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A review of tree root conflicts with sidewalks, curbs, and roads

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Abstract. Literature relevant to tree root and urban infrastructure conflicts is reviewed. Although tree roots can conflict with many infrastructure elements, sidewalk and curb conflicts are the focus of this review. Construction protocols, urban soils, root growth, and causal factors (soil conditions, limited planting space, tree size, variation in root architecture, management practices, and construction materials) are discussed. Because costs related to sidewalk and curb damage are substantial, a review of research addressing repair, mitigation, prevention, and litigation costs is included. Finally, future research needs are discussed.

Potential for conflicts between trees and sidewalks/curbs is high when one or more of these factors are present: tree species that are large at maturity, fast growing trees, trees planted in restricted soil volumes, shallow top soil (hard-pan underneath top-soil), shallow foundations underneath the sidewalk (limited or no base materials), shallow irrigation, distances between the tree and sidewalk of less than 2.0–3.0 m., trees greater than 15 to 20 years old.

The results of this survey indicate that cities are spending substantial sums of money to address conflicts between street tree roots and infrastructure. It can be inferred that most of these expenditures are spent dealing with problems that already exist. However, this raises the question: How much is being spent now to ensure that conflicts are minimized in the future?

Future research should concentrate on plant factors, site design, and construction of sidewalks and curbs. Also, more knowledge is needed about interactions between root growth and management techniques, such as pruning and irrigation. Finally, there is need for studies that will assist policy-makers to efficiently allocate funds among repair, mitigation, prevention, and legal remedies.

Keywords: urban trees, roots, infrastructure conflicts, sidewalks, curbs, roads

Introduction

Many papers describe the problem of conflicts between tree roots and infrastructure (Barker, 1983; Wong *et al.*, 1988; Benavides Meza, 1992; Kopinga, 1994). Coder (1998) lists sewer

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or septic lines, storm water drains, water supply lines, building foundations, sidewalks, streets, parking lots, curbs, walls and swimming pools as infrastructure elements damaged by roots.

This review focuses on research related to damage to sidewalks, curbs, and roads. Review areas include: 1) factors contributing to sidewalk damage, 2) an overview of associated costs, and 3) new areas for research.

As introductory and background information, papers that address sidewalk and curb construction protocols, urban soils and root distribution, and professional perspectives are reviewed.

Sidewalks, soils and roots

Sidewalks and curbs: construction protocols

We define a "sidewalk" as a paved strip, running along one or both sides of a road, for pedestrian use. Sidewalks in England (footpaths) are usually constructed with a surface layer consisting of concrete slabs or asphalt. The foundation is made of two layers of base and sub-base materials, called capping (Downing, 1977; Helliwell and Duncan, 1996) (figure 1). In Denmark, the traditional foundation is similar to the British model. However, underneath the concrete slabs, a thin layer of sand is used as bedding and often one to three layers of base materials are used (Thagesen, 1991) (figure 2). The base is often made of screened and graded gravel (Kristoffersen, 1998). The amount and depth of layers depend on the expected load force on the surface and the bearing state of the sub-grade. The capping layer provides a platform for the sub-base and surface layer and often also serves as a drainage layer, keeping groundwater from the sub-base.

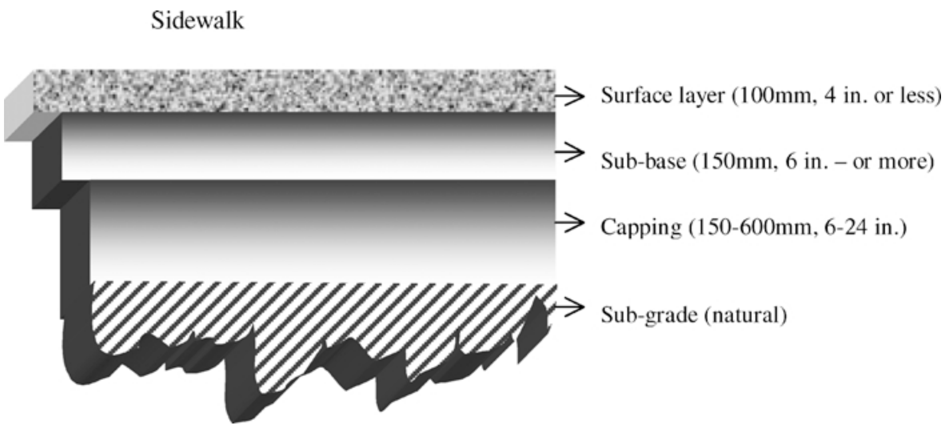

Figure 1. A typical sidewalk *surface layer* in the UK is usually made of asphalt, macadam or paving materials such as block paver. The *sub-base* is 150 mm (6 in.) thick or greater and made of compacted granular material. The *capping* is a more coarse material than the sub-base. The *sub-grade* is often native material. From: Downing (1977) and Helliwell and Duncan (1996).

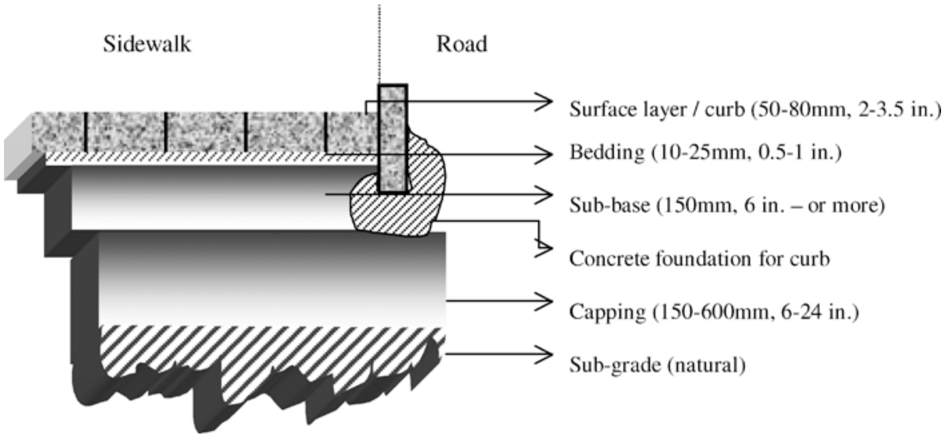

Figure 2. The sidewalk *surface layer* in Denmark is usually made of concrete slabs or concrete pavers. These are placed on a thin bed of sand or fine gravel, on top of one or more layers of compacted base materials. The *curb* is usually of concrete or granite, and is usually placed in a foundation of concrete poured on site. The *sub-base* and *capping* layers may be as thick as 600 mm, but will usually be approximately 150 mm thick for a standard sidewalk designed to carry only pedestrians and light equipment such as snow blowers, etc.

The curb acts as a barrier that helps to keep vehicles in the roadway, and also a means of directing storm runoff to nearby catch basins. In the United States, the curb is usually made of concrete (figure 3), while in Europe curbs are often made of granite or concrete. The shape of the curbs varies between the two continents (figures 2 and 3).

In the United States, sidewalks are typically made of 10 cm (4 inches) of un-reinforced concrete placed on-site. The foundation consists of only one base layer, e.g., compacted

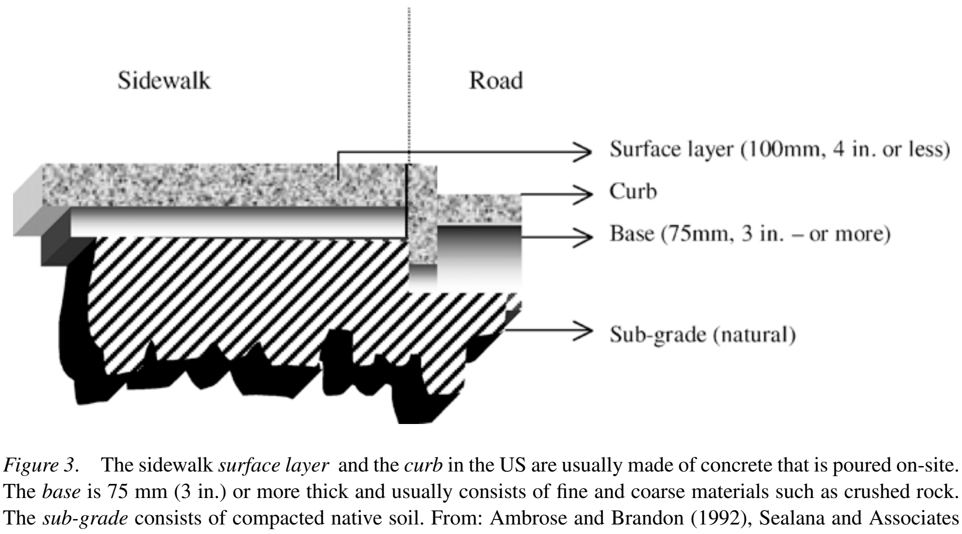

Figure 3. The sidewalk *surface layer* and the *curb* in the US are usually made of concrete that is poured on-site. The *base* is 75 mm (3 in.) or more thick and usually consists of fine and coarse materials such as crushed rock. The *sub-grade* consists of compacted native soil. From: Ambrose and Brandon (1992), Sealana and Associates (1994) and PCA (1998).

base rock (Ambrose and Brandow, 1992; Dunn, 1998), that also serves as a drainage layer (figure 3). Underneath the base layer, organic material is removed and the subsoil is compacted as needed (PCA, 1998). Concrete is a rigid material relative to asphalt, whereas bricks and pavers derive their structural integrity in large part from a well-prepared subbase (uniform and compacted), and the interlocking actions of individual pavers.

Helliwell and Duncan (1996) described the conflicting requirements of the urban infrastructure in the U.K. as follows: "The engineer has a responsibility to design and maintain surfaces and services capable of withstanding intensive use over long periods, with the minimum maintenance costs. To do this, the engineer designs surfacing constructions founded over relatively dry substrates compacted to the maximum achievable density. This substrate is kept relatively dry by impervious surfacing and sub-surface drainage. The development of any irregularity in the sub-surface layers is minimized by the exclusion of organic matter and, if possible, root growth. In contrast, the arboriculturalist seeks to meet the requirements of trees by creating a porous substrate that retains moisture within the tension range available to trees: is drained sufficiently to avoid prolonged saturation and ensure aeration: is soft enough to permit root growth laterally and to depth exceeding one meter and is recharged by rainfall during the growing season and subsequent winter." It is believed that as a principle, the conflict described above is relevant throughout the world. However, local and national rules, traditions and regulation may vary, which makes the conflict between tree roots and the infrastructure more significant in certain areas than in others.

Urban soils and root distribution

Urban soils are often disturbed, manipulated or handled in ways that change their properties and attendant characteristics (Craul, 1992). These modifications often adversely influence growing conditions (e.g., Kopinga, 1991; Jim, 1998a; Jim, 1998b). Under 'natural' growing conditions, 60–90% of the entire root volume is to be found in the top 0.2 m of a mineral soil, and virtually all the large structural supporting roots, are in the upper 0.6 m (Ruark *et al.*, 1982; Cutler *et al.*, 1990; Coutts and Nicoll, 1991; Dobson, 1995). Several authors state that roots proliferate in areas conducive for growth (e.g., Nicoll and Coutts, 1997; Harris *et al.*, 1999), such as near leaks where the infrastructure has been damaged.

Forces exerted by radial growth of roots can lift light structures such as paths, curbs, paving slabs, boundary walls or occasionally single story buildings (e.g., garages or porches) (Biddle, 1998). Displacement of structures is usually progressive (MacLeod and Cram, 1996). The U.S. Army Corps of Engineers (1996) distinguishes between different types of concrete sidewalk distress (Table 1). Sidewalk failures directly associated with root growth include cracking, vaulting, and faulting.

Factors associated with sidewalk damage

Trees

Limited space seems to be the major cause of root conflicts with infrastructure (Barker, 1983; Wong *et al.*, 1988; McPherson and Peper, 1995; Francis *et al.*, 1996). However, fast

Table 1. Adapted from U.S. Army Corps of Engineers (1996)

Type of failure	Cause of failure
Cracking and breaking	Vehicular loads, freeze-thaw cycles or tree roots
Vaulting and upheaval	Shrinking or swelling of soil, penetration of incompressible materials or tree root growth
Faulting and displacement	Settlement, pumping, eroding of materials, freeze-thaw cycles or tree root growth
Spalling, fracture	Incompressible materials in joints, weak concrete or freeze-thaw cycles
Surface deterioration	De-icing salts, freeze-thaw cycles, weak concrete or water accumulation

growing species like poplars (Kopinga, 1994) and *Eucalyptus* (Day, 1991) are known to cause conflicts. Nicoll and Armstrong (1998) found sidewalk conflicts up to 7.0 m from trees, and Kopinga (1994) did not find any distinct correlation between the distance of trees to roads and the frequency of conflicts. However, the limited available data suggest that the farther away the tree is situated from the sidewalk or curb, the lower the probability of conflicts.

Several studies have found strong correlations between tree size and conflicts with infrastructure (Table 2). Wagar and Barker (1983) found that large trees caused more conflicts than small trees. Also, more than half of the variation found for sidewalk conflicts was associated with tree diameter. Wong *et al.* (1988) found that most trees started to cause damage when they were 11–20 cm in diameter at breast height (dbh) (1.40 m). However, most oaks (*Quercus sp.*) and horse chestnuts (*Aesculus sp.*) did not cause damage until they were >20 cm in dbh.

Hamilton (1984) concluded that there is not a correlation between sidewalk distress and tree age. Barker (1983) suggested that the ages when trees significantly interfere with infrastructure is linked to their growth rates. He concluded that for trees with comparable height, the faster they grow, the earlier and more often their roots interfere with sidewalks and curbs. This observation agrees with findings by Day (1991) and McPherson and Peper (1995).

Table 2. Studies that have found relations between tree age and infrastructure conflicts

Tree age reported being the cause of damage	Reference
Younger age	Wagar and Barker, 1983
Younger age	Day, 1991
Age > 15–20 years	Sydnor *et al.*, 2000
Age minimum 30 years	McPherson and Peper, 1995
Age 30 years	Nicoll and Armstrong, 1998
Age 40 years	Kopinga, 1994
Some species only 5–7 years	Kopinga, 1994
Tree age varies	Barker, 1983
No specific age	Hamilton, 1984

Wagar and Barker (1983) found that slightly less than half of the variation found for curb conflicts was associated with tree species. However, both Dobson (1995) and McPherson and Peper (1995) stated that although differences in root architecture exist among species, the final pattern of an individual tree root development is determined more by environment than by genetic inheritance.

Large and fast growing species are more likely to cause problems than smaller and slow growing species. However, it has been reported that trees of the same species have caused conflicts at some locations, while in other locations, no conflicts occurred (Wagar and Barker, 1983; Wong *et al.*, 1988). Although some species are particularly problematic, most species will produce large surface roots if soil conditions are unfavorable.

In some cases tree roots act differently at the same location. There are no obvious reasons why roots of some trees are causing damage, while roots from other trees of same species and sizes are not causing damage. Local variations in the soil, (e.g., Short *et al.*, 1986; Jim, 1998a; McPherson *et al.*, 2000), as well as genetic differences (Burger and Taylor, 2000; Costello *et al.*, 2000a) are possible causes. However, conflicts appear to be more related to tree age, growing conditions, and amount of rooting volume, than to species.

Soils and infrastructure (sidewalks, curbs, and roads)

Damage caused by roots has been related to sidewalk engineering and design failures (Cutler, 1995; Brennan *et al.*, 1997; Coder, 1998). However, Sydnor *et al.* (2000) found that in 3 of 4 sampled soil complexes, sidewalk blocks of all ages were more likely to be raised where there were no trees than where trees were present.

The type of surface material may also be important in relation to the degree of damage made by roots. Wong *et al.* (1988) found significantly more conflicts between roots and sidewalks made with asphalt than concrete. Nicoll and Armstrong (1998) found that roots caused almost all conflicts when over 100 mm in diameter, and that conflicts were caused by fast growing roots as deep as 0.4 m below the sidewalk, as well as by roots directly below the surface.

Francis *et al.* (1996) stated that for tropical regions, such as Mexico and Puerto Rico, the critical dbh' for curb conflicts was much larger than for sidewalk conflicts. It appears that curbs are less likely to be damaged than sidewalks because adjacent streets have more compacted base materials and are more poorly aerated than base materials under sidewalks. Similarly, Kristoffersen (1999) showed that roots of *Tilia* × *vulgaris Fraxinus excelsior* and *Acer platanoides* did not penetrate a base material consisting of well-graded gravel that was constructed and compacted according to general standards.

Soil texture alone does not seem to explain the presence of sidewalk conflicts (Wagar and Barker, 1983). Both Kopinga (1994) and Costello *et al.* (2000a) reported that conflicts were observed in different types of soils. Kopinga (1994) found conflicts in relatively high humus-rich clay soils as well as sandy clay soils and poor sandy soils. Costello *et al.* (2000b) found sidewalk damage in 6 out of 9 locations that were sampled, all of which were sandy loams or sandy/silt loams. In tree locations where no damage was found, soil physical and chemical properties were similar to where damage occurred. Restrictions to root development were not found at sites where sidewalk damage was noted. They concluded that soil condition alone was not a reliable predictor of sidewalk damage. The authors observed that rootstock variation could be an important factor.

Day (1991) noted that damage seemed less severe for soft or loose soils that deformed as the roots grew, than for dense or hard soils (such as heavily compacted base materials). A plausible explanation is that tree roots under sidewalks are primarily found in the interface between either the surface layer and the sub-base or between different base materials (Kopinga, 1994; Sealana and Associates, 1994). The roots penetrate the interface attracted by the comparatively high degree of humidity underneath the road surface (Kopinga, 1994). Once the roots penetrate under the sidewalk they quickly absorb the small quantity of water present. This creates a soil humidity gradient that stimulates rapid apical growth of the roots. Limited moisture and low soil fertility may explain why these roots form few branches and fine lateral roots. Once the roots reach the soil on the other side of the pavement they return to a normal rooting pattern. Accelerated growth induces an increase in the diameter of roots under the sidewalk. Cracks begin to form after a period of time depending on factors such as thickness and elasticity of the sidewalk. High moisture of the soil under the sidewalk surface is a major factor in attracting tree roots and subsequent deformation of the concrete. Therefore, Kopinga (1994) suggested that differential rates of soil suction between the soil adjacent to and under the asphalt could be one explanation for root development under road surfaces. Nicoll and Armstrong (1998) concluded that roots might even grow faster directly under paved areas than outside, resulting in accelerated secondary thickening.

Certain sidewalk construction methods may favor root growth. A sidewalk made of concrete may function as a barrier against soil moisture loss by evaporation. In addition, the high moisture content of the soil, compared to the concrete, gives the soil high specific heat. When the sidewalk warms, heat radiates to the soil beneath it. Conversely, when the sidewalk cools its temperature drops more rapidly than the soil temperature and the underside of the sidewalk becomes a surface for condensation of soil moisture, which subsequently percolates back into the soil (Barker, 1988). Graves (1994) described how urban soil temperatures vary but are greatest under asphalt and concrete surfaces.

Irrigation and crown pruning

Irrigation is known to initiate new root growth (Phene *et al.*, 1991; Fernandez *et al.*, 1991; Carmi *et al.*, 1992; Neilsen *et al.*, 1997). Therefore, irrigation in urban areas may increase the tree root/infrastructure conflict.

It has been noted that some cities use regular crown pruning to control root growth and related conflicts with infrastructure. Coder (1997) concluded that significant crown pruning can slow root growth, and overall tree health can be compromised. However, the impact of crown pruning on roots may be proportional to the amount of crown removed. Thus, extensive heading will lead to severe root impacts, whereas light thinning probably has little effect on roots (Coder, 1997). Jones *et al.* (1998) found that crown pruning of *Prosopis juliflora* led to decreased root growth. The authors noted that similar effects were found for a variety of environmental conditions and for different species. Alder (*Alnus glutinosa*), poplar (*Populus tremula*) and sugar maple (*Acer saccharum*) showed net loss of root mass after half the leaf area was removed, presumably due to increased partitioning of photosynthate to shoots rather than roots after shoot pruning. Crown pruning of even relatively vigorous growing species like poplar will reduce the root growth rates and thus, possibly reduce conflicts with infrastructure. However, it appears that relatively heavy crown pruning is needed to significantly reduce root growth. Seen from an arboricultural and aesthetic viewpoint, this may not be a satisfying solution to tree root conflicts with infrastructure.

Root barriers

Root barriers are used with the intent of preventing or delaying conflicts between tree roots and infrastructure. By placing a physical or chemical barrier between tree roots and sidewalks/curbs, roots growing laterally are either deflected down below the depth of the barrier (physical barrier) or their growth is inhibited (chemical barrier). Roots that grow under the barrier are thought to be deep enough to avoid contact with infrastructure, thus reducing the potential for damage (e.g., Nicoll and Coutts, 1998; Harris *et al.*, 1999).

Research has shown variable effects of root barriers on root distribution. Wagar (1985) reported fewer number of roots of white mulberry (*Morus alba*) and zelkova (*Zelkova serrata*) trees in the surface 0.2 m with barriers in clay loam soil, but noted substantial surface rooting for some trees with barriers and suggested this resulted from soil compaction/poor aeration at certain locations in the study plot. Costello *et al.* (1997) found that ash (*Fraxinus oxycarpa* 'Raywood') and poplar (*Populus nigra* 'Italica') roots grew toward the soil surface after growing underneath plastic and fabric circular barriers. Similar results were found using a linear barrier with Southern live oak (*Quercus virginiana*) and sycamore (*Platanus occidentalis*) (Gilman, 1996). Barker (1995a, b) found that European hackberry (*Celtis australis*) and Southeastern black cherry (*Prunus serotina* 'Virens') generated deeper root systems with root barriers in well-drained, alluvial soil. However, at the same research site Peper (1998) and Peper and Mori (1999) found that Chinese hackberry (*Celsis sinensis*) and white mulberry roots returned to the surface. It was proposed by Gilman (1996) that "root barriers might be most effective in soils where they are least needed, i.e., in well-drained, non-compacted sites." Harris *et al.* (1999) note that "root-control devices appear to be least effective where most needed, that is, where poor soil aeration or compaction encourages shallow rooting."

Apparently, at least three types of barriers are available:

1. *Deflectors*: solid, interlocking thermoplastic panels, sheets, rolls or preformed planters.
   Roots grow to the inside face of the barrier and are deflected laterally or downward. Some products have vertical ribs built into the material to channel roots downward and prevent circling roots. Plastic deflectors are the most commonly-used type of barrier.
2. *Inhibitors*: landscape fabrics or screens impregnated with chemical compounds that inhibit root development.
   When roots grow into the zone of activity of the inhibitor, root meristem activity is suppressed. Inhibitors include herbicide-containing fabric (Harris *et al.*, 1999), copper screening and copper-infused fabric (e.g., Wagar and Barker, 1993). Environmental fate of herbicide used in fabric may be of concern to users.

3. *Traps*: screens, welded-fiber sheets and fabrics.
   Holes in these materials are small enough to allow root tips to penetrate, but radial growth is inhibited (Wagar and Barker, 1993, Edwards *et al.*, 1999). Copper screens can act as a trap and an inhibitor.

All three types of barriers can be used in a linear or circular configuration. Linear barriers includes deflectors, inhibitors or traps, which can be placed in a linear configuration alongside hardscape elements, such as along curbs, sidewalks and foundations. They are installed against the infrastructure element prior to planting or in trenches after root pruning (Harris *et al.*, 1999). Circular barriers are placed in a circular configuration outside the rootball of a newly-planted tree, circular barriers are commonly used in sidewalk cut-outs or other restrictive spaces. They surround the root system (to various depths) and allow root development only through the bottom of the barrier. In restrictive soils (e.g., hardpans) they may limit root development to the soil volume within the barrier, compromising root growth, distribution, and anchorage. In circular barriers, the structural stability of trees may be less than that for trees without barriers. Also, it is likely that the barrier may compromise buttress development and anchorage. However, Smiley *et al.* (2000) found that green ash (*Fraxinus pennsylvanica*) planted in circular barriers required more force to be pulled over than trees without barriers. Anchorage is more likely compromised in poor quality soils where conditions outside the barrier limit root development to the inside of the barrier.

For locations such as in planting strips or lawns, linear barriers should be used in order to allow optimum root growth. Plastic barriers are rigid, and became commercially available in the 1970's. They are widely used in California. The initial concept and design was based on work by Brayton (1967).

Many factors should be considered when selecting plastic barriers:

- type of plastic—the plastics industry recognizes high-density polyethylene as most resilient and durable.
- size—barrier thickness and depth.
- presence of interior ribs—particularly if barriers are used in planting wells. Peper (1998) indicated that internal ribs in circular barriers deflect roots downward, while Pittenger and Hodel (1999) did not find this effect.
- connector type—panels need to remain connected (or roots will possibly penetrate separations). They should not be easily pulled or twisted apart.
- watering tubes—can be included with the barrier but may add to cost. No research regarding positive or negative value has been found.
- the top edge of rigid barriers needs to remain visible (at least 2.5 cm above soil level or mulch) after installation or roots can grow over them and the effect of the barriers may be lost (Nicoll and Coutts, 1998; Harris *et al.*, 1999).
- rigid plastic materials must be UV resistant or the exposed edge will possibly deteriorate; also, plastic is a durable material, but can become brittle in freezing weather.
- ease of installation—time and expense are factors to consider (Peper and Barker, 1994).

Table 3. Costs in relation to tree—infrastructure damage (+/− is standard error)

Cost types	Costs per capita ($)*	Frequency of repair (repairs per tree)*	Avr. repair costs ($)*	% of total expenditures*	Annual costs ($)
Sidewalk repair	0.88 +/− 0.36	1:99	480	44	3.01/tree**
Street surface repair	0.32 +/− 0.05	1:151	288	5	
Curb & gutter repair	0.45 +/− 0.10	1:169	277	8	1.14/tree***
Mitigation and prevention (total)	0.17 +/− 0.08			9	
(Root pruning)		1:86	79		
(Grinding)		1:72	44		
(Ramping)****		1:13,782	31		
(Root barriers)		1:293	40		
Tree removal and replacement	0.26 +/− 0.14	1:596	537	13	
(Replacement costs)			154		
Trip and Fall cases	0.26 +/− 0.06		6,245 (avr. payment)	7	
Legal staff time	0.12 +/− 0.06			7	
Inspection and repair program adm.	0.22 +/− 0.05			7	
Total	2.68			100	

*18 California cities (McPherson, 2000).
**15 US cities (McPherson and Peper, 1995).
***5 US cities (McPherson and Peper, 1995).
****Ramping or tapering the walk with asphaltic concrete or a similar product.

Costs associated with root and sidewalk conflicts

The repair and renovation of infrastructure is expensive (McPherson and Peper, 1995, 1996) and frequently results in damage to the trees themselves (e.g., Gulick, 1986; Morell, 1992; Nicoll and Armstrong, 1998), or their premature removal (e.g., Bernhardt and Swiecki, 1989; Ottman *et al.*, 1996). Various costs associated with infrastructure damage by tree roots are presented in Table 3.

A survey of 18 California cities reported that annual expenditures for tree-related sidewalk repair totaled $6.6 million (McPherson, 2000), and tree-related curb and gutter repair costs for 5 cities were 38% of sidewalk repair costs (McPherson and Peper, 1995).

In the California survey, only 8 of 18 cities fully funded sidewalk repair. Property owners were required to pay all tree-related sidewalk and curb and gutter repair costs in the two largest cities, Los Angeles and San Jose. Of the total $6.6 million spent on sidewalk repair in the 18-city sample, 61% was paid with municipal funds and 39% was passed through to property owners. Property owners paid 17% of total curb and gutter repairs, while the municipalities paid for all street repairs. Because municipalities pay for much of the repairs, all tax payers are still paying for the costs of repairs even though they may not have damage on their property. Morell (1992) described that in Park Ridge, IL, the property owner pays for infrastructure improvements related to tree root damage through their property taxes. Furthermore, expenses to repair the infrastructure may be covered from one department (street maintenance) while the trees usually are managed in a different department, e.g., parks (Barker, 1983; Morell, 1992; Rolf and Stal, 1994). Dunn (1998) described Sunnyvale, CA as one of few cities where street tree maintenance and concrete maintenance were in the same department (Public Works) and managed by the same person.

In the California survey (McPherson, 2000), mitigation and prevention measures included root pruning, grinding, ramping, and use of root barriers (Table 3). Infrequently applied measures included tree well engineering, water jetting, and narrowing sidewalks to accommodate flared tree trunks and shallow roots. The cost of implementing these strategies accounted for 8% of total mitigation/prevention expenditures.

Tree removal and replacement also plays a significant part in municipal budgets (Table 3). Furthermore, benefits are foregone when a large tree is prematurely removed because of a conflict with surrounding infrastructure. The value of annual benefits produced by a large street tree in a San Joaquin Valley community like Modesto, CA can exceed \$100 (McPherson *et al.*, 1999a). On the other hand, cities like Modesto spend \$20 to \$40 per year to maintain a street tree of this size, so benefits can exceed costs by a factor of 2 or more (McPherson *et al.*, 1999b). Replacement trees are a net cost for the first 5 to 10 years because establishment costs are greater than benefits from the relatively small tree crown. Therefore, premature removal and replacement of large trees results in considerable payment for work performed (\$691/tree on average), and a substantial loss of net benefits formerly produced by the tree (approximately \$70/tree).

An interesting finding from the California survey was the relatively large cost for trip and fall payments and legal staff (Table 3) (McPherson, 2000). Annual expenditures were variable, ranging from \$1,300 in Lompoc to \$1.3 million in Los Angeles. The highest single trip and fall payment reported was \$120,000, and the average payment was \$6,245. Expenditures for inspectors and staff administering repair programs totaled 7% of total costs for the 18 California cities. Inspection costs accounted for 55% of the total expenditure.

Results from the California survey indicate that on average communities spent over \$2/capita or \$11/tree each year on expenses related to conflicts between tree roots and infrastructure. In 1992 California cities budgeted an average of \$4.36/capita or \$18.32/tree for their tree programs (Bernhardt and Swiecki, 1993). Repair costs alone accounted for 60% of total expenditures, and sidewalk repair was the single largest cost category, accounting for about 33% of total expenditures. But other costs are important. For example, Californians spent \$2.26 on legal remedies for every \$1 spent on mitigation and prevention.

The distribution of expenditures varies among cities, reflecting how each city has chosen to deal with the problem historically, as well as each city's willingness to fund repair activities in the present. For example, in 1996 the City of Los Angeles, CA had an estimated \$375 million sidewalk repair backlog due to inadequate funds for repairs beginning in 1976 (Los Angeles Department of Public Works 1996). Only recently has funding become available to begin to alleviate this problem. As a result, in 1996 the City spent only \$0.69/capita on tree-related infrastructure issues and 51% of this amount was spent to pay claims and legal fees. The disproportionate expenditure on legal remedies reflects a long-term failure to adequately maintain the infrastructure in combination with an increasingly litigious urban population.

The City of Lompoc, CA, adopted a different strategy. In 1996 it spent an average of \$10.67/capita on tree root-infrastructure conflict issues, the largest amount reported for the 18-city sample (McPherson, 2000). Although Lompoc spent the most for repair (\$5.85/capita) and mitigation/prevention (\$2.44/capita), it had the lowest expenditure rate for trip and fall payments and legal fees (\$0.01/capita). Lompoc spent \$863 for repair, mitigation, and prevention for each \$1 spent for trip and fall.

Management and research needs

Many citations in this review are based on observations, surveys, and interviews. Few manipulated and controlled experiments have been conducted within this research field. There is need for more systematic and comprehensive studies. Opportunities for research exist in newly created urban forests as well as redevelopment sites within cities. A proactive approach is needed to solve existing problems as well as design more harmonious relationships between the emerging green and gray infrastructures.

Species selection and plant propagation

The importance of genetic improvement as a means for reducing infrastructure conflicts was discussed as early as 1983 (Barker, 1983) and repeated by Costello *et al.* (1997), who emphasized that species selection should be a key element in strategies to reduce infrastructure conflicts. Costello *et al.* (2000a) went a step further, suggesting that various rootstocks used for propagation have varying potentials for sidewalk breakage. There is potential to select deep rooting species and rootstock as described by Burger and Taylor (2000). However, most trees develop shallow root systems and urban growing conditions favor shallow root growth. Therefore, current species selection for urban uses should focus on trees ability to withstand the specific urban site and soil conditions (Nicoll and Coutts, 1997).

In a study carried out in Cincinnati, OH, Sydnor *et al.* (2000) concluded that trees were not the principal reason for sidewalk failures. However, similar research in other locations is needed to verify these findings.

Construction of sidewalks and curbs

Helliwell and Duncan (1996) suggested that fundamental research into the geotechnical/physical conditions that prevent root extension needs to be carried out. Also, tests of different construction techniques and base materials related to growth responses of different tree species are needed. Trials should include the interaction between roots and infrastructure, as well as the soil moisture regime under paving systems, for a range of natural and manufactured soils.

Soil and stone mixes as base materials

The introduction of new soil mixes for use under sidewalks (Grabosky and Bassuk, 1995, 1996; Kristoffersen, 1998, 1999) appear to promote a broader distribution of roots, ultimately leading to a reduced amount of sidewalk damage. However, some root experts are skeptical about this idea since secondary root growth, even of deep roots, may displace the soil/stone mixture and ultimately displace the sidewalk (Nicoll and Armstrong, 1998). Long-term monitoring of existing and new installations is needed to determine impacts on root growth rates, vertical root distribution, and sidewalk displacement.

Porous surface layers

The traditional way of constructing sidewalks may favor root growth at the interface between the soil and the concrete. Porous surface layers that limit condensation and lower the temperature under concrete slabs might reduce rooting at the interface. Furthermore, porous surfaces increase infiltration of rainwater into the soil. Examples of porous materials are porous asphalt, porous concrete, and paving blocks with open joints or drainage holes. Theoretically, these materials ought to have a distinctive effect on the urban climate, because: 1) they have lower thermal capacity and conductivity than their impervious counterparts; 2) they interact with the atmosphere more intimately, through ventilation of the interior of the pavement; and 3) they might be less costly to repair. More research is needed to determine the net effect of porous surfaces on root growth.

Root growth and pruning

Although root pruning is widely practiced, research has yet to document its impact on tree health, structural integrity, and longevity. Similarly, questions remain about the effects of root barriers on the stability of trees and long-term rooting patterns. Research is needed to understand interactions between these strategies and tree performance. Life cycle benefit-cost analyses are needed to fully evaluate the long-term efficacy of root pruning and root barriers.

The practice of crown pruning to reduce root growth and conflicts between tree roots and infrastructure is common, but there is little information on its efficacy. The reaction of different species to different levels of crown reduction and related root growth should be examined.

Conclusions

Potential for conflicts between trees and sidewalks/curbs is high when one or more of these factors are present: tree species that are large at maturity, fast growing trees, trees planted in restricted soil volumes, shallow top soil (hard-pan underneath top-soil), shallow foundations underneath the sidewalk (limited or no base materials), shallow irrigation, distances between the tree and sidewalk of less than 2.0–3.0 m., trees greater than 15 to 20 years old.

It is evident that we do not know as much as we need to, in relation to all of the above mentioned factors. First of all, trees are in most cases not part of the original planning for street- and townscapes. This lack of planning leads to problems with trees and the infrastructure. In very few cases, pro-active solutions are made to prevent potential problems. Secondly, work in this field has so far been very specific, and there needs to be a broader spectrum and multi-disciplinary approach to the problem. Furthermore, most information in relation to the problem is observational, rather than based on research, which includes repeatable studies. Since the scope of the problem is highly dependent on the specific location, a combination of controlled experiments and *in situ* testing should be used in the future.

The results of this survey indicate that cities are spending substantial sums to address conflicts between street tree roots and infrastructure. It can be inferred that most of these expenditures are spent dealing with problems that already exist.

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