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COSTS OF STREET TREE DAMAGE TO INFRASTRUCTURE*

E Gregory McPherson† and Paula P Peper†

Summary

Street trees are an important component of the 'green infrastructure' in cities but damage caused by roots to sidewalks, kerbs 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 per cent of annual tree maintenance expenditures; sidewalk repair costs are the single largest expense in all cities, averaging $3.01 per tree. Annual kerb, gutter and sewer repair costs averaged $1.14 and $1.66 per tree respectively and damage is highly variable among cities tending to be most severe in older city areas with deteriorating infrastructure and large trees. Mitigation measures applied by tree managers are discussed.

Introduction

According to KIELBASO and COTRONE (1990) there are an estimated 55 to 65 million street trees existing in the United States, with open spaces for the planting of a further 65–75 million. Street trees are an important component of the 'green infrastructure' in cities. In Chicago, McPHERSON (1994) estimated that planting 50,000 street trees and maintaining them for 30 years would cost $8.4 million, while benefits conferred by the trees would be $23.5 million, or $303 per tree planted. However, in many cities damage to sidewalks, kerbs, and sewer lines from tree roots is a multimillion dollar problem and controlling these costs poses a formidable challenge to municipal foresters. The need to reduce these costs is

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†USDA Forest Service, Pacific Southwest Research Station, Western Center for Urban Forest Research and Education, c/o Department of Environmental Horticulture, University of California, Davis, California 95616, USA.

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, information was collected from a small sample of cities regarding costs of repairing damage caused by street trees to sidewalks, kerbs and sewer/water lines. The survey addressed several questions. Are infrastructure repair costs large relative to other service expenditures? If these costs are large, what data are needed to better understand how these costs vary for trees of different species, age and location? What are the range of repair costs across communities and do patterns exist based on typical tree lawn dimensions, street tree structure, city size, and other variables? Although sidewalk damage can result in secondary costs, such as payments resulting from physical injury claims, this analysis is limited to repair costs.

Literature Review

Infrastructure repair cost information has not been well researched and published. HAMILTON *et al.* (1975) surveyed 22 northern California cities and reported an average annual cost of $27,000 per city for root damaged sidewalk repair. In 1988 the League of California Cities surveyed 154 cities and in 1991 the City of Hayward Landscape Division surveyed 14 San Francisco Bay Area cities. (CITY OF HAYWARD, 1993). Eighty-two per cent of all of the 168 cities surveyed participate in sidewalk repair when damage is caused by street trees in the public right of way. Of these participating cities, 88 per cent pay 100 per cent of the repair costs and 12 per cent share costs with residents. In most cases, contractors rather than the city perform the repairs. In the Bay Area survey, the approximate annual cost for sidewalk repair ranged from $500 to $1,000 per location.

In a sidewalk survey of residential and collector streets in San Jose, 2,274,400 square feet of sidewalk damage was found and the estimated repair cost was $14.3 million (SEALANA AND ASSOCIATES, 1994). The average extent of the damage was 58 square feet per property and the average repair cost per property was $368. A total of 107,000 linear feet of kerb and gutter damage had an estimated repair cost of $2.7 million, or 19 per cent of the cost of sidewalk repair. Damage was most extensive and severe in areas developed before 1964. About 68 per cent of the damaged sample locations were adjacent to street trees. Species most closely associated with concrete damage were zelkova (*Zelkova serrata*) sweetgum (*Liquidamber styraflua*) and camphor (*Cinnamomum camphora*).

A sidewalk survey conducted in Oak Park, Illinois determined that on average, one in twenty street trees was causing sidewalks to heave (defined as displacement of 1 inch or more) (STANKOVICH, 1990). American elm (*Ulmus americana*) accounted for 58 per cent of all heaving incidents. Fifty-nine per cent of all heaves were caused by immature trees (30+ inch dbh) and 17 per cent were mature trees (20–29 inch dbh). Part of the sidewalk repair problem in Oak Park was attributed to past planting practices. Although planting strip widths are spacious throughout most of 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 centre of the planting strip to maximise distance between trees and adjacent sidewalks and kerbs.

The geometry of planting strips has been defined by BARKER (1976) and BARKER and DURRANT (1978) and the causal relationship between trees, planting strip geometry and soils has been examined by WAGAR and BARKER (1983). In the latter study, 763 tree sites were surveyed and a regression analysis applied to the data obtained. Tree diameter and species were associated with over 80 per cent 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 variation in the regression for sidewalk damage as well as for kerb damage. Not surprisingly, the severity of sidewalk and kerb damage increased with tree diameter and decreased as planting strip width increased. Damage to sidewalks exceeded damage to kerbs perhaps due to thicker and deeper concrete used in kerb construction. The analysis accounted for only 38 per cent of total variation in sidewalk damage and thus, other physical factors are likely to contribute to sidewalk and kerb damage. The influence of these factors on tree root growth, infrastructure damage, and root control technologies has been the focus of much research and debate (WATSON and NEELY, 1994).

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. (BERNHARDT and SWIECKI, 1988). 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 kerbs. 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 and 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. (BERNHARDT and SWIECKI, 1994). Root barriers are widely used, but only 25 per cent of the respondents believe that they were effective. Root pruning is another commonly practised 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.

In summary, studies of sidewalk and kerb 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 practice (e.g. root and crown pruning, fertilisation, irrigation) and other environmental conditions (e.g. vehicular and pedestrian traffic). Sidewalk damage appears to be more ubiquitous and costly to repair than damage to kerbs and gutters.

ROLF and STAL (1994) is the only study of the interaction between tree roots and sewers. They note that water both inside and outside sewer pipes creates an environment conducive to root growth and that the 'root tip follows the pipe and penetrates where there is a weakness'. Condensation on the outside of clay pipes attracts opportunistic roots. Old concrete and clay sewer pipes without rubber gaskets in their joints are most prone to invasion by tree roots, while pipes made of PVC plastic and fibreglass are resistant if properly constructed. In older parts of many cities, clay pipes run from buildings to sewer mains. Problems occur at the coupling of the two lines where deterioration is most common.

Once roots enter pipes they can be cut off mechanically in roto-rooter fashion. This provides only temporary control as root regrowth can be rapid, in some cases requiring annual treatment. Chemicals can be flushed into the sewer to retard growth, but this practice is not permitted in certain areas due to adverse impacts on water quality and plumbing systems. Relining involves using water pressure to place a rigid resin liner where the pipe is broken. A similar concept is pipe sliplining wherein a plastic pipe is drawn or pushed through the defective pipe and ultimately jointed to the original pipe with rubber rings and sockets. Finally, broken pipes can be replaced with new pipes. Repair costs typically range from $1,000 for excavation and replacement to $100 for rodding and roto-rootering.

Annual tree root removal and sewer repair costs were studied at three main sites at Malmo, Sweden. (ROLF and STAL, 1994). Annual sewer maintenance costs ranged from $11 to $186 per metre ($36 to $610 per foot) of pipe. Treatment at one site, where an old concrete sewer line was penetrated by willow roots included tree removal and replacement ($105/m^2 or $1,130/ft^2), as well as relining with acid resistant fibre impregnated with resin ($200/m or $656/foot). At another site relining was estimated to cost $170/m ($558/foot).

Costs associated with tree impacts on other elements of urban infrastructure (e.g. street damage, invasion of water lines, blocking of street lights and signs, leaf litter and storm debris removal) have been omitted from this analysis. In certain circumstances these costs can be substantial. For example, due to the nature of the water main and service line construction, root damage is usually negligible. However, annual water line repair costs due to tree related damage were reported to average $0.17 per tree in San Jose and $0.10 per tree in Sacramento. Damage was attributed to pressure from expanding roots that dislodged water meters and water lines damaged from concussive force (concussion) when large trees fell above them.

Methods

Municipal foresters in 15 (14 in USA and one in Canada) cities were surveyed between 1991 and 1994 for their tree management costs. During 1991 and 1992, questionnaires were addressed to arborists in person in Atlanta, Boston, Dallas, Minneapolis, Rock Valley, Iowa and Washington DC. These seven cities were selected out of twelve for another study that modelled benefits and costs of community tree planting. Infrastructure repair costs were unavailable from the other 5 cities. In 1992, the questionnaire was modified and administered in person by mail to city arborists in Chicago and Oak Park, Illinois, Hayward, Modesto, Sacramento, San Jose and Santa Maria, California and Vancouver, British Columbia, Canada. The cities were selected for their information records of street trees and infrastructure repair costs. The sample of cities encompasses a broad geographic range, but is not representative of cities or regions (Figure 1).

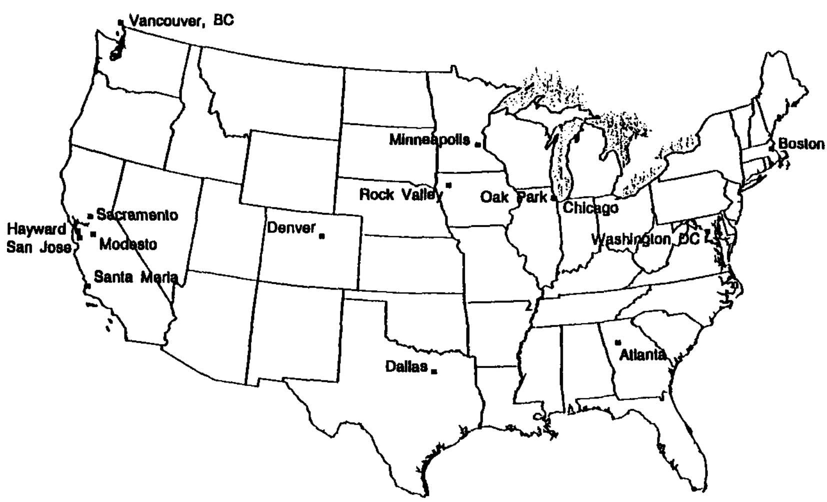

FIGURE 1. Location of 15 cities surveyed for this study

In the first questionnaire respondents were asked to estimate average annual repair costs for sidewalks, kerb 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 kerb and gutter repair costs due to tree roots was problematic because concrete repair is often associated with major street construction projects and 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 soils. 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 the percentage of total repair costs due to trees was estimated on the basis of personal observation and limited field data. The accuracy of these estimates is unknown and add to the uncertainty associated with the presented results. It was noted that when estimates of concrete repair costs were not broken up into separate costs for sidewalks and kerbs and gutters, sidewalk repair costs were typically greater for sidewalks than for kerbs and gutters.

Based on this experience, the second questionnaire asked respondents to list years for which average annual repair costs were provided and to note the estimated percentage due to trees if tree related costs were not directly reflected in the data provided. Additional background information on tree population and tree management was requested. The average diameter at breast height of the tree populations was estimated as greater repair costs in cities were anticipated for older and large trees. Similarly, the average width of continuous planting strips was estimated, recognising that this varies throughout the city and that 'tree pits' surrounded by concrete are often common in urban core areas. Values that are presented should be viewed as rough indicators of average tree sizes and planting strip widths because precise quantitative data was lacking for most cities. Because of differences in the two survey instruments, the data are not completely uniform, despite attempts to fill in the missing information.

Estimates of the total number of street trees and total annual street tree expenditures were obtained to analyse repair costs on a per tree and per budget basis. The average annual repair cost per street tree as a basis for comparing costs across cities was calculated by dividing tree related repair costs by the street tree population. As an indication of the relative magnitude of the infrastructure repair costs, total annual repair costs are presented as a percentage of the annual tree maintenance budgets for the cities that provided the budget information. In cities such as Chicago, sidewalk repair costs are split between the residents and the city. City funds are administered by the Transportation Department, not Forestry. In San Jose and most other cities surveyed, residents are assessed the entire cost of sidewalk repair. Ultimately citizens pay one way or another for the damage tree roots cause and it is instructive to see how this amount compares with the money spent planting and caring for street trees. Because of the preliminary nature of this work and the relatively small size of the sample, estimated means and their standard deviations are presented. The questionnaires sent to San Jose, Modesto, Sacramento and Vancouver BC were followed with open ended questions concerning the actions being taken to reduce conflicts between trees, concrete and sewers. Observations made by municipal foresters in each of these cities are discussed.

Results

The sample contained cities with a wide range of human and street tree populations (Table 1). The number of street trees per capita in the sample ranged from 0.08 in Boston to 1.11 in Rock Valley, Iowa, with a mean of 0.32 street trees per capita. This mean compares favourably with a mean of 0.37 found for 22 street populations (McPHERSON and ROWNTREE, 1989), but is substantially less than the mean of 0.63 obtained from a recent survey of 419 municipalities (TSCHANTZ and SACAMANO, 1994). The latter discrepancy is probably due to the inclusion of park and other public trees in their survey. Annual tree budgets ranged from $4,000 in Rock Valley to $11.3 million in Chicago. The sample mean of $2.56 million is substantially greater than the mean of $279,307 reported in 1994 survey of 419 cities. (TSCHANTZ and SACAMANO, 1994). In the following sections sidewalk repair costs of 15 cities, kerb and gutter repair costs for five cities and sewer repair costs for eight cities are reported.

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 ($6), Vancouver, BC ($6.53) and Hayward ($8.13) (Table 2). Costs for Modesto and Hayward are inflated because kerb and gutter repair costs are not deducted from sidewalk repair costs. The mean repair cost of $3.01 per tree and the standard deviation of $2.50 reflects the large variation in repair costs among cities.

Sidewalk repair costs are equivalent to 40 per cent of San Jose's annual tree maintenance budget, although they are estimated to be only $2.73 per tree (Table 3). In six other cities, annual sidewalk repair costs are estimated to be equal to 20 per cent or more of their respective budgets (Atlanta,

TABLE 1. Background Information on the Sample Cities

City	Region[a]	Pop. (1,000s)	Area sq miles	Pop./ sq mile	Budget ($)	Tree Pop.	Trees/ capita	Plt. Strip Width (ft)	Avg. Dbh (in)
Atlanta,	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	3.01		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
RockValley, 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		558	98	6.3	2,558,075	121,057	0.32	4.7	16.8
(SD)		(655)	(90)	(3.6)	(2,927,071)	(115,036)	(0.23)	(1.4)	(4.7)

[a]Regions represent distinct climates and population centers (Andersson *et al.* (1986)).
[b]Blanks indicate data were unavailable.

TABLE 2. Reported Annual Costs for Sidewalk and Kerb and Gutter Repair

City	Sidewalk			Kerb 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	677,636		3.01	333,252		1.14	391,905	3.39
(SD)	(957418)		(2.50)	(312,726)		(1.21)	(344,885)	(2.74)

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

Hayward, Modesto (includes kerb and gutter), Rock Valley, Vancouver and Washington, DC). In Boston, Minneapolis and Oak Park, Illinois, sidewalk repair costs are less than five per cent of annual tree expenditure.

Kerb and Gutter Repair Costs

Annual repair costs for kerb 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 of the sample of five cities is $1.14. The mean cost for kerb and gutter repair is 38 per cent of the mean sidewalk repair costs. Although repair costs are less for kerbs and gutters than sidewalks in all five cities, differences are surprisingly small in Denver ($0.87 and $0.96) and Sacramento ($3.51 and $3.97).

In Sacramento, kerb and gutter repair costs are equal to 13 per cent of the annual tree budget (Table 3). Values for other cities range from 0.4 per cent in Oak Park to 3.4 per cent in Vancouver, BC.

Total annual concrete repair costs, calculated as the sum of sidewalk and kerb and gutter costs, average $3.39 per tree (Table 2). Cities spending the

TABLE 3. Total Annual Repair Costs Per Tree and As a Percentage of Total Annual Street Tree Budget

City	Total Costs Per Tree ($)	Percent of Total Annual Budget			
		Sidewalk	Kerb & 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, TX	2.50				
Denver, CO	1.83				
Hayward, CA[a]	8.13	19.5			19.5
Minneapolis, MN	0.18	0.4			0.4
Modesto, CA[a]	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	4.28	16.8	5.7	10.8	25.2
(SD)	(3.87)	(11.1)	(4.7)	(10.3)	(18.6)

[a]Sidewalk and kerb and gutter repair costs are not broken out.

most per tree to repair concrete damage are Hayward ($8.13), Sacramento ($7.48), Vancouver ($7.27) and Washington, DC ($6.36).

Sewer Repair Costs

Sewer repair costs range from $0.11 per tree in Boston to $6.39 per tree in Vancouver, BC (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 eight cities. Vancouver's relatively high costs are due to 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 positions to invade the lines.

Expenditure associated with repairing tree damaged sewer lines are equivalent to 13 per cent or more of the annual tree budgets in Sacramento (13 per cent), Atlanta (15 per cent), Rock Valley (20 per cent) and Vancouver (30 per cent) (Table 3). Percentages for the remaining four cities are 3.1 per cent 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 $3.87) and range from $0.18 in Minneapolis to $13.65 in Vancouver, BC (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

TABLE 4. Reported Annual Costs for Sewer Repair

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	421,564		1.66
(SD)	(661,072)		(2.07)

the predictor variables selected. It may be possible to predict more accurately costs using similar variables applied to specific streets or neighbourhoods within the city, but it is not known if this has been accomplished.

Total concrete and sewer repair costs average 25 per cent of total tree maintenance budgets (19 per cent standard deviation) and range from 0.4 per cent to 63 per cent in Vancouver, BC (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 the tree budget. This is primarily due to their relatively small budgets but relatively large tree populations.

Results of Survey follow-up

Tree species belonging to such genera as *Liquidamber, Fraxinus, Zelkova, Gleditsia* and *Prunus* headed the lists of those most often associated with concrete damage, with *Liquidamber* causing sidewalk, kerb and gutter upheaval within 15–20 years of planting (about 10–12 inch dbh). However, the species listed by tree managers also represented the dominant species planted in each of the cities. All managers agreed that the damage is less species specific and more site specific, noting that damage tended to be most severe with plantings of trees aged thirty or 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 often than once every eight years 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 which cities specifically apply to avoid trip and fall accidents and the possibility of litigation due to concrete upheaval include yearly inspections, enforcing policies of homeowner repair to damaged sidewalks, kerbs and gutters and grinding concrete 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, responsible for all concrete replacement, are required to contact the city Tree Services Division to inspect the site once concrete is removed so as to determine the cause of the damage. If roots are the cause, the city prunes them and removes them before the sidewalk is replaced. The inspector may recommend that the sidewalk is curved out around the tree or that the width of the sidewalk be reduced in order to increase planting space and reduce

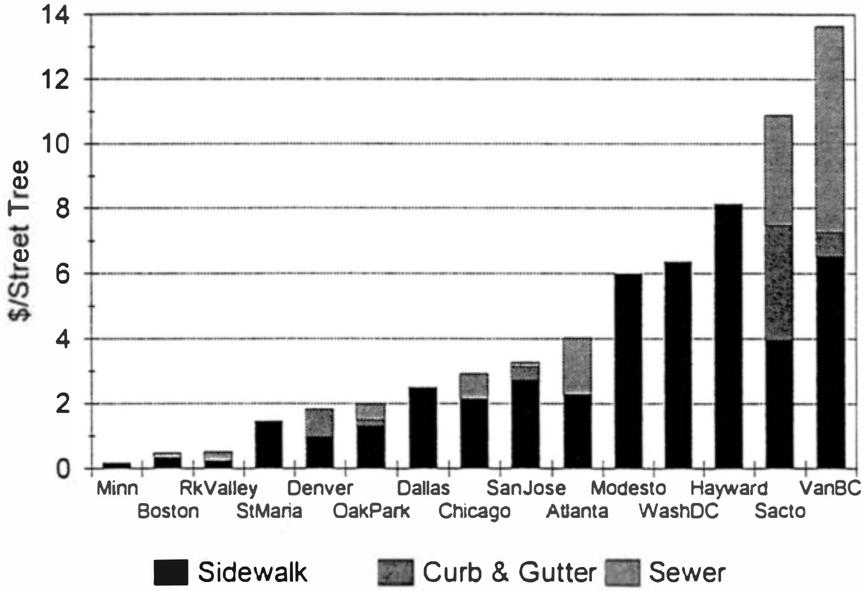

FIGURE 2. Annual infrastructure repair costs per street tree.

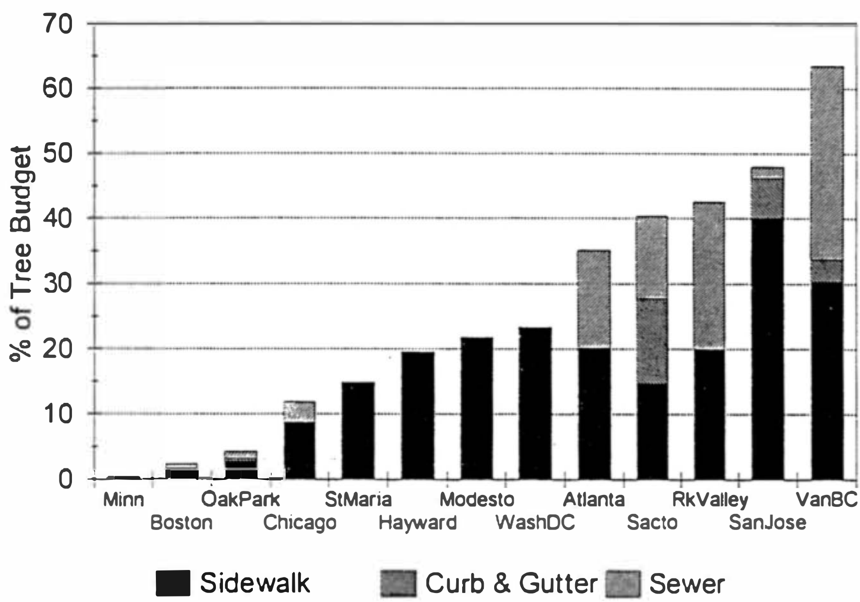

FIGURE 3. Annual infrastructure repair costs as percentage of annual tree budgets.

the chance of the damage recurring. In Vancouver, current replacement methods include relocating sidewalks where possible and using asphalt or crushed rock sidewalk inserts in lieu of concrete where there are repeated problems.

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 an eight inch deep apron on the tree side to act as a root barrier. Chemical barriers are also being experimented with as a method for deflecting potentially invasive roots. Other cities are using a variety of commercial 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 hardscape engineering perspective. Sacramento has experimented with a foam additive to concrete designed to produce a more elastic sidewalk, one which would bend rather than break and lift, as roots beneath grew 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.

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 the survey results published by BERNHARDT and SWIECKI (1988 and 1994), several of the tree managers stated that root damage to sidewalks, kerbs 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 piping. They consistently report intrusion occurring only where there are pre-existing leaks in the sewer lines. These managers also confirm ROLF and STAL (1994) observations that clay and concrete pipes 'sweat' more than PVC plastic types, and roots tend 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 of 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 of 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 systems in need of replacement.

Overall, responses 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. The problem tends to be viewed as site related, involving inter-relationships between tree species, tree growth and spatial requirements and existing site limitations.

Conclusions

Costs for repairing infrastructure damaged by street trees are substantial. Total annual costs are estimated to average $4.28 per tree for the 15 sample cities. On average, this cost amounted to 25 per cent of the sample cities' total annual tree budgets. A national survey of 419 cities found that the mean annual expenditure per public owned tree is only $4.64 (TSCHANTZ and SACAMANO, 1994). Estimates of infrastructure repair costs are conservative because data on kerb and gutter and sewer repair costs are lacking for half of 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 provide a better estimate of 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 relationships evident between costs and predictable variables such as city population, population density, average dbh and average planting strip width. Within a given city, costs are higher in older areas where the 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 minimised by locating trees and infrastructure to minimise conflicts, using 'tree resistant materials' and selecting species that are the most suitable for the 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 ensure that experiments are designed to reproduce results that will be statistically sound and published for the benefit of a wide 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 understand better 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 and fertilisation])
repair methods, installation and continuing maintenance costs, and durability over time

Understanding cause and effect relationships between trees and infrastructure damage is difficult because of complex interactions between 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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References

ANDERSSON, B., CARROLL, W. and MARTIN, W. (1986). Aggregation of US population centers using climatic parameters related to building energy use. *J. Clim and Appl. Meterol*, **25**, 596–614.

BARKER, P.A. (1976) Planting strips in street rights of way; a key public land resource. pp. 263–274. In Trees and Forests for Human Settlements, J.W. Andresen, Editor, University of Toronto Press, Toronto. Ontario. Canada.

BARKER, P.A. and DURRANT, M.G. (1978) Space for trees in street rights of way, pp. 463–467. In North America's Forest; Gateway to Opportunity. *Proc. Soc. American Foresters and the Can Soc Foresters*, Society of American Foresters, Bethesda, Maryland, USA.

BERNHARDT, E. and SWIECKI, T.J. (1988) The State of Urban Forestry in California: Results of the 1988 California Urban Forestry Survey, California Department of Forestry and Fire Protection. Sacramento, California, USA.

BERNHARDT, E. and SWIECKI, T.J. (1994). The state of Urban Forestry in California—1992. California Department of Forestry and Fire Protection, Sacramento, California, USA.

CITY OF HAYWARD (1993). Implementation of the 1993/94 Sidewalk Rehabilitation Program, City of Hayward, Hayward, California, USA.

HAMILTON, D., OWEN, W. and DAVIS, W. (1975). Street Tree Root Problem Survey. University of California Cooperative Extension, Alameda County.

KIELBASO, J.J. and COTRONE, V. (1990). The State of the Urban Forest, pp. 11–18. In Make Our Cities Safe for Trees. P.D. Rodbell editor. American Forestry Association, Washington, DC. USA.

McPHERSON, E.G. (1994). Benefits and costs of tree planting and care in Chicago. pp. 115–134. In Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. E.G. McPherson, F.J. Nowak and R.A. Rowntree, editors. Northeastern Forest Experiment Station, Radnor, Pennsylvania, USA.

McPHERSON, E.G. and ROWNTREE, R.A. (1989). Using structural measures to compare twenty-two US street tree populations. *Landscape Journal*, **8**, 13–23.

ROLF, K., and STAL, O. (1994). Tree roots in sewer systems in Malmo, Sweden. *Sweden Jour. Arbor.* **20**, 329–335.

SEALANA and ASSOCIATES (1994). City of San Jose Sidewalk Survey and Analysis Study, City of San Jose, Department of Streets and Parks, San Jose, California, USA.

STANKOVICH, M. (1990). Sidewalks and Trees. Village of Oak Park, Oak Park, Illinois, USA.

TSCHANTZ, B.A. and SACAMANO (1994). Municipal Tree Management in the United States. International Society of Arboriculture, Savoy, Illinois, USA.

WAGAR, J.A. and BARKER, P.A. (1983). Tree root damage to sidewalks and curbs. *J. Arbor.* **9**, 177–181.

WATSON, G.W., and NEELY, D. (1994). The Landscape Below Ground, International Society of Arboriculture, Savoy, Illinois, USA.

Résumé

Les arbres des rues sont une importante partie des espaces verts des villes, mais les dommages causés aux trottoirs, aux rigoles, et aux égouts par les racines s'élèvent à plusieurs millions de dollars.

Afin de déterminer l'amplitude de ce problème, des enquêtes ont été menées dans 15 villes par des forestiers urbains. Chaque année, le coût total des réparations des trottoirs et des égouts attribué aux arbres s'élève environ à \$4.28 par arbre avec un minimum de \$0.18 et un maximum de \$13.65. En moyenne, le coût des réparations équivaut à 25% du budget annuel de la ville, environ \$3.01 par arbre. En ce qui concerne les bordures et les rigoles, les réparations atteignent respectivement \$1.14 at \$1.66 par arbre.

Suivant les villes, ces dommages sont très variable et tendent à augmenter dans les quartiers les plus anciens où les infrastructures sont vétustes et les arbres sont gros. Les mesures appliqués aux arbres sont en cours de discussion afin de limiter les dégats.

Sumario

Los árboles de las calles son importantes componentes de la "infraestructura verde" de las ciudades, pero el daño aparentemente causado por las raíces en las veredas, cunetas y acequias, y alcantarillas es un problema de milliones de dolares. Silvicultores municipales en 15 ciudades fueron investigados para determinar la magnitud de este problem. El costo total anual de la reparación del concreto y las alcantarillas dañados por los árboles fue de un promedio de \$4,28 por árbol y fluctuó entre \$0,18 y \$13,65 por árbol. En promedio, el costo de las reparaciones es equivalente al 25 por ciento del presupuesto anual del programa para gastos en árboles. Las reparaîcones de las veredas son siempre las mas caras de todas las reparaciones en todas las ciudades, con un promedio de \$3,01 por árbol. Las reparaciones de las cunetas y acequías, y alcantarillas costaron en termino medio \$1,14 y \$1,66 por árbol, respectivamente. El daño varía bastante de cuidad a ciudad y tiende a ser más severo en áreas mas antiguas con infraestructuras en deterioro y grandes árboles. Medidas de mitigación aplicadas por los administradores de bosques son discutidas.