maple	561	1,719	3,479	4,675	-	1,212	-	-	-	11,646
Tulip poplar	858	2,162	2,091	3,983	-	-	-	-	-	9,094
Chinese elm	368	488	3,444	5,642	45,167	12,756	-	-	-	67,866
Chaste tree	324	2,621	5,714	4,453	-	14,323	-	-	-	27,435
Chinaberry	449	1,253	1,587	2,213	3,001	-	-	-	-	8,504
Mexican fan palm	751	2,898	-	2,898	-	-	-	-	-	6,546
Drake Chinese elm	742	1,336	2,896	4,643	-	-	-	-	-	9,617
Sugar maple	-	345	1,616	8,571	8,621	-	-	-	-	19,154
American hornbeam	-	2,055	7,145	-	-	-	-	-	-	9,200
Sago palm	5,836	-	1,449	2,898	-	-	-	-	-	10,182
Yaupon holly	527	2,215	-	-	-	-	-	-	-	2,742
Slash pine	-	-	-	11,362	8,196	13,314	-	-	-	32,872
Chinese privet	723	1,033	-	-	-	-	-	-	-	1,757
American plum	942	-	3,609	-	-	-	-	-	-	4,552
Windmill palm	247	664	534	-	-	-	-	-	-	1,445
Winged elm	-	-	-	13,292	9,846	16,113	-	-	-	39,250
Leyland cypress	978	-	-	-	-	-	-	-	-	978
Dixie rosemallow	784	-	-	-	-	-	-	-	-	784
Japanese maple	559	394	-	4,098	-	-	-	-	-	5,051
Black tupelo	138	-	5,181	-	17,795	-	-	-	-	23,114
Jerusalem thorn	1,099	-	-	-	-	-	-	-	-	1,099
Sasanqua camellia	603	-	-	-	-	-	-	-	-	603
Camphor tree	128	-	3,810	6,308	10,130	-	-	-	-	20,376
Dawn redwood	621	-	-	-	-	-	-	-	-	621
Scarlet oak	-	1,293	1,356	3,550	-	-	-	-	-	6,199
Littleleaf linden	231	-	1,263	2,043	-	-	-	-	-	3,537
Canary island date palm	3,867	4,654	-	-	-	-	-	-	-	8,521
Cherry plum	742	-	-	-	-	-	-	-	-	742
Kwanzan cherry	-	1,156	-	-	-	-	-	-	-	1,156
Darlington oak	-	-	-	-	25,810	-	-	28,696	-	54,505
Pin oak	-	345	2,850	2,573	-	-	-	-	-	5,768
Corkscrew willow	806	-	-	-	-	-	-	-	-	806
Bitternut hickory	-	-	-	12,493	-	-	-	-	-	12,493
Atlantic white cedar	140	1,018	-	-	-	-	-	-	-	1,157
Persimmon	297	445	-	-	-	-	-	-	-	742
Longleaf pine	-	-	2,246	-	21,702	-	-	-	-	23,949
Eastern cottonwood	-	337	1,399	-	-	-	-	-	-	1,736
Yew podocarpus	201	714	-	-	-	-	-	-	-	915
Plum	642	-	-	-	-	-	-	-	-	642
Peach	348	345	-	-	-	-	-	-	-	693
White oak	-	-	-	5,305	10,349	20,735	-	-	-	36,389
Wisconsin weeping willow	464	-	-	2,453	-	-	-	-	-	2,917
Paper mulberry	297	-	-	-	-	-	-	-	-	297

Species	0–3	3–6	6–12	12–18	18–24	24–30	30–36	36–42	>42	Total
Showy forsythia	211	-	-	-	-	-	-	-	-	211
White ash	140	460	-	-	-	-	-	-	-	599
Chinese holly	90	517	-	-	-	-	-	-	-	607
Star magnolia	149	488	-	-	-	-	-	-	-	637
Sweet olive	289	-	-	-	-	-	-	-	-	289
Virginia pine	360	-	-	-	-	-	-	-	-	360
White poplar	213	-	915	-	-	-	-	-	-	1,128
Sawtooth oak	-	1,016	-	-	-	-	-	-	-	1,016
Post oak	-	-	-	3,513	9,637	-	-	-	-	13,150
Black oak	-	-	-	-	7,743	-	-	28,696	-	36,439
Slippery elm	-	-	-	7,289	-	-	-	-	-	7,289
Trident maple	-	-	1,539	-	-	-	-	-	-	1,539
Amur maple	131	-	-	-	-	-	-	-	-	131
Pignut hickory	-	-	-	5,442	-	-	-	-	-	5,442
Sour orange	105	-	-	-	-	-	-	-	-	105
Yellowwood	-	388	-	-	-	-	-	-	-	388
Kousa dogwood	123	-	-	-	-	-	-	-	-	123
Silver dollar eucalyptus	105	-	-	-	-	-	-	-	-	105
Sydney blue gum	-	517	-	-	-	-	-	-	-	517
Chinese parasoltree	-	-	-	3,278	-	-	-	-	-	3,278
Black walnut	-	-	-	4,643	-	-	-	-	-	4,643
Chinese flame tree	170	-	-	-	-	-	-	-	-	170
Umbrella magnolia	-	-	1,241	-	-	-	-	-	-	1,241
Fire thorn	217	-	-	-	-	-	-	-	-	217
Swamp chestnut oak	-	-	1,722	-	-	-	-	-	-	1,722
Black locust	-	-	717	-	-	-	-	-	-	717
Black willow	-	374	-	-	-	-	-	-	-	374
Christmasbush	105	-	-	-	-	-	-	-	-	105
American basswood	-	-	-	-	4,098	-	-	-	-	4,098
Black haw	-	443	-	-	-	-	-	-	-	443
Japanese wisteria	239	-	-	-	-	-	-	-	-	239
Moundlily yucca	25	-	-	-	-	-	-	-	-	25
Citywide total	427,399	1,926,806	3,084,259	4,483,482	7,694,324	9,832,209	7,061,316	5,286,815	2,700,224	42,496,834

Appendix C—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

A stratified random sample of street trees, drawn from Charleston's municipal tree database, was inventoried to establish relations between tree age, size, leaf area and biomass; subsequently, estimates for determining the magnitude of annual benefits in relation to predicted tree size were derived. The sample was composed of the 19 most abundant species; from these data, growth of all street trees was inferred. The species were as follows:

- Live oak (*Quercus virginiana*)
- Crapemyrtle (*Lagerstroemia indica*)
- Sabal palmetto (*Sabal palmetto*)
- Water oak (*Quercus nigra*)
- Laurel oak (*Quercus laurifolia*)
- Flowering dogwood (*Cornus florida*)
- Loblolly pine (*Pinus taeda*)
- Jelly palm (*Butia capitata*)
- Red maple (*Acer rubrum*)
- Southern magnolia (*Magnolia grandiflora*)
- Honeylocust (*Gleditsia triacanthos*)
- Willow oak (*Quercus phellos*)
- American holly (*Ilex opaca*)
- Sweetgum (*Liquidambar styraciflua*)
- Hackberry (*Celtis laevigata*)
- Southern red oak (*Quercus falcata*)
- American sycamore (*Platanus occidentalis*)
- Callery pear (*Pyrus calleryana*)
- Pecan (*Carya illinoensis*)

To obtain information spanning the life cycle of predominant tree species, the inventory was stratified into nine DBH classes:

- 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 to seventy randomly selected trees of each species were 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 crown base (to nearest 0.5 m by altimeter), crown diameter in two directions (parallel and perpendicular to nearest street to nearest 0.5 m by sonar measuring device), tree condition and location. Replacement trees were sampled when trees from the original sample population could not be located. Tree age was determined by street tree managers. Fieldwork was conducted in September 2004.

Crown volume and leaf area were estimated from computer processing of tree crown images obtained using a digital camera. The method has shown greater accuracy than other techniques (±25% of actual leaf area) in estimating crown volume and leaf area of open-grown trees (Peper and McPherson 2003).

Linear regression was used to fit predictive models—with DBH as a function of age—for each of the 19 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).

Replacement Value

The monetary worth, or value, of a tree is based on people's perception of it (Cullen 2000). There are several approaches that arborists use to develop a fair and reasonable perception of value (CTLA 1992, Watson 2002). The cost approach is widely used today and assumes that the cost of production equals value (Cullen 2002).

The trunk formula method (CTLA 1992), also called depreciated replacement cost, is a commonly used approach for estimating tree value in terms of cost. It assumes that the benefits inherent in a tree are reproduced by replacing the tree, and therefore, replacement cost is an indication of value. Replacement cost is depreciated to reflect differences in the benefits that would flow from an "idealized" replacement compared to the imperfect appraised tree.

We regard the terms "replacement value" and "replacement cost" as synonymous indicators of the urban forest's value. Replacement value is indicated by the cost of replacing existing trees with trees of similar size, species, and condition if all were destroyed, for example, by a catastrophic storm. Replacement cost should be distinguished from the value of annual benefits produced by the urban forest. The latter is a "snapshot" of benefits during one year, while the former accounts for the long-term investment in trees now reflected in their number, stature, placement, and condition. Hence, the replacement value of a street tree population is many times greater than the value of annual benefits it produces.

The trunk formula method uses tree size, species, condition, and location factors to determine tree replacement value. Tree size is measured as trunk area (*TA*, cross-sectional area of the trunk based on DBH), while the other factors are assessed subjectively relative to a "high-quality" specimen and expressed as percentages. The equation is

$$\text{Replacement value} = \text{Basic value} \times \text{Condition\%} \times \text{Location\%}$$

$$\text{Basic value} = \text{Replacement cost} + (\text{Basic price} \times [TA_{\text{A}} - TA_{\text{R}}] \times \text{Species\%})$$

where

Condition% = Rating of structural integrity and health; a higher percentage indicates better condition (CTLA 1992).

Location% = Rating of the site itself (relative market value), contribution of the tree in terms of its aesthetic and functional attributes, and placement, which reflects the effectiveness of realizing benefits; location is the sum of site, contribution, and placement divided by three (CTLA 1992). A higher percentage indicates better location.

Replacement cost = Sum of the cost of the replacement tree (of size TA_R) and its installation .

Basic price = Cost of the largest available transplantable tree divided by TA_R ($/in^2).

TA_A = Trunk area of appraised tree (in^2) or height of clear trunk (linear ft) for palms.

TA_R = Trunk area of replacement tree (in^2) or height of clear trunk (linear ft) for palms.

Species% = Rating of the species's longevity, maintenance requirements, and adaptability to the local growing environment. (CTLA 1992).

In this study, data from the "Southeastern U.S. Tree Species Rating Guide" are used to calculate replacement value (Smiley and Coder 2005). Species rating percentages are the midpoint for the ranges reported for zone 8. Street tree condition ratings are based on the inventory (or set at 70% when no data are available) and location ratings are arbitrarily set at 70%, indicative of a tree located along a typical street. TA_R is assumed to be 7.065 in^2 for a 3" caliper tree; TA_A is calculated using the midpoint for each DBH class. The basic price is $66/in^2 TA. Replacement costs for trees are not specified in the Southeastern Guide, so the replacement cost of $530 for a typical 3" caliper shade tree is adopted from the Minnesota Supplement (Minnesota Society of Arboriculture 1996).

There were no palm data for the region, so basic prices ($/linear ft of clear trunk) and replacement costs ($/palm), which vary by species, are from the Western Chapter ISA Regional Supplement for the North Coast of California (WC-ISA 2004). TA_R is assumed to be 15 linear ft; TA_A is calculated as the midpoint for each palm height class.

Replacement values are calculated using the trunk formula equation for each species by DBH class, then summed across DBH classes and species to derive total replacement value for the population.

Identifying and Calculating Benefits

Annual benefits for Charleston'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 did consider average annual mortality.) This approach directly connects benefits with tree-size variables such as DBH and LSA. Many functional benefits of trees are related to processes that involve interactions between leaves and the atmosphere (e.g., interception, transpiration, photosynthesis); therefore, benefits increase as tree canopy cover and leaf surface area increase.

For each of the modeled benefits, an annual resource unit was determined on a per-tree basis. Resource units are measured as MWh of electricity saved per tree; MBtu 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; cubic feet of stormwater runoff reduced per tree; and square feet of leaf area added per tree to increase property values.

Prices were assigned to each resource unit (e.g., heating/cooling energy savings, air-pollution absorption, stormwater runoff reduction) using economic indicators of society's willingness to pay for the environmental benefits trees provide.

Estimates of benefits are initial approximations as some benefits are difficult to quantify (e.g., impacts on psychological health, crime, and violence). In addition, limited knowledge about the physical processes at work and their interactions makes estimates imprecise (e.g., fate of air pollutants trapped by trees and then washed to the ground by rainfall). Therefore, this method of quantification provides first-order approximations. It is meant to be a general accounting of the benefits produced by urban trees—an accounting with an accepted degree of uncertainty that can, nonetheless, provide a science-based platform for decision-making.

Energy Savings

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

Warmer temperatures in cities have other implications. Increases in CO_2 emissions from fossil-fuel power plants, increased municipal water demand, unhealthy ozone levels, and human discomfort and disease are all symptoms associated with urban heat islands. In Charleston, 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 19 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 Charleston's climate based on consultation with forestry supervisors (Burbage 2005).

Average energy savings per tree were calculated as a function of distance and direction using tree location distribution data specific to Charleston (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 2004.

Land use (single-family residential, multifamily residential, commercial/industrial, other) for right-of-way trees was based on the same tree sample. 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. Thermostat settings were 78°F for cooling and 68°F for heating, with a 60°F night setback in winter. 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 C1*).

Weather data for a typical meteorological year (TMY2) from Charleston were used (Renewable Resource Data Center 2005). Dollar values for energy savings were based on electricity and natural gas prices of $0.09339/kWh and $1.19742/therm, respectively (SCANA 2005a, b).

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 modify the effects of shade and climate on heating and cooling loads:

$$\Delta UEC_x = \Delta UEC^{sh}_{SFD} \times F^{sh} + \Delta UEC^{cl}_{SFD} \times F^{cl}$$ *Equation 1*

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.

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*):

$$\text{Total change} = N \times \Delta UEC_x$$ *Equation 2*

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.

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

In addition to localized shade effects, which were assumed to accrue only to street trees within 18–60 ft of buildings, lowered air temperatures and wind speeds due to neighborhood tree cover (referred to as climate effects) produce a net decrease in demand for summer cooling and winter heating. Reduced wind speeds by themselves may increase or decrease cooling demand, depending on the circumstances. To estimate climate effects on energy use, air-temperature and wind-speed reductions were estimated as a function of neighborhood canopy cover from published values following McPherson and Simpson (1999), then used as input for the

Table C1*—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	14	63	76	14	63	76	14	63	76	14	63	76	14	63	76	86	86	86
Evaporative cooler	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wall/window unit	59	23	5	59	23	5	59	23	5	59	23	5	59	23	5	9	9	9
None	27	14	19	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5
Adjusted cooling saturation	28	69	77	28	69	77	28	69	77	28	69	77	28	69	77	88	88	88

building-energy-use simulations described earlier. Peak summer air temperatures were assumed to be reduced by 0.2°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 C1*) or heating (*Table C2*) equipment by vintage. Equipment factors of 33 and 25% were assigned to homes with evaporative coolers and room air conditioners, respectively. These factors were combined with equipment saturations to account for reduced energy use and savings compared to those simulated for homes with central air conditioning ($F_{equipment}$). Building vintage distribution was combined with adjusted saturations to compute combined vintage/saturation factors for air conditioning (*Table C3*). Heating loads were converted to fuel use based on efficiencies in *Table C2*. 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 C3*).

Multi-Family Residence Analysis

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

Table C2*—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	11.5	16.9	42.1	11.5	16.9	42.1	11.5	16.9	42.1	11.5	16.9	42.1	11.5	16.9	42.1	4.9	4.9	4.9
Heat pump	6.7	9.9	24.6	6.7	9.9	24.6	6.7	9.9	24.6	6.7	9.9	24.6	6.7	9.9	24.6	5.4	5.4	5.4
Adjusted electric heat saturations	2.7	4.2	9.7	2.7	4.2	9.7	2.7	4.2	9.7	2.7	4.2	9.7	2.7	4.2	9.7	1.7	1.7	1.7
Natural gas and other heating saturations																		
Natural gas	72.7	62.0	28.6	72.7	62.0	28.6	72.7	62.0	28.6	72.7	62.0	28.6	72.7	62.0	72.7	89.7	89.7	89.7
Oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other	9.1	11.3	4.8	9.1	11.3	4.8	9.1	11.3	4.8	9.1	11.3	4.8	9.1	11.3	4.8	0	0	0
NG heat saturations	82	73	33	82	73	33	82	73	33	82	73	33	82	73	33	90	90	90

Table C3—*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	26.9	39.6	33.6	26.9	39.6	33.6	26.9	39.6	33.6	26.9	39.6	33.6	26.9	39.6	33.6	100	100	100
Tree distribution by vintage and building type	20.1	29.6	25.2	0.5	0.7	0.6	1.8	2.7	2.3	0.2	0.2	0.2	0.3	0.4	0.3	4.2	2.4	4.9
Combined vintage, equipment saturation factors for cooling																		
Cooling factor: shade	5.59	19.99	19.04	0.13	0.47	0.45	0.45	1.61	1.53	0.03	0.11	0.11	0.03	0.10	0.10	1.3	0.4	0.0
Cooling factor: climate	5.71	20.45	19.48	0.13	0.46	0.44	0.42	1.51	1.44	0.02	0.07	0.07	0.03	0.12	0.11	1.1	2.2	0.0
Combined vintage, equipment saturation for heating																		
Heating factor, natural gas: shade	7.90	18.96	23.29	1.02	2.46	3.02	1.00	2.41	2.96	0.07	0.17	0.21	0.13	0.31	0.38	1.2	0.4	0.0
Heating factor, electric: shade	0.54	1.21	2.39	0.01	0.03	0.06	0.04	0.10	0.19	0.00	0.01	0.01	0.00	0.01	0.01	0.02	0.01	0.00
Heating factor, natural gas: climate	16.46	21.70	8.39	0.21	0.28	0.11	1.44	1.89	0.73	0.05	0.07	0.03	0.10	0.13	0.05	4.5	8.8	0.0
Heating factor, electric: climate	0.55	1.24	2.45	0.01	0.02	0.03	0.05	0.11	0.21	0.00	0.00	0.01	0.00	0.01	0.02	0.09	0.17	0.0

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 1* did not change for C/I and I/T land uses.

Atmospheric Carbon Dioxide Reduction

Sequestration (the 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 when calculating volume. Fresh weight (kg/m^3) and specific gravity ratios from Alden (1995, 1997) are then applied to convert volume to biomass. When volumetric equations for urban trees are unavailable, biomass equations derived from data collected in rural forests are applied (Tritton and Hornbeck 1982; Ter-Mikaelian and Korzukhin 1997).

Carbon dioxide released through decomposition of dead woody biomass varies with characteristics of the wood itself, the fate of the wood (e.g., amount left standing, chipped, or burned), and local soil and climatic conditions. Recycling of urban waste is now prevalent, and we assume here that most material is chipped and applied as landscape mulch. Calculations were conservative because they assumed that dead trees are removed and mulched in the year that death occurs, and that 80% of their stored carbon is released to the atmosphere as CO2 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 Charleston was 1.0% per year for the first five years after planting for street trees and 0.6% every year thereafter (Burbage 2005). Finally, CO2 released during tree maintenance was estimated to be 0.34 lb CO2 per inch DBH based on annual fuel consumption of gasoline (~2,000 gal) and diesel fuel (~2,000 gal) (Burbage 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 Charleston. The fuel mix for electrical generation included mainly coal (66.5%) and nuclear (32.9%) (U.S. EPA 2003).

Emissions factors for electricity (lb/MWh) and natural gas (lb/MBtu) fuel mixes are given in Table C4. The monetary value of avoided CO2 was $0.0075/lb based on average high and low estimates for emerging carbon trading markets (CO2e.com 2005).

Improving Air Quality

Calculating 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 (NO2)—both precursors of ozone (O3) formation—as well as sulfur dioxide (SO2) and particulate matter of <10 micron diameter (PM10). Changes in average annual emissions and their monetary values were calculated in the same way as for CO2, again using utility specific emission factors for electricity and heating fuels (US EPA 2003). The prices of emissions savings were derived from models that calculate the marginal cost of controlling different pollutants to meet air quality standards (Wang and Santini 1995). Emissions concentrations were obtained from U.S. EPA (2005, Table C4), and population estimates from the US Census Bureau (2003).

Calculating Deposition and Interception

Trees also remove pollutants from the atmosphere. The hourly pollutant dry deposition per tree is expressed as the product of the deposition velocity

***Table C4**—Emissions factors and monetary implied values for CO_2 and criteria air pollutants.*

	Emission factor		Implied
	Electricity (lb/MWh)[a]	Natural gas (lb/MBtu)[b]	value[c] ($/lb)
CO_2	1,368	118.0	0.0075
NO_2	2.641	0.1020	1.04
SO_2	8.346	0.0006	1.28
PM_{10}	0.669	0.0075	0.76
VOCs	0.668	0.0054	1.48

[a]USEPA 1998, eGRID 2002, except Ottinger et al. 1990 for VOCs
[b]USEPA 1998
[c]CO_2 from CO2e.com (2005), values for all other pollutants are based on methods of Wang and Santini (1995) using emissions concentrations from U.S. EPA (2005) and population estimates from the U.S. Census Bureau (2003).

$Vd = 1/(Ra+Rb+Rc)$, pollutant concentration (C), canopy projection (CP) area, and time step. Hourly deposition velocities for each pollutant were calculated using estimates for the resistances Ra, Rb, and Rc 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 Charleston were obtained from the South Carolina Department of Environmental Quality (Shrenk 2004). The year 2003 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 Charleston, SC during September 2004. The amount of foliar biomass present for each year of the simulated tree's life was unique for each species. Hourly air temperature and solar radiation data for 2003 described in the pollutant uptake section were used as model inputs. Hourly emissions were summed to get annual totals (*Table B4*).

The ozone-reduction benefit from lowering summertime air temperatures, thereby reducing hydrocarbon emissions from biogenic sources, was estimated as a function of canopy cover following McPherson and Simpson (1999). Peak summer air temperatures were reduced by 0.2°F for each percentage increase in canopy cover. Hourly changes in air temperature were calculated by reducing this peak air temperature at every hour based on the hourly maximum and minimum temperature for that day, the maximum and minimum values of total global solar radiation for the year. Simulation results from Los Angeles indicate that ozone reduction benefits of tree planting with "low-emitting" species exceeded costs associated with their BVOC emissions (Taha 1996). This is a conservative approach, since the benefit associated with lowered summertime air temperatures and the resulting reduced hydrocarbon emissions from anthropogenic sources were not accounted for.

Reducing Stormwater Runoff

The social benefits that result from reduced peak runoff include reduced property damage from flooding and reduced loss of soil and habitat due to erosion and sediment flow. Reduced runoff also results in improved water quality in streams, lakes, and rivers. This can translate into improved aquatic habitats, less human disease and illness due to contact with contaminated water and reduced stormwater treatment costs.

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 surface and flow down the stem surface to the ground. Some of the stored water will evaporate. Tree canopy parameters related to stormwater runoff reductions include species, leaf and stem surface area, shade coefficient (visual density of the crown), tree height, crown diameter, 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. Tree surface saturation was 0.04 in. Species-specific shading coefficient, foliation period, and tree surface saturation storage capacity influence the amount of projected throughfall.

Hourly meteorological and rainfall data for 2003 at the Youmans Farm climate monitoring station (SCAN, site number: 2038, latitude: 32° 40' N, longitude: 81° 12' W, elevation: 75 feet) in Hampton County, SC, were used in this simulation. The year 2003 was chosen because it most closely approximated the 30-yr average rainfall of 52 in (1,320 mm). Annual precipitation at Youman's Farm during 2003, however, was 61.2 in (1,554.7 mm); we made use of this data set because it was the most complete available. Storm events less than 0.2 in (5.1 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).

The social benefits that result from reduced peak runoff include reduced property damage from flooding and reduced loss of soil and habitat due to erosion and sediment flow. Reduced runoff also results in improved water quality in streams, lakes, and rivers. This can translate into improved aquatic habitats, less human disease and illness due to contact with contaminated water and reduced stormwater treatment costs.

Charleston, SC assesses monthly stormwater fees to cover the costs of its stormwater management program. These fees were used as a proxy for the public's willingness to pay for stormwater management. Residential and commercial customers are charged monthly $4 per 2,200 ft^2 of impervious surface, which is $79.20 per acre of impervious surface (McCrary 2005). The cost of controlling runoff from a 10-year storm was used as the basis for valuing rainfall interception by trees in Charleston. This event was selected because most Best Management Practices (BMPs), such as retention-detention basins, are designed to operate effectively for storm events up to this size. Runoff from larger events are assumed to bypass BMPs, directly entering the system without pretreatment. Also, tree crown interception does not increase after crowns are saturated, which usually occurs well before storm events reach this magnitude.

Runoff from 1 acre of impervious surface for a 10-year, 24-hour storm event (6.8 inches, South Carolina Department of Health and Environmental Control 2003) was 156,975 gals, assuming an average runoff coefficient of 0.85. Assuming an annual stormwater management fee of $950.40 per acre of impervious surface, the resulting control cost is $0.00605 per gal.

Property Value 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 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, sometimes containing more vegetative diversity than surrounding rural areas. 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 Property Values and Other Benefits

In an Athens, GA, study (Anderson and Cordell 1988), a large front-yard tree was found to be associated with a 0.88% increase in average home resale values. In our study, the annual increase in leaf surface area of a typical mature large tree (25-year-old live oak, average leaf surface area 2,758 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 Charleston, each large tree would be worth $1,615 based on the 3rd quarter, 2005, average single-family-home resale price in Charleston ($183,500) (National Association of Realtors 2005). 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 (0.935) was applied to prorate trees' value based on the assumption that trees adjacent to different land-uses make different contributions to property sales prices. For this analysis, the street reduction factor reflects the distribution of street trees in Charleston by land-use. Reduction factors were single-home residential (100%), multi-home residential (70%), small commercial (66%), industrial/institutional/large commercial (40%), park/vacant/other (40%) (Gonzales 2004, McPherson et al. 2001).

Given these assumptions, a typical large street tree was estimated to increase property values by $0.34/$ft^2$ of LSA. For example, it was estimated that a single, street-side live oak added about 212 ft^2 of LSA per year when growing in the DBH range of 12–18 in. Therefore, during this period of growth, live oak trees effectively added $72.21, annually, to the value of an adjacent home, condominium, or business property (212 ft^2x $0.34/$ft^2$ = $72.21).

Estimating Magnitude of Benefits

Resource units describe the absolute value of the benefits of Charleston'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, cubic feet of stormwater runoff reduced per tree, and square feet 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 Charleston required four steps: (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 DBH classes described at the beginning of this chapter.

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 red 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 283.4 kWh and 665 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: 85,020 kWh of electricity saved and 199,500 kBtu of natural gas saved.

Matching Significant Species with Modeled Species

To extrapolate from the 19 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).
- Broadleaf evergreen: large (BEL), medium (BEM), and small (BES).
- Coniferous evergreen: large (CEL), medium (CEM), and small (CES).
- Palm: large (PEL), medium (PEM), and small (PES).

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 = Pecan (*Carya illinoensis*)
BDM Other = Pear (*Pyrus calleryana*)
BDS Other = Crapemyrtle (*Lagerstroemia indica*)
BEL Other = Live oak (*Quercus virginiana*)
BEM Other = Southern magnolia (*Magnolia grandiflora*)
BES Other = American holly (*Ilex opaca*)
CEL Other = Loblolly pine (*Pinus taeda*)
CEM Other = Eastern red cedar (*Juniperus virginiana*)
CES Other = Bolander beach pine (*Pinus contorta*)
PEL Other = Canary Island date palm (*Phoenix canariensis*)
PEM Other = Sabal palmetto (*Sabal palmetto*)
PES Other = Jelly palm (*Butia capitata*)

When local data were not measured for certain categories (e.g., CES, PEL), 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.

Charleston 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 3

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 4*

BCR = $B – C$ *Equation 5*

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