Infrastructure Repair Costs Associated with Street Trees in 15 Cities

E. Gregory McPherson and Paula J. Peper

Street trees are an important component of the "green infrastructure" in cities but damage caused by roots to sidewalks, curbs and gutters, and sewers is a multimillion dollar problem. To determine the magnitude of this problem, municipal foresters were surveyed in 15 cities. Total annual concrete and sewer repair costs attributed to tree damage averaged $4.28 per street tree and ranged from $0.18 to $13.65 per tree. On average, repair costs are equivalent to 25% of the annual tree program expenditures. Sidewalk repair costs are the single largest expense in all cities, averaging $3.01 per tree. Annual curb and gutter and sewer repair costs averaged $1.14 and $1.66 per tree, respectively. Damage is highly variable among cities and tends to be most severe in older areas of cities with deteriorating infrastructure and large trees. Mitigation measures applied by tree managers are discussed.

According to Kielbaso and Cotrone (9) there are an estimated 55 to 65 million existing street trees in the United States, with open spaces for planting of 65 to 75 million more. Street trees are an important component of the "green infrastructure" in cities. They provide a myriad of aesthetic, social, environmental, and economic benefits (7). In Chicago, McPherson (10) estimated that the planting of 50,000 street trees and maintaining them for 30 years would cost $8.4 million, while the benefits conferred by the trees would be $23.5 million, or $303 per tree planted. However, in many cities, damage to sidewalks, curbs, and sewer lines from tree roots is a multi-million dollar problem. Controlling these costs poses a formidable challenge to municipal foresters. The need to reduce these costs is especially great in times of dwindling municipal budgets for tree care because money saved on infrastructure repair can be well spent on other tree related activities.

To better understand the extent and magnitude of the infrastructure repair problem, we collected information from a small sample of cities regarding costs of repairing damage caused by street trees to sidewalks, curbs and gutters, and sewer or water lines. The survey addresses several questions. Are infrastructure repair costs large relative to other program expenditures? If these costs are large, what data are needed to better understand how these costs vary for trees of different species, age, and

E. Gregory McPherson, Research Forester and Project Leader, Paula J. Peper, Research Associate, USDA Forest Service, Pacific Southwest Research Station, Western Center for Urban Forest Research and Education. c/o Dept. of Environmental Horticulture, University of California, Davis, CA 95616

cation? What are the range of repair costs across communities and do ıtterns exist based on typical tree lawn dimensions, street tree structure, ty size, and other variables? Although sidewalk damage can result in ɜcondary costs, such as payments resulting from physical injury claims, our ıalysis is limited to repair costs.

Literature Review

Infrastructure repair cost information has not been well researched and ıblished. Only one published study compiled information from cities on frastructure repair costs. In 1975, Hamilton and others surveyed 22 orthern California cities and reported an average annual cost of $27,000 ɜr city for root-damaged sidewalk repair (8). More recently, two unpub-ɜhed surveys compiled information on the sidewalk repair programs in alifornia cities (6). In 1988 the League of California Cities surveyed 154 ties and in 1991 the City of Hayward Landscape Maintenance Division ırveyed 14 San Francisco Bay Area cities. Eighty-two percent of all 168 ties surveyed participate in a sidewalk repair program when damage is ıused by street trees in the public right-of-way. Of these participating cities, 8 percent pay 100 percent of the repair cost and 12 percent share costs with ɜsidents on a 50-50 basis. In most cases, contractors rather than the city erform repair work. In the Bay Area survey, the approximate annual cost for idewalk repair ranged from $500 to $1000 per location.

In a sidewalk survey of residential and collector streets in San Jose, .274,400 square feet of sidewalk damage was found and the estimated ɜpair cost was $14.3 million (13). The average extent of damage was 58 quare feet per property and the average repair cost per property was $368. total of 107,000 linear feet of curb and gutter damage had an estimated ɜpair cost of $2.7 million, or 19 percent of the cost of sidewalk repair. The ost of repairing 144,300 square feet of driveway damage was estimated at 1 million. Damage was most extensive and severe in areas developed efore 1964. About 68 percent of the damaged sample locations were djacent to street trees. The species most closely associated with concrete amage were zelkova (*Zelkova serrata*), sweetgum (*Liquidamber styraciflua*), nd camphor (*Cinnamomum camphora*). The report contains a number of ɜcommendations, including implementation of an automated infrastructure ıanagement system to provide a current inventory and work management ırogram for sidewalks, curbs, and street trees.

A sidewalk survey conducted in Oak Park, Illinois determined that on ıverage, one of every twenty street trees was causing sidewalk heaving defined as displacement of 1 inch or more) (14). American elm (*Ulmus ımericana*) and Norway maple (*Acer platanoides*) accounted for 58 and 7 ɜercent of the all heaving incidents, respectively. Fifty-nine percent of all ıeaves were by overmature trees (30+ inch dbh) and 17 percent were by ıature trees (20 - 29 inches dbh). Part of the sidewalk repair problem in Oak

Park was attributed to past planting practices. Although planting strip widths are spacious throughout Oak Park, years ago trees were planted within three feet of the sidewalk. Flaring root crowns of mature trees are impacting the sidewalks. Now trees are planted in the center of the planting strip to maximize distance between trees and adjacent sidewalks and curbs.

Research by Drs. Philip A. Barker and J. Alan Wagar has helped define the geometry of planting strips (2,3). They examined causal relations between trees, planting strip geometry, and soils (16). In the latter study, 763 tree sites were surveyed and regression analysis applied. Tree diameter and species were associated with over 80 percent of the sidewalk damage that was accounted for in the analysis. Planting strip width and soil texture accounted for a relatively small amount of the total variation in the regression for sidewalk damage, as well as for curb damage. Not surprisingly, the severity of sidewalk and curb damage increased with tree diameter and decreased as planting strip width increased. Damage to sidewalks exceeded damage to curbs, perhaps due to thicker and deeper concrete used in curb construction. The analysis accounted for only 38 percent of the total variation in sidewalk damage. The influence of these factors on tree root growth, infrastructure damage, and root control technologies has been the focus of much recent research and debate (17).

Results from a 1988 survey of city and county tree managers in California indicate that street tree roots are a serious problem in most of the state's cities (4). When asked to list undesirable characteristics of trees that influence selection, root damage was cited 320 times. The second most common reply was aphids at 123. Damage by roots to sewers was cited less frequently than was damage to sidewalks and curbs. Root damage was the most frequently cited reason for discontinuing use of a tree species. Twenty percent of all city and county trees that were removed in 1987 were reported to be damaging sidewalks or other structures. In the 1992 follow-up survey, planting tree species that are thought to be less likely to cause root damage was reported as the most widely used and effective method to reduce root damage (4). Root barriers are widely used, but only 25 percent of the respondents believe that they are effective. Root pruning is another commonly practiced control method whose effectiveness is not widely accepted. A frequent concern is the tendency of some species to become prone to failure after root pruning. Eliminating tree lawns by constructing sidewalks adjacent to streets and realigning sidewalks are methods used to reduce sidewalk damage from tree roots by the majority of respondents, and believed to be more effective than root barriers and root pruning (5).

In summary, studies of sidewalk and curb damage due to trees indicate that many variables are responsible for damage and their relative importance depends on conditions specific to each site. In general, the following factors may be involved: tree size, species, and proximity to concrete, planting strip width, age of concrete, soil conditions, horticultural practices

.g., root and crown pruning, fertilization, irrigation), and other environmental onditions (e.g., vehicular and pedestrian traffic). Sidewalk damage appears be more ubiquitous and costly to repair than damage to curbs and gutters.

We could locate only one study on tree roots and sewers. Rolf and Stal 2) note that water in and outside sewer pipes creates an environment onducive to root growth and that the "root tips follow the pipe and penetrate here there is a weakness" (p. 329). Condensation on the outside of clay pes attracts opportunistic roots. Old concrete and clay sewer pipes without ubber gaskets in the joints are most prone to invasion by tree roots, while pes made of PVC plastic and fiberglass are resistant if properly conructed. In older parts of many U.S. cities, clay pipe runs from buildings to ewer mains. Problems occur at the coupling of the two lines where eterioration is most common.

Once roots enter pipes, they can be cut off mechanically in roto-rooter ashion. This provides only temporary control as root regrowth can be rapid, some cases requiring annual treatments. Chemicals can be flushed into e sewer to retard root growth, but this practice is not permitted in certain reas due to adverse impacts on water quality and plumbing systems. elining involves using water pressure to place a rigid resin liner where the ipe is broken. A similar concept is pipe sliplining, wherein a plastic pipe is rawn or pushed through the defective pipe and ultimately joined to the riginal pipe with rubber rings and sockets (12). Finally, broken pipes can be eplaced with new pipes. Repair costs typically range from $1,000 for xcavation and replacement to $100 for rodding and roto-rooting (10).

Annual tree root removal and sewer repair costs were studied at three ites in Malmo, Sweden (12). Annual sewer maintenance costs ranged from 11 to $186 /meter ($36 to $610 /ft) of pipe. Treatment at one site, where an ld concrete sewer line was penetrated by willow tree roots, included tree emoval and replacement ($105 /m^2 or $1,130 /ft^2), as well as relining with cid-resistant polyester fiber impregnated with resin ($200 / m or $656 /ft). t another site relining was estimated to cost $170 / m ($558 / ft).

There are costs associated with tree impacts on other elements of urban ifrastructure (e.g., street damage, invasion of water lines, blocking of street ghts, and signs, leaf litter and storm debris removal). We omit these costs om this analysis while recognizing that they can be substantial in certain ituations. For example, due to the nature of water main and service line onstruction, root damage is usually negligible. However, annual water line epair costs due to tree-related damage were reported to us to average $0.17 ree in San Jose and $0.10 /tree in Sacramento.

Methods

We surveyed municipal foresters in 15 cities between 1991 and 1994 to ather information on tree management costs. During 1991 and 1992 we dministered a questionnaire in person to arborists in Atlanta, Boston,

Dallas, Denver, Minneapolis, Rock Valley, Iowa, and Washington, D.C. These cities were 7 of 12 selected for another study that modeled benefits and costs of community tree planting. Infrastructure repair cost information was unavailable from the other 5 cities. In 1992 the questionnaire was modified and administered in person and by mail to city arborists in Chicago and Oak Park, Illinois; Hayward, Modesto, Sacramento, San Jose, and Santa Maria, California; and Vancouver, British Columbia. These cities were selected because we knew that they had information concerning street trees and infrastructure repair costs. Our sample of cities encompasses a broad geographic range, but is not representative of any particular population of cities or regions (Figure 1).

In the first questionnaire respondents were asked to estimate average annual repair costs for sidewalks, curb and gutter, and sewer lines attributed to damage caused by tree roots. Information came from a variety of sources and in different forms. In most cases, cost data were obtained from city departments of forestry, engineering, public works, transportation, sanitation, and water. Attributing the proportion of total sidewalk and curb and gutter repair costs due to tree roots was problematic. Because concrete repair is often associated with major street construction projects and these projects generally occur where infrastructure damage is most severe, it is difficult to discern the exact cause of damage. For example, concrete can be damaged by impacts from vehicles and other heavy objects, exfoliation caused by de-icing salts and extreme temperatures, and expansion and contraction of clay soil. Cities with recent sidewalk damage surveys provided annual costs for tree-related damage directly. More often, respondents gave total annual repair costs or the number of repairs made per year and average cost per repair. Then they estimated the percentage of total repair costs due to trees based on personal observation and limited field data. The accuracy of these estimates are unknown and add to the uncertainty associated with the results we present. We note when estimates of concrete repair costs were not broken out into separate costs for sidewalks and curbs and gutters,

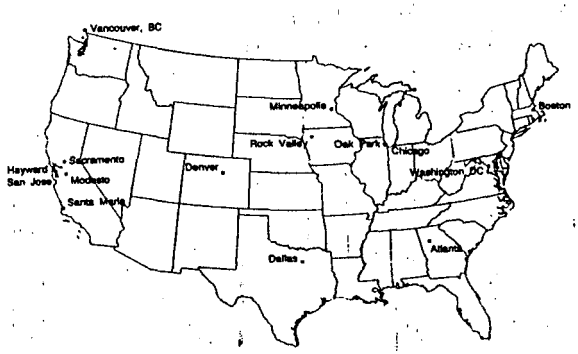

Figure 1. Location of 15 cities surveyed for the study.

nd list these data under sidewalks because repair costs were typically reater for sidewalks than for curbs and gutters.

Based on this experience, the second questionnaire asked respondents) list the years for which average annual repair costs were provided and note ıe estimated percentage due to trees if tree-related costs were not directly eflected in the data provided. Additional background information on the treet tree population and the tree management program was requested as ell. Respondents estimated the average diameter at breast height of their treet tree populations since one might anticipate greater repair costs in ties with many large, old trees. Similarly, the average width of continuous lanting strips was estimated, recognizing that this varies throughout the city nd that "tree pits" surrounded by concrete are often common in urban core reas. Values that we present should be viewed as rough indicators of verage tree sizes and planting strip widths because precise quantitative ata were lacking for most cities. Because of differences in the two survey ıstruments, the data are not compl tely uniform, despite recent attempts to l in missing information.

Estimates of the total number of street trees and total annual street tree rogram expenditures were obtained to analyze repair costs on a per tree nd per program budget basis. We calculate the average annual cost per treet tree as a basis for comparing costs across cities by dividing tree-lated repair costs by the street tree population. As an indication of the lative magnitude of infrastructure repair costs, we present total annual pair costs as a percentage of the total annual tree program budget for cities ıat provided budget information. It should be recognized that municipal restry budgets are not usually charged the full amount of these costs. In ties such as Chicago, sidewalk repair costs are split between the residents nd the city. City funds are administered by the Transportation Department, ot Forestry. In San Jose and most cities surveyed, residents are assessed ıe entire cost of sidewalk repair. Ultimately, citizens pay one way or another r the damage tree roots cause and it is instructive to see how this amount ompares with money spent planting and caring for street trees. Because of ıe preliminary nature of this work and the relatively small size of the sample, e simply present estimated means and standard deviations.

In four cities (San Jose, Modesto, Sacramento, and Vancouver, B.C.) the uestionnaire was followed-up with open-ended questions concerning ac-ons being taken to reduce conflicts between trees, concrete, and sewers. bservations made by municipal foresters in each of these cities are iscussed.

Results

Our sample contained cities with a wide range of human and street tree opulations (Table 1). The number of street trees per capita in our sample nged from 0.08 in Boston to 1.11 in Rock Valley, Iowa, with a mean of 0.32.

This mean of 0.32 street trees per capita compares favorably with a mean of 0.37 found for 22 street tree populations (11), but is substantially less than the mean of 0.63 obtained from a recent survey of 419 municipalities (15). The latter discrepancy is probably due to inclusion of park and other public trees in their survey. Annual tree program budgets ranged from $4,000 in Rock Valley to $11.3 million in Chicago. Our sample mean of $2.56 million is substantially greater than the mean of $279,307 reported in the 1994 survey of 419 cities (5). In the following sections we report sidewalk repair costs for 15 cities, curb and gutter repair costs for 5 cities, and sewer repair costs for 8 cities.

Sidewalk repair costs. Annual sidewalk repair costs due to tree-related damage are estimated to be under $1 per tree in four cities (Minneapolis, Rock Valley, Boston, and Denver) and $6 or greater per tree in Modesto, Vancouver, B.C., and Hayward (Table 2). Costs for Modesto and Hayward are inflated because curb and gutter repair costs are not broken out from sidewalk repair costs. The mean repair cost is $3.01 per tree and the standard deviation of $2.50 reflects the large variability in repair costs among cities.

Table 1. Background information on the sample cities.

City	Region[a]	Pop. (1,000s)	Area sq miles	Pop./ sq mile	Program Budget ($)	Tree Pop.	Trees/ capita	Plt. Strip Width (ft)	Avg. Dbh (in)
Atlanta, GA	South	437	132	3.3	800,000	70,000	0.16	3.5	21.0
Boston, MA	GL-NE	520	46	11.3	865,000	44,000	0.08	3.5	15.0
Chicago, IL	GL-NE	2,780	237	11.7	11,330,000	459,000	0.17	4.0	16.0
Dallas, TX[b]	Cent. TX	1,000	331	3.0		240,000	0.24	4.0	10.0
Denver, CO[b]	Mt	468	155	3.0		130,000	0.28		
Hayward, CA	CA Coast	122	61	2.0	1,250,000	30,000	0.25	3.5	24.0
Minneapolis, MN	N. Tier	375	59	6.4	5,800,000	143,000	0.38	5.0	25.0
Modesto, CA	Semi-Arid	182	34	5.4	2,068,000	75,000	0.41	4.0	12.0
Oak Park, IL	GL-NE	54	5	12.0	887,000	19,000	0.35	7.0	18.0
Rock Valley, IO	GL-NE	3	1	3.0	4,000	3,340	1.11	8.0	15.0
Sacramento, CA	Semi-Arid	385	98	3.9	3,100,000	115,000	0.30	5.0	24.0
San Jose, CA	CA Coast	838	173	4.8	1,700,000	250,000	0.30	3.5	13.0
Santa Maria, CA	CA-Coast	78	18	4.3	245,000	25,000	0.32	6.0	14.0
Vancouver, BC	Pac. NW	509	44	11.6	2,205,975	102,510	0.20	5.0	13.5
Washington, DC	NE	623	69	9.0	3,000,000	110,000	0.18	4.0	15.0
Mean (SD)		558 (655)	98 (90)	6.3 (3.6)	2,558,075 (2,927,071)	121,057 (115,036)	0.32 (0.23)	4.7 (1.4)	16.8 (4.7)

[a] Regions represent distinct climates and population centers (1).
[b] Blanks indicate data were unavailable.

Sidewalk repair costs are equivalent to 40 percent of San Jose's annual tree program budget, although they are estimated to be only $2.73 per tree. In six other cities annual sidewalk repair costs are estimated to be equal to 20 percent or more of their respective program budgets (Atlanta, Hayward, Modesto [includes curb and gutter], Rock Valley, Vancouver, and Washington, D.C.) (Table 3). In Boston, Minneapolis, and Oak Park, Illinois, sidewalk repair costs are less than 5 percent of annual tree programs expenditures.

Curb and gutter repair costs. Annual repair costs for curb and gutter damage due to trees range from $0.18 per tree in Oak Park to $3.51 per tree in Sacramento (Table 2). The mean for our sample of 5 cities is $1.14. The mean cost for curb and gutter repair is 38 percent of the mean sidewalk repair cost. Although repair costs are less for curbs and gutters than sidewalks in all 5 cities, differences are surprisingly small in Denver ($0.87 versus $0.96) and Sacramento ($3.51 versus $3.97).

In Sacramento, curb and gutter repair costs are equal to 13 percent of the annual tree program budget (Table 3). Values for other cities range from 0.4

Table 2. Reported annual costs for sidewalk and curb and gutter repairs.

City	Sidewalk			Curb and Gutter			Total Concrete	
	Total Repair Cost ($)	Tree-Related (%)	Cost/ Tree ($)	Total Repair Cost ($)	Tree-Related (%)	Cost/ Tree ($)	Total Repair Cost ($)[a]	Cost/ Tree ($)
Atlanta, GA	161,000	100	2.30				161,000	2.30
Boston, MA	15,300	100	0.35				15,300	0.35
Chicago, IL	3,000,000	33	2.16				990,000	2.16
Dallas, TX	3,000,000	20	2.50				600,000	2.50
Denver, CO	125,000	100	0.96	750,000	15	0.87	237,500	1.83
Hayward, CA[b]	244,000	100	8.13				244,000	8.13
Minneapolis, MN	25,176	100	0.18				25,176	0.18
Modesto, CA[b]	450,000	100	6.00				450,000	6.00
Oak Park, IL	125,000	20	1.32	17,500	20	0.18	28,500	1.50
Rock Valley, IO	800	100	0.24				800	0.24
Sacramento, CA	608,115	75	3.97	673,177	60	3.51	859,992	7.48
San Jose, CA	1,003,904	68	2.73	150,584	68	0.41	785,052	3.14
Santa Maria, CA	36,500	100	1.46				36,500	1.46
Vancouver, BC	669,750	100	6.53	75,000	100	0.73	744,750	7.27
Washington, DC	700,000	100	6.36				700,000	6.36
Mean (SD)	677,636 (957418)		3.01 (2.50)	333,252 (312,726)		1.14 (1.21)	391,905 (344,885)	3.39 (2.74)

[a] Totals are for tree-related damage to sidewalks and curbs and gutters.
[b] Sidewalk and curb and gutter repair costs are not broken out.

percent in Oak Park to 3.4 percent in Vancouver B.C.

Total annual concrete repair costs, calculated as the sum of sidewalk and curb and gutter costs, average $3.39 per tree (Table 2). Cities spending the most per tree to repair concrete damage are Hayward ($8.13), Sacramento ($7.48), Vancouver ($7.27), and Washington, D.C. ($6.36).

Sewer repair costs. Sewer repair costs range from $0.11 per tree in Boston to $6.39 per tree in Vancouver, B.C. (Table 4). Other cities with costs over $1 per tree are Atlanta ($1.71) and Sacramento ($3.40). The mean annual repair cost is $1.66 per tree for 8 cities. Vancouver's relatively high costs are due the large number of clay and concrete lines that are over 100 years old. Also, the lines were placed under the middle of the planting strip and trees were planted directly above the lines. Today the city has a deteriorating sewer system with large, old trees placed in perfect position to invade the lines.

Expenditures associated with repairing tree damaged sewer lines are

Table 3. Total annual repair costs per tree and as a percentage of total annual street tree program budget.

City	Total Costs Per Tree ($)	Percent of Total Annual Program Budget			
		Sidewalk	Curb & Gutter	Sewer	Total
Atlanta, GA	4.01	20.1		15.0	35.1
Boston, MA	0.46	1.8		0.6	2.3
Chicago, IL	2.92	8.7		3.1	11.8
Dallas	2.50				
Denver, CO	1.83				
Hayward, CA*	8.13	19.5			19.5
Minneapolis, MN	0.18	0.4			0.4
Modesto, CA*	6.00	21.8			21.8
Oak Park, IL	2.01	2.8	0.4	1.1	4.3
Rock Valley, IO	0.51	20.0		22.5	42.5
Sacramento, CA	10.88	14.7	13.0	12.6	40.4
San Jose, CA	3.26	40.2	6.0	1.8	47.9
Santa Maria, CA	1.46	14.9			14.9
Vancouver, BC	13.65	30.4	3.4	29.7	63.4
Washington, DC	6.36	23.3			23.3
Mean (SD)	4.28 (3.87)	16.8 (11.1)	5.7 (4.7)	10.8 (10.3)	25.2 (18.6)

* Sidewalk and curb and gutter repair costs are not broken out.

Table 4. Reported annual costs for sewer repairs.

City	Total Repair Cost ($)	Tree-Related (%)	Cost/ Tree ($)
Atlanta, GA	120,000	100	1.71
Boston, MA	5,000	100	0.11
Chicago, IL	350,000	100	0.76
Oak Park, IL	9,600	100	0.51
Rock Valley, IO	900	100	0.27
Sacramento, CA	2,059,512	19	3.40
San Jose, CA	100,000	30	0.12
Vancouver, BC	727,500	90	6.39
Mean (SD)	421,564 (661,072)		1.66 (2.07)

equivalent to 13 percent or more of the annual tree program budgets in Sacramento (13%), Atlanta (15%), Rock Valley (20%), and Vancouver (30%) (Table 3). Percentages for the remaining four cities are 3.1 percent or less.

Total repair costs. On a per tree basis, total annual concrete and sewer repair costs attributed to tree-related damage average $4.28 (standard deviation of $3.87) and range from $0.18 in Minneapolis to $13.65 in Vancouver, B.C. (Figure 2 and Table 3). Scatter plots showed no patterns of relation between cost per tree and independent variables such as city population, population density, average planting strip width, or average tree dbh. This finding is not surprising given the site specific nature of infrastructure damage and the city-wide nature of the predictor variables selected. It may be possible to more accurately predict repair costs using similar variables applied to specific streets or neighborhoods within a city, but to our knowledge this has not been accomplished.

Total concrete and sewer repair costs average 25 percent of total tree program budgets (19% deviation) and range from 0.4 percent in Minneapolis to 63 percent in Vancouver, B.C. (Figure 3 and Table 3). Rock Valley, Iowa and San Jose had relatively low costs per tree but relatively high costs as a percentage of program budget. This fact is primarily due to their relatively small program budgets but relatively large street tree populations.

Results of Survey Follow-Up

Tree species belonging to genera such as *Liquidambar*, *Fraxinus*, *Zelkova*, *Gleditsia*, and *Prunus* topped the lists of those most often associated with concrete damage, with *Liquidambar* causing sidewalk, curb and gutter upheaval within 15 to 20 years of planting (about 10-12 inches dbh).

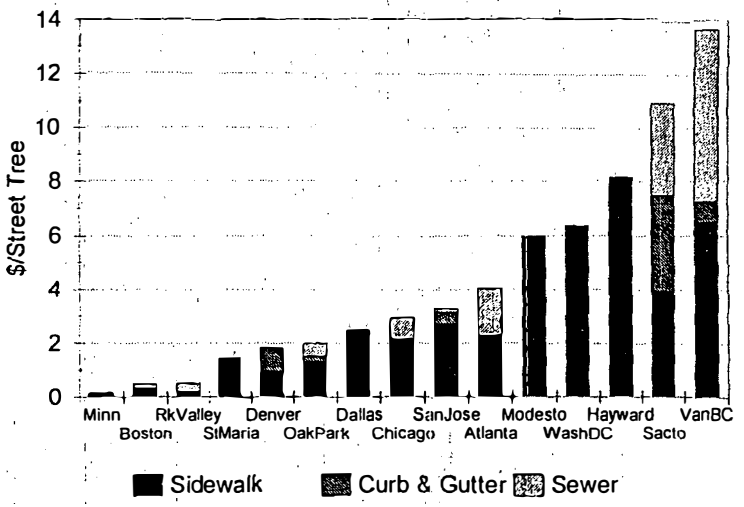

Figure 2. Annual infrastructure repair costs per street tree.

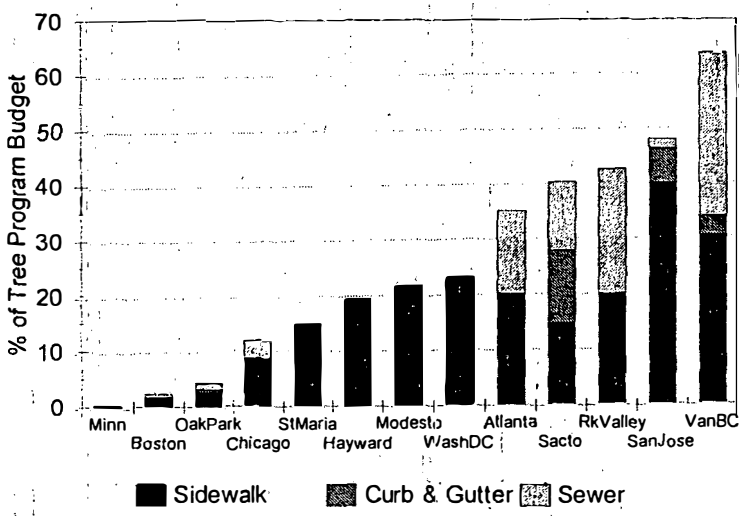

Figure 3. Annual infrastructure repair costs as percentages of annual tree program budgets.

However, the species listed by tree managers also represented the dominant species planted in each of their cities. All managers agreed that damage is less species specific and more site specific, noting that damage tended to be most severe with plantings of trees, aged thirty and older, growing in narrow planting strips. At sites where trees repeatedly uplifted sidewalks, the concrete replacement cycle ranged from five to ten years, whether or not root cutting was part of the replacement procedure. The Sacramento Tree Services Division has adopted a policy of removing "repeat offender" trees

if the concrete requires replacement more than once every eight years at sites where sidewalk relocation is not feasible. Removal still remains a last resort option in Sacramento, as it does in the other three cities contacted.

Measures the cities specifically apply to avoid trip and fall accidents and the possibility of litigation due to concrete upheaval include yearly visual inspections, enforcing policies of homeowner repair of damaged sidewalks, curbs and gutters, and grinding pavement uplifts as a short term remedy until replacement is possible.

Respondents' repair methods consist of variations on the general theme of removing old concrete, root-pruning or cutting, and pouring new concrete. San Jose routinely cuts roots to an 18-inch depth during sidewalk removal and replacement. Homeowners in Sacramento, who are responsible for all concrete replacement, are required to contact the City Tree Services Division to inspect the site once concrete is removed so a determination can be made as to the cause of the damage. If roots are the cause, the city prunes and removes them before the sidewalk is replaced. The inspector may recommend that the sidewalk be curbed or bowed out around the tree or that the width of the sidewalk be reduced in order to increase planting space and reduce the chance of damage recurrence. In Vancouver, current replacement methods include relocating sidewalks where possible and using asphalt or crushed rock sidewalk inserts in lieu of concrete where repeated problems occur.

Although respondents listed species selection and diversity as key components in avoiding concrete damage (particularly where planting space cannot be increased), all are considering, and in some cases applying, methods developed to deter damage and lengthen the concrete replacement cycle. When fiscally possible, replacement sidewalks in Modesto are poured with and 8-inch deep apron on the tree side to act as a root barrier. Chemical barriers are also being used as an experimental method for deflecting potentially invasive roots. Other cities are using a variety of physical root barrier products on an experimental basis and San Jose is proposing the use of trenching and copper screening. Two of the cities are tackling the root damage problem from a engineering perspective. Sacramento has experimented with a foam additive for concrete designed to produce a more elastic sidewalk, one which would bend rather than break and lift, as roots beneath grow and expand. In a similar vein, Vancouver is experimenting with sidewalks engineered with an air gap left between the bottom of the walk and the soil surface. The use of trenches backfilled with a growing medium that will direct roots away from concrete is being considered in conjunction with these air gaps, as well.

All four cities share a common desire to retain existing trees while designing and planning a future urban forest that is less damaging to the infrastructure, therefore less costly to maintain. In line with results published in Bernhardt and Swiecki's surveys (4,5), several of the tree managers

stated that root damage to sidewalks, curbs and gutters is far more pervasive and costly than the damage to sewers. Moreover, the damage to concrete structures is directly attributed to trees while damage to sewer lines is not. In addressing damage to sewer lines, our respondents refer to tree roots as opportunists taking advantage of the fertile, moist environment provided by deteriorating clay and concrete pipe. They consistently report root intrusion occurring only where there are pre-existing leaks in the sewer lines. These managers also confirm Rolf and Stal's (12) report that clay and concrete pipes "sweat" more than PVC plastic types, and roots are tending to run along pipe exteriors, invading pipe interiors at leaking joints or other breaks in the lines. As these invasive roots expand, the pipe joints often rupture. None of the respondents reports using chemicals to purge invasive roots from lines. Root cutting remains the preferential method for removing blockages. PVC pipe and couplings are used for repairs whenever possible and plastic-to clay rubber couplings used to connect new pipe to old systems. This coupling can be a weak link in the newly replaced section since several managers commented on problems with slippage as the pipe expands and contracts, potentially creating new leaks that will attract roots. To date, however, this repair method remains the financially feasible option for cities with thousands of linear feet of old clay and concrete sewer systems in need of replacement.

Overall, responses to our questions indicate that the tree managers are testing a variety of methods to reduce root damage to the infrastructure, all focusing on methods to promote retention of trees. None could list any one method as the key to damage reduction. They tend to view the problem as site-related, involving interrelationships between tree species, tree growth and spatial requirements, and existing site limitations.

Summary and Conclusions

Costs for repairing the infrastructure damaged by street trees are substantial. Total annual costs are estimated to average $4.28 per tree for our sample of 15 cities. On average, this cost amounted to 25 percent of the sample cities' total annual tree program budgets. A national survey of 419 cities found that the mean annual expenditure per public-owned tree is only $4.65 (15). Our estimates of infrastructure repair costs are conservative because data on curb and gutter and sewer repair costs are lacking for half the cities in the sample. Also, sewer repair costs paid by residents but caused by street trees are not included. Data from sewer repair contractors are needed to better estimate the magnitude of these costs. Costs are self-reported and may reflect the bias of individuals. For example, individuals who view trees as the "enemy" may report higher costs than those who view trees as an "amenity."

Repair costs are extremely variable from city to city with no strong relations evident between costs and predictor variables such as city popu-

lation, population density, average tree dbh, and average planting strip width. Within a given city, costs are highest in older areas where infrastructure is deteriorating and trees are likely to be large. Cost-effective mitigation that preserves benefits from existing tree cover while reducing repair costs is critical in these situations. In new developments, repair costs can be minimized by locating trees and infrastructure to minimize conflicts, using "tree resistant" materials, and selecting species that are most suitable for site conditions.

Many tree managers and several researchers are conducting experiments to evaluate the effectiveness of different mitigation measures, particularly related to concrete damage. This work is extremely important given the magnitude of infrastructure damage associated with street trees. Close collaboration between scientists and managers is needed to insure that experiments are designed to produce results that will be statistically sound and published for the benefit of a wider audience. Survey and field research that document the extent of concrete and sewer damage due to trees at specific sites over long periods of time are needed to better understand the nature of tree-related damage. Data required to identify the roles of different factors and to evaluate the long term cost-effectiveness of different design and mitigation measures include:

- full documentation of design details
- extent of concrete/sewer damage and repair costs
- type, location, and age of the infrastructure
- tree species, location, health, and growth over time
- environmental conditions below ground (e.g., soil type, bulk density, moisture), at the surface (e.g., planting strip width, cover type, site uses), and above ground (e.g., atmospheric conditions, management practices [pruning, irrigation, fertilization])
- repair methods, installation and on-going maintenance costs, and durability over time.

Understanding cause and effect relations between trees and infrastructure damage is difficult because of complex interactions among the many factors involved at each particular site. Developing legitimate research results that will guide managers in their efforts to reduce infrastructure repair costs will require combining the practical knowledge of managers with the scientific expertise of researchers.

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