A Review of Benefits and Challenges in Growing Street Trees in Paved Urban Environments

Authors: Jennifer Mullaney[1,2], Terry Lucke[1], Stephen J Trueman[1]

Affiliations: [1]Faculty of Science, Health, Education and Engineering, University of the Sunshine Coast, Maroochydore DC, Qld 4558, Australia.

[2]Corresponding author. Email: Jennifer.mullaney@research.usc.edu.au

Journal: Landscape and Urban Planning (2015) 134, 157-166
DOI: 10.1016/j.landurbplan.2014.10.013

Impact factor: 3.037 (2014)

Abstract

Street trees are an integral element of urban life. They provide a vast range of benefits in residential and commercial precincts, and they support healthy communities by providing environmental, economic and social benefits. However, increasing areas of impermeable surface can increase the stresses placed upon urban ecosystems and urban forests. These stresses often lead tree roots to proliferate in sites that provide more-favourable conditions for growth, but where they cause infrastructure damage and pavement uplift. This damage is costly and a variety of preventative measures has been tested to sustain tree health and reduce pavement damage. This review explores a wide range of literature spanning 30 years that demonstrates the benefits provided by street trees, the perceptions of street trees conveyed by urban residents, the costs of pavement damage by tree roots, and some tried and tested measures for preventing pavement damage and improving tree growth.

Introduction

Urbanisation increases the area of land covered by impervious surfaces such as rooftops, roads, driveways and parking areas (Gill et al. 2007), which can impose dramatic changes on a catchment by altering its natural drainage characteristics (Lee & Heaney 2003; Miller et al. 2014). Increasing the amount of impervious surface effectively seals off much of the underlying soil and prevents precipitation from infiltrating into the soil. An increase in impervious surface coverage in the urban environment can increase water stress on urban forests and ecosystems (Kjelgren & Clark 1994; Iakovoglou et al. 2001) Parks and street tree plantings create interesting and dynamic public spaces within the urban environment but tree growth may be limited when tree plots are not properly designed to minimise water stress. The primary purpose of street trees has changed over the last 30 years from an aesthetic role of beautification and ornamentation to one that also includes the provision of services such as stormwater reduction, energy conservation and improved air quality (Seamans 2013). However, these benefits are not fully realised because street tree growth is often limited by critical landscape design issues that affect access of the tree roots to water, air and nutrients.

Tree growth is influenced by a range of abiotic factors including soil moisture, soil volume, soil porosity, soil chemistry, canopy irradiance and air quality (Iakovoglou et al. 2001; Morgenroth, Buchan & Scharenbroch 2013). A change in the availability of soil moisture and soil nutrients in the urban environment can result in costly damage to infrastructure. For example, tree roots proliferate in areas beneath impervious sidewalks and roads that provide sufficient water and nutrients for tree survival and growth (D'Amato et al. 2002). The use of pervious surfaces, which allow water to infiltrate through the pavement surface and into the soil, has been the focus of recent research (Volder, Watson & Viswanathan 2009; Morgenroth & Visser 2011; Mullaney et al. 2012; Mullaney & Lucke 2014). Most studies have investigated whether pervious pavements increase the growth or survival of street trees, while some studies have investigated whether permeable pavements minimise damage to pavements and other urban infrastructure (Mullaney & Lucke 2014). The underlying theme of these studies is that the drainage layers required underneath permeable pavements may, effectively, create a root barrier beneath the pavement surface, forcing roots to grow at greater depths. These layers can potentially also increase the pavement's water storage capacity, promoting tree health directly while minimising pavement damage.

This review describes and discusses the benefits of street trees, residents' perceptions of street trees, challenges in growing trees in urban environments, and potential methods to increase street tree health and prevent pavement damage. The review focuses on interactions between pavements and street tree roots while acknowledging that other tree organs such as trunks and branches can also cause damage to urban infrastructure. Most of the available literature was derived from temperate regions including the United States and Europe, but the review also covers studies from tropical regions.

Street Tree Benefits

Street trees play an integral role in supporting healthy urban communities and they have a significant social impact by improving human health (Donovan et al. 2013), reducing crime (Kuo & Sullivan 2001), increasing community interaction (Van Dillen et al. 2012) and boosting property values (Pandit, Polyakor & Sadler 2012). The benefits provided by street trees are typically categorized as environmental, economic or social although some benefits span more than one category.

Environmental Benefits

Street trees increase the liveability of towns and cities by reducing stormwater runoff, improving air quality, storing carbon, providing shade, and ameliorating the urban heat-island effect. Street trees also enhance biodiversity by providing food, habitat and landscape connectivity for urban fauna (Burden 2006; Rhodes et al. 2011). Increases in impervious surface area and soil compaction, due to urbanisation, reduce water infiltration into soil and increase stormwater runoff and peak flow rates. For example, urban runoff from summer rainfall is much higher from asphalt (62%) than from surfaces with tree pits (20%) or turf (<1%), highlighting the effect that trees can have on stormwater reduction (Armson, Stringer & Ennos 2013). Leaves and branches intercept, absorb and temporarily store water before it evaporates from tree surfaces or gradually infiltrates into the soil. Mature deciduous trees, such as sweetgum, intercept between 1.89 and 2.65 kL of water per year (Seitz & Escobedo 2011), while evergreen trees including pines can intercept more than 15.41 kL per year (Cappiella, Schueler & Wright 2005).

Emissions and noise from road traffic can be a serious health issue but trees are particularly effective at diminishing noise and capturing airborne pollutants including ozone, nitrogen oxides, sulphur oxides, sulphur dioxides, carbon monoxide, carbon dioxide (CO_2) and particles less than 10 μm in size (Tallis et al. 2011). Large healthy trees can remove between 60 and 70 times more air pollution than smaller trees (McPherson, Nowak & Rowantree 1994). Trees remove CO_2 from the atmosphere through photosynthesis, and they decrease the consumption of fuel for heating and cooling by providing shade and insulation (Ferrini & Fini 2010). The inner-city tree population of Melbourne, Australia (~100,000 trees) is estimated to have sequestered one million tonnes of carbon (Moore 2009). The cooling effect provided by trees is directly related to tree size, canopy cover, tree location, and planting density. As much as 80% of the cooling effect of trees results directly from shading (Shashua-Bar, Pearlmutter & Erell 2009). Street trees can reduce daytime temperatures by between 5°C and 20°C, making everyday activities more pleasurable and healthier (Burden 2006; Killicoat, Puzio & Stringer 2002).

Street trees also provide habitat for urban fauna, and some fauna species are so well-adapted to urban environments that they are more abundant in cities than in surrounding natural vegetation (Alvey 2006; Davis, Taylor & Major 2012; Lambert et al. 2009). However, fauna abundance is often lower in the inner city, where tree density is lower, than in suburban and outer-urban areas (Davis, Taylor & Major 2012). The type and height of street tree can also influence fauna abundance and fauna diversity, and planting a diversity of native tree species is often recommended for preventing homogenisation of the urban fauna (Alvey 2006). Non-native species are the predominant birds in parts of many European and North American cities that have the lowest vegetation cover (Savard, Clergeau & Mennechez 2000), while urban areas with high proportions of native trees in Australian cities have high bird diversity and high native-bird abundance (Young, Daniels & Johnston 2007; Ikin et al. 2013). Similarly, native tree species are widely utilised by bats and iguanas in residential parts of California and Nicaragua, respectively, but both species prefer to roost in large trees at sites that are close to forest or large numbers of preferred food trees (Evelyn, Stiles & Young 2004; González-García et al., 2009). Street trees also provide connectivity between forest remnants and riparian vegetation strips in cities, providing corridors for the dispersal of small mammals, birds and less-conspicuous fauna such as butterflies, moths and beetles (Angold et al. 2006; Konvicka & Kadlec 2011; Jones & Leather 2012; Threlfall, Laws & Banks 2012; Ikin et al. 2013; Vergnes et al. 2013).

Social Benefits

Greenspace in an urban environment promotes contact between community residents, encourages physical activity, reduces stress and stimulates social cohesion (Van Dillen et al. 2012). Reduced crime and increased public safety have often been associated with urban areas that have a high abundance of street trees (Kuo & Sullivan 2001; Tarran 2009). Building areas with high levels of vegetation can have approximately 50% lower crime levels than areas with low levels of vegetation (Kuo & Sullivan 2001), and a 10% increase in the amount of tree cover has been associated with a 12% decrease in crime (Troy, Grove & O'Neil-Dunne 2012). Also, larger street trees are associated with a decrease in both the incidence of crime and the fear of crime (Donovan & Prestemon 2013). The reduced crime levels in areas with well-maintained vegetation are sometimes thought to result from a greater sense of community care by residents (Kuo & Sullivan 2001).

Another social benefit of street trees is their ability to act as a visual and physical barrier between motorists and pedestrians. Street trees can create a vertical wall between the foot path and the road. This gives motorists a defining edge to help guide their movements and to help them assess their speed, thereby increasing community safety (Tarran 2009). Trees also provide a physical defence for pedestrians against vehicle injury.

Economic Benefits

The benefits of street trees are often underappreciated, while the costs of damage and nuisance that trees cause are widely reported (Moore 2009). Unlike conventional forestry and fruit trees, the economic benefits associated with urban street trees cannot be easily quantified as they usually do not have a market value (Pandit, Polyakor & Sadler 2012). However, estimating the economic benefits of street trees can provide a quantifiable basis for maintaining municipal tree-care programs and planting more trees. Presenting the benefits in monetary terms allows the benefits to be easily understood by policy and decision makers. Unfortunately, trees are often removed and not replaced when they are viewed more as liabilities than assets due to inherent misunderstandings (McPherson 2007).

Street trees can reduce energy costs and increase business income and property values. The potential energy savings gained through planting street trees are well documented (McPherson, Nowak & Rowantree 1994; Donovan & Butry 2009; Pandit & Laband 2010). A 10% increase in tree cover can reduce total heating and cooling energy use by 5–10% (US$50 to $90) (McPherson, Nowak & Rowantree 1994). A single tree was found to decrease annual heating costs by 1.3% and cooling costs by 7% (McPherson, Nowak & Rowantree 1994). Trees planted on the west and south sides of houses in Sacramento, CA, reduced summertime electricity use by 185 kWh (5.2%) per household (Donovan & Butry 2009), and trees in Auburn, AL, reduced summer energy use by 3.8% compared with houses with no shade (Pandit & Laband 2010). Electricity consumption was decreased by 1.29 kWh/day for every 10% of shade coverage (Pandit & Laband 2010).

Trees contribute to the character and identity of a town’s malls and streets. Treescaping can increase business income by 20% (Burden 2006). Consumers will sometimes spend an additional 9% on an item in retail developments that include street trees compared with the same item in a non-treescaped retail outlet (Wolf 2005). This added value results from perceptions of a more-positive atmosphere, increased comfort level and a more favourable environment for visiting and shopping (Wolf 2005). In Alabama, 75% of residents indicated the presence of street trees influenced their choice of a new residence (Zhang et al. 2007). Prices of houses with a tree within 100 m of the house in Dakota and Ramsey Counties, MN, were valued, on average, 0.48% higher than houses without a nearby tree (Sander, Polasky & Haight 2010). House prices in Perth, Australia, were higher by an average of 20–30% when there was tree cover on the public space next to, or near, the property (Pandit, Polyakor & Sadler 2012). Hedonic price modelling estimated that house prices in Portland, OR, were increased by 3% by the presence of a street tree (Donovan & Butry 2010).

In theory, any difference in the price of two houses that are identical except for their tree cover should be due to the presence of the tree (Anderson & Cordell 1988). This difference can sometimes be difficult to verify. None the less, energy savings, carbon sequestration, stormwater management and air quality benefits can be determined through direct estimation and implied valuation. A range of software packages, including STRATUM (USDA Forest Service 2005), UFORE (USDA Forest Service 2005), and iTree (USDA Forest Service 2013), performs computer-based modelling that places a value on street trees. STRATUM and UFORE have been the most popular models used by municipalities across the USA (Bonifaci 2010). These programs are preferred for their ability to quantify the value of services that trees provide in actual dollars. However, iTREE has been used in research studies to quantify street tree benefits (McPherson et al. 2002; Bonifaci 2010).

Functional benefits of trees such as the removal of air pollution by leaves, and the reduction of stormwater flows through root uptake and canopy interception, increase as tree canopy cover increases. Therefore, the economic benefits of street trees often correlate with physical tree variables such as trunk diameter and leaf surface area (Killicoat, Puzio & Stringer 2002; McPherson et al. 2002; Bonifaci 2010). Individual components of the net benefits are provided in Table 1. The following sections describe the individual economic benefits assigned to the environmental benefits discussed previously.

Stormwater Benefits

Street trees intercept large volumes of rainwater, depending on the site characteristics and the tree species (McPherson et al., 1999; Bonifaci 2010; Soares et al. 2011). Reduced stormwater runoff, resulting from interception by street trees, has the potential to reduce significantly the peak volumes of catchment runoff and the amount of costly stormwater-drainage infrastructure. It can also lower downstream-pollution levels and minimise the need for stormwater treatment systems, which are often expensive and difficult to install. Estimated annual reductions in stormwater runoff volume have ranged from 3.2 kL to 11.3 kL per tree, and the assigned annual values to stormwater reduction vary from US$2.78 to $47.85 per tree (Table 2). Most studies place the value assigned to stormwater reduction below US$7.00 per tree per year (McPherson et al., 1999; Killicoat, Puzio & Stringer 2002; Xiao & McPherson 2002; Bonifaci 2010; McPherson et al. 2011). However, two studies have valued the benefits at US$28.00 per tree per year (McPherson et al. 2005) and US$47.85 per tree per year (Soares et al. 2011). The reasons for these much higher values may be a change in the economic climate or an increase in the assigned benefit value. Trees clearly capture high volumes of stormwater but there is evidently a large discrepancy in the value assigned to their benefits. However, all research studies (Table 2) have shown a significant reduction in stormwater management costs through the presence of street trees.

Energy, CO_2 and Air Pollution Benefits

Street trees provide energy savings through their shading and cooling effects in summer and the wind-chill protection they offer in winter. Energy cost reductions due to the presence of street trees have been estimated at US$2.16 to $64.00/tree/year (Table 2), with these values likely to differ depending on local climatic conditions at the study sites. The reasons for the one exceptionally high saving of $64.00 (Killicoat, Puzio & Stringer 2002) are not clear but may be due to the very-different energy use assumptions and assigned cost values used in the study. Average savings in electricity due to street trees have been estimated at 95 kWh/tree/year, equating to an annual saving of US$15.00/tree/year (McPherson et al. 2005). A later study calculated a power saving of 30 kWh/tree/year (Moore 2009).

Reduction in energy use leads to reduced emission of CO_2, nitrogen dioxide (NO_2), very fine particulate matter (PM_{10}) and volatile organic compounds (VOCs). Air pollution is removed primarily through uptake via leaf stomata, although some gases are removed by other parts of the plant surface (Scott, McPherson & Simpson 1998; Nowak, Crane & Stevens 2006). Street trees also remove air pollution by intercepting airborne pollutant particles on leaves and branches (Nowak, Crane & Stevens 2006). The economic benefits from removing air pollution range from US$1.52 to $34.50/tree/year (Table 2). Varying results across studies are possibly due to different locations, tree sizes and tree species.

The economic benefit of CO_2 reduction by street trees is less than that of other benefits (Table 2), with three studies assigning a value of less than US$1.00/tree/year (McPherson et al. 2005; McPherson et al. 2011; Soares et al. 2011). A higher benefit of US$4.93/tree/year was attributed to a difference in tree species (McPherson et al. 1999). The value of $1.71/tree/year (Killicoat, Puzio & Stringer 2002) was based on the results of previous research studies that were used to calculate a benefit value.

Overall Economic Benefits

The overall economic benefits of street trees have been reported in two ways in this review, as a total benefit and as a net benefit, with expenditures such as maintenance and repairs subtracted in the calculation of net benefit. Urban street trees clearly generate significant economic benefits for communities and local governments, regardless of the reporting format (Table 3). The annual net benefit per tree is between US$21 and $159 (Table 3), most often around $50 (McPherson et al. 1999; Maco & McPherson 2003; McPherson et al. 2011).

Resident Perceptions

Residents' attitudes and perceptions of street trees and urban green spaces have been researched and documented through visual simulations, questionnaires and other methods (Hitchmough & Bonguli 1997; Lohr et al. 2004; Flannigan 2005; Schroeder, Flannigan & Coles 2006; Moskell & Broussard Allred 2013). Residents consistently express a positive view of street trees, and most residents believe that the benefits provided by street trees clearly outweigh any detriments (Sommer et al. 1989; Schroeder, Flannigan & Coles 2006). Attitudes to street trees remain positive due to their many perceived benefits, despite residents identifying potential problems such as falling branches, leaf litter, tree debris and infrastructure damage. High importance is placed by residents on the aesthetic and practical attributes of street trees such as beautification, shade provision, increased property values, added privacy and noise reduction. Most residents cite aesthetics and shade provision as the most important reasons for wanting street trees in their neighbourhoods (Summit & McPherson 1998; Flannigan 2005; Zhang et al. 2007; Moskell & Broussard Allred 2013). The majority of residents in American cities list the shading or cooling effect of street trees as their main benefit. The calming effect of street trees is also highly ranked (Lohr et al. 2004). Residents studied across a range of US cities including Toledo, OH, Davis, CA, and in Illinois and Michigan, communicated a preference for larger trees over smaller trees (Kalmbach & Kielbaso 1979; Summit & Sommer 1999; Heimlich et al. 2008).

Most research on residents’ perceptions of street trees has been undertaken in the USA (Kalmbach & Kielbaso 1979; Sommer et al. 1993; Sommer & Summit 1999; Heimlich et al. 2008). Extrapolation of findings from the temperate northern hemisphere can be problematic due to differences in climate, vegetation, landscape and cultural values (Williams 2002). For example, residents in Melbourne, Australia, identify a slight preference for medium trees over large or small trees (Williams 2002). The reasons for contrasting preferences in tree size are not clear although they could be the result of changes in the attitudes of residents as they become more aware of management problems associated with larger trees (Williams 2002). They may also be associated with different local environmental conditions, socio-economic and educational backgrounds, and durable perceptions of the value of trees (Kendal, Williams & Williams 2012; Kirkpatrick, Davidson & Daniels 2012). Residents who remove large trees from their gardens in Australian cities associate strongly with two distinguishable tree-attitude groups, ‘arboriphobes’ and ‘tree hazard minimizers’, among which household incomes and the proportions of residents with tertiary education are lower than most of the five other categories describing the residents (Kirkpatrick, Davidson & Daniels 2012).

Conflict with Urban Surfaces

Street trees provide multiple environmental, social and economic benefits but they can also cause disruptive and costly damage to pavement infrastructure. Preventative measures have been researched to try to reduce the incidence of damage, increase tree health, and decrease pavement and tree replacement costs.

Damage

Growth of tree roots can cause extensive pavement damage such as cracking and uplifting of pavement surfaces and kerbing (Day 1991; Francis, Parresol & Marin de Patino 1996; Blunt 2008). Infrastructure damage has high cost implications including pavement maintenance, pavement repair or replacement, injury compensation payments, and loss or replacement of the street tree. Urban forestry managers in California and city residents in Australia both report infrastructure damage as one of the most common reasons for tree removal (Costello et al. 2000; Kirkpatrick, Davidson, & Daniels 2012). Many of these conflicts are preventable with proper consideration and planning for long-term tree growth, and by using appropriate materials and installation procedures for pavements and trees (Coder 1998). Street trees are used frequently as a scapegoat for poor workmanship, inappropriate design and unsuitable engineering practices (Coder 1998).

Root growth is commonly limited by drought, waterlogging, hypoxia, soil compaction, salinity and high concentrations of heavy metals (Bengough et al. 2011; Franco et al. 2011). This can result in street tree roots proliferating in micro-sites that are more favourable for growth. Soil nearest the surface often has good aeration and the highest nutrient concentrations (Jobbágy & Jackson 2001; Göransson et al. 2006; Li et al. 2013), with more than 70% of coarse woody roots often found within 50 cm of the soil surface in tree plantations (Mou et al. 1995; Puhe 2003). The temperature of pavements can increase rapidly during the daytime, transferring heat into the soil below. At dusk, pavement surfaces cool more rapidly than the underlying soil and this causes condensation to form on the underside of the pavement (Barker & Peper, 1995). Damage often occurs as a result of tree roots growing at shallow depths and expanding at the interface of the paving structures and the top soil layers (Lesser 2001). Some researchers have concluded that sidewalks can actually promote root growth (D'Amato et al. 2002).

Fertile soil and growing space are often limited in urban environments, and one of the greatest challenges for street trees is the volume of root-penetrable soil available to support healthy growth (Lindsey & Bassuk 1992; Grabosky et al. 1998a). Trees require a porous soil through which roots can proliferate freely, while most urban infrastructure requires a load bearing base that will support pedestrian and vehicular traffic (Grabosky et al. 1998b). The level of soil compaction required to support the expected pavement loading can often be problematic for planted trees. Compaction of soil restricts growth by narrowing the soil pore spaces through which roots tips extend and young roots expand radially (Grabosky, Hoffner & Bassuk 2009). Tree roots often encounter compacted soil as they grow toward the edges of planting pits, and this hinders growth by limiting access to oxygen, water and nutrients (Loh, Grabosky & Bassuk 2003; Lucke et al. 2011; Tracy et al. 2011). A lack of adequate rooting space is probably the main factor affecting street trees' long-term access to water and nutrients (Grabosky & Bassuk 1995).

Other factors that reduce street tree health in highly-urban areas include vandalism, traffic congestion, building development, the use of de-icing salts, and air pollution

(Blunt 2008; Lu et al. 2010). Urban street trees generally have a lower life expectancy than their counterparts in urban parks and dedicated green spaces, possibly because of higher temperatures, restricted water and nutrient availability under impervious surfaces, and vandalism. For example, the average life span of street trees across 20 American cities was found to be 13 years in highly urban areas, increasing to 37 years in surrounding residential areas (Skiera & Moll 1992). Urban street trees in Baltimore, MD, have an average life span of 15 years, but with only 30% of the trees living beyond 15 years (Nowak, Kuroda & Crane 2004). Meta-analysis of life-expectancy literature provided an estimated annual survival rate of 96% and an average life span of 22 years for *Acer campestre* trees in the business district of Philadelphia, PA (Roman & Scatena 2011). The longer life expectancies in this study compared with earlier studies (Skiera & Moll 1992; Nowak, Kuroda & Crane 2004) were presumably due to variations in species, sites and environmental conditions, or to the models used to extrapolate life expectancy. Despite the challenges faced by street trees and those responsible for maintaining them, trees continue to be planted in urban settings as they are an integral and valuable part of urban life.

Pavement damage and poor street tree health can often be resolved by making appropriate choices prior to planting. Street trees have a greater chance of survival when planted in lawn strips (78%) than in sidewalk planting pits (67%) (Lu et al. 2010). Roots can quickly outgrow planting pits and spread beneath pavements surfaces, causing uplift and cracking of the pavements (Kristoffersen 1998). Landscapers need to select tree species carefully to ensure that trees will be able to grow in the specific site and space conditions provided, without harming the surrounding infrastructure. There is often a strong correlation between tree size and the degree of damage to infrastructure (Wagar & Barker 1983; Francis, Parresol & Marin de Patino 1996; Randrup, McPherson & Costello 2001), and the probability of damage is reduced with the use of smaller tree species and increasing planting distances to the pavement (Wagar & Barker 1983; Francis, Parresol & Marin de Patino 1996).

Resulting Costs

Pavement damage due to tree roots has significant budgetary implications for local government and transport authorities. Many authorities spend millions of dollars each year on repairing damage to infrastructure from street trees (Hillsborough County

2010; McPherson 2000). The costs often include pavement repair or replacement, tree removal and replacement, and legal expenses and payments due to injury claims (Foster, Lowe & Winkelman 2011). Estimated repairs from tree damage across 15 cities in the United States have averaged US$3.01/tree (McPherson & Peper 1996). Approximately US$71 million annually has been spent state-wide across California due to conflicts between street trees and infrastructure (McPherson 2000). Much of this was spent on pavement repairs (US$23 million) with the remaining expenditure consisting of litigation costs due to trip- and fall-claims by residents, maintenance costs associated with removing and replacing trees, root pruning, tree and pavement inspections, and the installation of root barriers.

Seventeen cities across the United States have reported spending a total of US$1.28 million, or US$0.17 per capita, on reducing conflicts between street trees and paving infrastructure, with 56% spent on root pruning and 21% spent on grinding and ramping of sidewalks to prevent trips and falls on displaced paving surfaces (McPherson 2000). The remaining 23% was spent on a combination of other methods including root barriers, pavement narrowing and tree-well engineering (McPherson 2000). Another preventative measure was the narrowing of pavements to allow room for roots to spread. However, this was the most expensive preventative measure at US$151/tree (McPherson 2000). In addition to the mitigation costs, the surveyed cities spent a total of US$1.6 million for tree removal and US$0.3 million for tree replacement (McPherson 2000). The cost of repairs from street tree damage was US$9 million in one Florida county alone in 2009, with 55 miles of pavement requiring repairs, equating to US$101.38 per metre of repaired sidewalk (Hillsborough County 2010). The potential costs for pavement reconstruction and repair in this county by the year 2020 may be as high as US$30 million annually (Hillsborough County 2010).

Litigation costs arising from pavement damage by tree roots are also significant. The City of Cincinnati spent US$2.0 million annually to repair pavements as part of a sidewalk safety program but, in one year alone, the City was involved in 21 lawsuits seeking damages for personal injury caused by damaged pavements (Sydnor et al. 2000). Fourteen Californian cities have reported a combined annual trip- and fall-payout of US$1.77 million due to pavement damage from tree roots (McPherson 2000). The highest single payment was US$120,000 and the average payment was US$6,245 (McPherson 2000).

Preventative Measures

Continuing use of the pavement by pedestrians becomes increasingly difficult as trees become larger (Smiley et al. 2006). A tree-friendly approach to conflicts between trees and pavements is needed desperately to prevent the continued removal of street trees (Morgenroth, Buchan & Scharenbroch 2013). Urban forest managers have relied previously on selecting a suitable tree species or using the most appropriate planting technique to minimise potential conflicts between trees and pavements. This is often not practicable due to site constraints, budgets and residents' preferences. However, an increased understanding of the problems, costs and risks associated with pavement damage has led to the development of new preventative measures to minimise these conflicts. Root-zone based preventative strategies include soil and water management techniques that aim to guide roots away from pavement infrastructure and encourage deeper root growth and more-even root distribution (Costello & Jones 2003). These include the use of root barriers, structural soils, and pervious surfaces with underlying drainage layers to minimise pavement damage by tree roots.

Root Barriers

Root barriers were developed in the 1970s to provide a commercially viable solution to damage caused by street trees (Randrup, McPherson & Costello 2001). They are designed to confine root growth within designated areas and deflect root growth away from infrastructure. There are three main types of root barrier: traps, inhibitors and deflectors (Coder 1998). Traps are composed of woven-nylon or copper screen, which allow root tips to penetrate through small holes. These barriers allow gas exchange and water movement but they can cause tree instability by restricting the development of large roots in one or more directions (Costello & Jones 2003; Morgenroth 2008). Inhibitors are often composed of fabric impregnated with a chemical control agent, such as slow-release herbicide, to contain root growth. Deflectors are generally barriers made from solid plastic, metal or wood that alters root orientation by deflecting roots away from the barrier. They are normally installed vertically along the sides of roads or kerbs to keep tree roots from reaching the pavement structure.

Root barriers can be an effective treatment to prevent root growth when used correctly (Barker & Peper 1995) but they are sometimes least effective in the urban locations where they are most needed (Thompson 2006). Root barriers are particularly effective at deterring root growth from infrastructure in well-drained and non-compacted soils but these sub-surface conditions are rare in urban environments (Thompson 2006). For instance, root growth of oak (*Quercus virginia*) and sycamore (*Platanus occidentalis*) trees at a site with a high water table was similar to root growth in plots with a bio-barrier (an inhibitor type of barrier), but root distribution was affected greatly by the underlying water (Gilman 1996). Trees of the two species were planted alternately at 1.8 m spacing in soil between two trenches (15 m long, 5 cm wide, 30 cm deep and 1.5 m apart) that had a continuous length of bio-barrier installed vertically down the middle of each trench. Control trees were planted without bio-barriers. At 3 years after planting, 80% of oak roots and 72% of sycamore roots (>3-mm diameter) had reached 0.9 m horizontally away from the trunk in the top 30 cm of soil in plots without a bio-barrier, compared with 42% of oak and 38% of sycamore roots in plots with a barrier. The bio-barrier forced roots deeper into the soil but the high water table caused many roots to return to the soil surface once they had grown under the barrier. The possibility that roots proliferated in the less-compacted and better-aerated soil created by trench excavation was a major reason proposed for the roots growing upwards rather than deeper into the soil (Gilman 1996).

Structural Soils

Structural soils were developed to improve street tree growth in paved situations, while also providing a supporting base with sufficient load-bearing capacity for pedestrians and light vehicles (Grabosky, Bassuk & Marranca 2002). The pore spaces of typical urban soils collapse when they are compacted, limiting the supply of water, nutrients and oxygen to tree roots. Structural soils are generally more porous (30-35%) than urban soils, aiding tree growth and improving stormwater infiltration (Grabosky & Bassuk 1995; Grabosky et al. 1998b; Bartens et al. 2008; Day & Dickinson 2008; Xiao & McPherson 2011). Structural soils have been used to encourage deeper root growth and reduce uplifting of pavements and kerbs (Smiley et al. 2006; Buhler, Kristoffersen & Larsen 2007). The additional rooting space provided by structural soils also supports a larger canopy area, which can intercept and absorb larger volumes of rainfall. This potentially reduces stormwater infrastructure costs and decreases flooding (Bartens et al. 2009).

The length of tree roots is generally greater in structural soils than in standard urban soils (Grabosky et al. 1998b; Grabosky, Bassuk & Marranca 2002; Loh, Grabosky & Bassuk 2003; Smiley 2008). The roots of *Tilia cordata*, *Acer campestre* and *Malus* sp. trees grow more deeply in a structural soil, composed of a soil/gravel mix, than a standard soil sub-base under pavements (Grabosky et al. 1998b). Roots of *Tilia cordata* and *Acer campestre* did not penetrate deeper than 20 cm into the soil, or into the subgrade, of the standard pavement profile. Roots of one of the species (*Malus* sp.) only penetrated 1–2 cm into the subgrade. The wider pore spaces created by the soil/gravel mix appeared to increase aeration to a greater depth, leading to deeper root growth, despite some compaction of the structural soil (Grabosky et al. 1998b). The total length of *Prunus serrulata* roots is approximately 11% higher in a structural soil than in an urban soil that was decompacted by a backhoe excavator (Smiley 2008). A distinct difference in tree growth, foliage colour and root growth is often noted in trees growing in structural soils compared with compacted urban soils (Smiley 2008).

Comparisons of Root Barriers and Structural Soils

A 10-year study, comparing five root barrier and structural soil methods for reducing concrete-pavement damage by *Platanus* × *acerifolia* roots, showed that damage is often greatest when a high surface area of roots grows in contact with the pavement surface (Smiley 2008). Surface roots from four of the five trees in control pavements caused cracking at joints across the surface, as did roots from three out of five trees installed with a vertical polyethylene root barrier or with a structural soil that was 10 cm deep and composed of 5 parts gravel : 2 parts clay-loam. Pavement cracking was not evident in the other three treatments: a vertical 'DeepRoot Tree Root Universal Barrier'; a 10-cm thick layer of gravel; or a 10-cm horizontal layer of 'Foamular' (an extruded polystyrene-foam board similar to styrofoam used for building insulation). The two vertical treatments (the DeepRoot barrier and the polyethylene barrier) both reduced total root length and mean root diameter. However, the three treatments with the greatest root surface area in contact with the pavement (the control, the structural soil, and the polyethylene barrier) were the ones that permitted pavement cracking (Smiley 2008). Trees in the gravel plots caused minimal sidewalk lift (<1.5 cm) compared with structural soils (>2.5 cm) (Smiley 2008). The 'Foamular' and gravel treatments encouraged deeper root growth than other treatments (Smiley 2008).

Roots of *Platanus orientalis* trees also grow deeper under standard concrete pavements with a gravel sub-base than under pavements with a range of other root barriers and structural soils (Gilman 2006). Roots within plots with a 22-cm gravel layer were found 19 cm below the soil surface, whereas roots in plots with a control urban soil or a Deeproot Biobarrier® only reached 11 cm below the surface. The use of a root barrier in conjunction with a horizontal under-pavement treatment, such as a gravel layer, might further reduce pavement damage, although this hypothesis remains to be tested (Smiley 2008).

Pervious Surfaces

Another approach to making the soil beneath pavements conducive to street tree growth is the use of pervious pavements (Volder, Watson & Viswanathan 2009; Morgenroth & Visser 2011; Mullaney & Lucke 2014). Pervious pavements potentially increase the availability of water and oxygen in the tree root zone, reducing some of the below-ground stress imposed on trees (Viswanathan et al. 2011). Pervious surfaces can also reduce stormwater runoff by allowing water to infiltrate through the paving surface where it may be harvested for reuse, released slowly into the underlying soil, or discharged into stormwater drainage systems or receiving waters (Lucke & Beecham 2011). The drainage layers typically installed under pervious pavements, between the paving surface and the soil, may help to increase root depth and tree stability and decrease damage by tree roots (Janssen 2008; Smiley 2008; Morgenroth & Buchan 2009; Volder, Watson & Viswanathan 2009; Johnson, Cameron & Moore 2011; Mullaney et al. 2012; Mullaney & Lucke 2014). Repeated drying of the drainage layers beneath the pavement surface is expected to suppress root growth, encouraging root proliferation at deeper layers where moisture levels are more stable.

Ability to increase the health of *Platanus orientalis* street trees has been compared between a concrete porous pavement, with or without a 20 cm deep aggregate sub-base, and a non-porous concrete pavement, also with or without a sub-base (Morgenroth 2011; Morgenroth & Visser 2011). In the absence of the sub-base, trees in the porous concrete surface were 28% taller at 18 months and had 400 g greater root biomass than trees in the non-porous pavement. There was minimal difference in tree height and root biomass between the pavement types in the presence of a sub-base. Roots grew deeper under pavements without a gravel sub-base. For example, only 42% of roots were found in the uppermost 10 cm of the soil under pavements without a sub-base. However, 56% of roots were found in the uppermost 10 cm of the soil under pavements with a sub-base (Morgenroth 2011).

The growth of *Pyrus calleryana* trees in permeable pavements with two different gravel sub-base designs has also been compared with the growth of trees in impermeable concrete-block pavements (Mullaney et al. 2012). One of the permeable pavement designs included a 10-cm deep sub-base of level gravel. The other included a sloping gravel sub-base that was 25-cm deep at its deepest point. Trees in the level-gravel permeable pavement grew slightly taller than those in the sloping-gravel permeable pavement (2%) and the impermeable concrete-block control pavement (5%) (Mullaney et al. 2012). These studies have provided encouraging results but the study durations have been too short to make long-term predictions on the effects of pervious pavements on street tree growth and infrastructure life spans. Further research is required to determine the longer-term engineering, environmental and other benefits of pervious pavements.

Conclusion

Street trees play an integral role in supporting healthy urban communities through the provision of environmental, social and economic benefits. They improve the liveability of towns and cities through shade provision, stormwater reduction, improved air quality, and habitat and landscape connectivity for urban fauna. Social benefits include a sense of community and safety, and reduced rates of crime. City residents consistently express a positive view of street trees, with the majority believing that the benefits of trees outweigh their negative impacts. High importance is assigned by residents to aesthetic and practical attributes, including beautification, shade provision, and increased property values. However, the economic values of street trees are often underappreciated, while the costs of damage by trees cause are widely reported. The ability to quantify environmental benefits in monetary terms allows the benefits of street trees to be easily understood and reported by policy and decision makers.

The installation, survival and growth of street trees can often be challenging in urban environments that have ever-increasing areas of impervious surface. Urban surfaces can reduce the moisture, nutrients and soil volume available for plant growth, resulting in tree roots surviving and growing in sites where they are likely to cause damage to pavements and other infrastructure. The high costs of pavement repair or replacement, tree removal and replacement, and litigation have led to a number of treatments being trialled to help street trees grow in urban environments. Earlier treatments included root barriers and structural soils. Recently, pervious pavements have emerged as a promising technology to increase street tree health and reduce pavement damage.

A large proportion of the literature available for review emanated from temperate regions of the globe including the United States and Europe. This may be the result of increased funding available for research in these regions, and increased interest or access to information about street trees. This geographic limitation on available literature restricts the scope and conclusions of the review, and further research on street trees is required in tropical regions. An increase in information on street tree benefits, damage to infrastructure by trees, and methods to prevent infrastructure damage will be highly valuable in guiding the management of street trees in urban environments.

References

Anderson, LM & Cordell, HK 1988, 'Influence of trees on residential property values in Athens, Georgia (U.S.A): a survey based on actual sales prices', *Landscape and Urban Planning*, vol 15, no. 1, pp. 153-164.

Alvey, AA 2006, 'Promoting and preserving biodiversity in the urban forest', *Urban Forestry and Urban Greening*, vol. 5, no. 4, pp. 195-201.

Angold, PG, Sadler, JP, Hill, MO, Pullin, A, Rushton, S, Austin, K, Small, E, Wood, B, Wadsworth, R, Sanderson, R & Thompson, K 2006, 'Biodiversity in urban habitat patches', *Science of the Total Environment*, vol. 360, no. 1-3, pp. 196-204.

Armson, D, Stringer, P & Ennos, AR 2013, 'The effect of street trees and amenity grass on urban surface water runoff in Manchester, UK', *Urban Forestry and Urban Greening*, vol. 12, no. 3, pp. 282-286.

Barker, PA & Peper, PJ 1995, 'Strategies to prevent damage to sidewalks by tree roots', *Arboriculture Journal*, vol. 19, pp. 295-309.

Bartens, J, Day, SD, Harris, JR, Dove, JE & Wynn, TM 2008, 'Can urban tree roots improve infiltration through compacted subsoils for stormwater management?', *Journal of Environmental Quality*, vol. 37, no. 6, pp. 2048-2057.

Bartens, J, Day, SD, Harris, JR, Wynn, TM & Dove, JE 2009, 'Transpiration and root development of urban trees in structural soil stormwater reserves', *Environmental Management*, vol. 44, no. 4, pp. 646-657.

Bengough, AG, McKenzie, B., Hallett, PD & Valentine, TA 2011, 'Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits', *Journal of Experimental Botany*, vol. 62, no. 1, pp. 59-68.

Blunt, SM 2008, 'Trees and pavements – are they compatible?', *Arboriculture Journal: International Journal of Urban Forestry*, vol. 31, no. 2, pp. 73-80.

Bonifaci, E 2010, 'Selling the urban forest - calculating the environmental and economic benefits of street trees', Master of Landscape Architecture, Harvard University, United States of America.

Buhler, U, Kristoffersen, P & Larsen, SU 2007, 'Growth of street trees in Copenhagen with emphasis on the effect of different establishment concepts', *Arboriculture and Urban Forestry*, vol. 33, no. 5, pp. 330-337.

Burden, D 2006, *22 benefits of urban street trees*, viewed 3 May 2014, <www.michigan.gov/documents/dnr/22_benefits_208084_7.pdf>.

Cappiella, K, Schueler, T & Wright, T 2005, *Urban Watershed Forestry Manual: Part 1 – Methods for Increasing Forest Cover in a Watershed*. Newton Square, PA: United States Department of Agriculture, Forest Service, Northeastern Area, State and Private Forestry.

Coder, KD 1998, *Tree roots and infrastructure damage*. Tree root growth control series. March. University of Georgia Cooperative extension service forest resource publication. FOR98-8.

Costello, LR, McPherson, EG, Burger, D, Perry, EJ & Kelley, D (eds) (2000-2001). *Strategies to reduce infrastructure damage by tree roots*. Proceedings of a Symposium for Researchers and Practitioners. International Society of Arboriculture. Western Chapter, Cohasset, California.

Costello, LR & Jones, KS 2003, *Reducing infrastructure damage by tree roots: a compendium of strategies.* Western Chapter of the International Society of Arboriculture, Cohasset, California.

D'Amato, N, Sydnor, TD, Kane, M, Hunt, R & Bishop, B 2002, 'Which comes first, the root or the crack?', *Journal of Arboriculture*, vol. 28, no. 6, pp. 277-282.

Davis, A, Taylor, CE & Major, RE 2012, 'Seasonal abundance and habitat use of Australian parrots in an urbanised landscape', *Landscape and Urban Planning*, vol. 106, no. 2, pp.191-198.

Day, RW 1991, 'Damage of structures due to tree roots', *Journal of Performance of Construction Facilities*, vol. 5, no. 3, pp. 200-207.

Day, SD & Dickinson, SB 2008, *Managing stormwater for urban sustainability using trees and structural soils*. Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Donovan, GH & Butry, DT 2009, 'The value of shade: Estimating the effect of urban trees on summertime electricity use', *Energy and Buildings*, vol. 41, pp. 662-668.

Donovan, GH & Butry, DT 2010, 'Trees in the city: valuing street trees in Portland, Oregon', *Landscape and Urban Planning*, vol. 94, no. 2, pp. 77-83.

Donovan, GH & Prestemon, JP 2012, 'The effects of trees on crime in Portland, Oregon', *Environment Behavior*, vol. 44, no. 1, pp. 3-30.

Donovan, GH, Butry, DT, Michael, YL, Prestemon, JP, Liebhold, AM, Gatziolis, D & Mao, MY 2013, 'The relationship between trees and human health: evidence from the spread of the Emerald ash borer', *American Journal of Preventative Medicine*, vol. 44, no. 2, pp. 139-145.

Evelyn, MJ, Stiles, DA & Young, RA, 2004, 'Conservation of bats in suburban landscapes: roost selection by Myotis yumanensis in a residential area in California', *Biological Conservation*, vol. 115, no. 3, pp. 463-473.

Faast, R & Cooling, M 2010, *Independent inquiry into management of trees on public land (2010) Issues paper*. Ecological associates report EL001-1-A prepared for Independent inquiry into trees on public land, Adelaide.

Ferrini, F & Fini, A 2010, 'Sustainable management techniques for trees in the urban areas', *Journal of Biodiversity and Ecological Sciences*, *vol.* 1, no. 1, pp. 1-20.

Flannigan, J 2005, 'An evaluation of resident's attitudes to street trees in southwest England', *Arboriculture Journal*, vol. 28, no. 4, pp.219-241.

Foster, J, Lowe, A & Winkelman, S 2011, *The value of green infrastructure for urban climate adaption*. The Centre for Clean Air Policy, Washington.

Francis, JK, Parresol, BR & Marin de Patino, J 1996, 'Probability of damage to sidewalks and curbs by street trees in the tropics', *Journal of Arboriculture*, vol. 22, no. 4, pp. 193-197.

Franco, JA, Bañon, S, Vicente, MJ, Miralles, J & Martínez-Sánchez, JJ 2011, 'Root development in horticultural plants grown under abiotic stress conditions – a review,' *Journal of Horticultural Science and Biotechnology*, vol. 86, no. 6, pp. 543-556.

Gill, SE, Handley, JF, Ennos, AR & Pauleit, S 2007, 'Adapting cities for climate change: the role of the green infrastructure', *Built Environment*, vol. 33, no. 1, pp. 115-133.

Gilman, EF 1996, 'Root barriers affect root distribution', *Journal of Arboriculture*, vol. 22, no. 3, pp. 151-154.

Gilman, EF 2006, 'Deflecting roots near sidewalks', *Arboriculture and Urban Forestry*, vol. 32, no. 1, pp. 18-23.

González-García, A, Belliure, J, Gómez-Sal, A & Dávila, P 2009, 'The role of urban greenspaces in fauna conservation: the case of the iguana *Ctenosaura similis* in the 'patios' of León city, Nicaragua', *Biodiversity Conservation*, vol. 18, no. 7, pp. 1909-1920.

Göransson, H, Wallander, H, Ingerslev, M & Rosengren, U 2006, 'Estimating the relative nutrient uptake from different soil depths in *Quercus robur*, *Fagus sylvatica* and *Picea abies', Plant and Soil*, vol. 286, no. 1-2, pp. 87-97.

Grabosky, J & Bassuk, N 1995, 'A new urban tree soil to safely increase rooting volumes under sidewalks', *Journal of Arboriculture*, vol. 21, no. 4, pp. 187-201.

Grabosky, J, Bassuk, N, Irwin, N & Van Es, H 1998a, 'Structural soil investigations at Cornell University', in D Neeley & G Watson (eds), *The Landscape Below Ground II: Proceedings of an International Workshop on Tree Root Development in Urban Soils,* International Society of Arboriculture, Champaign, Illinois, pp. 203-209.

Grabosky, J, Bassuk, N, Irwin, L & Van Es, H, 1998b, 'Pilot field study of structural soil materials in pavement profiles, in D Neeley & G Watson (eds), *The Landscape Below Ground II: Proceedings of an International Workshop on Tree Root Development in Urban Soils,* International Society of Arboriculture, Champaign, Illinois, pp. 210-221.

Grabosky, J, Bassuk, N & Marranca. BZ 2002, 'Preliminary findings from measuring street tree shoot growth in two skeletal soil installations compared to tree lawn plantings', *Journal of Arboriculture*, vol. 28, no. 2, pp. 106-108.

Grabosky, J, Hoffner, E & Bassuk, N 2009, 'Plant available moisture in stone soil media for use under pavement while allowing urban tree root growth', *Arboriculture and Urban Forestry*, vol. 35, no. 5, pp. 271-278.

Heimlich, J, Sydnor, TD, Bumgardner, M & O'Brien, P, 2008, 'Attitudes of residents toward street trees on four streets in Toledo, Ohio, U.S. before removal of ash trees *(Fraxinus spp.)* from emerald ash borer *(Agrilus planipennis)', Arboriculture and Urban Forestry*, vol. 34, no. 1, pp. 47-53.

Hillsborough County Florida 2010, *Sidewalks and street trees reported by planning and growth management department and public works department*, viewed 12 April 2014, <http://www.slideshare.net/kimford/sidewalks-report-draft-updated-09152010>.

Hitchmough, JD & Bonguli, AM 1997, 'Attitudes of residents of a medium sized town in southwest Scotland to street trees', *Landscape Research*, vol. 22, no. 3, pp. 327-337.

Iakovoglou, V, Thompson, J, Burras, L & Kipper, R 2001, 'Factors related to tree growth across urban-rural gradients in the Midwest, USA', *Urban Ecosystems*, vol. 5, no. 1, pp.71-85.

Ikin, K, Knight, E, Lindenmayer, DB, Fischer, J & Manning, AD 2013, 'The influence of native versus exotic streetscape vegetation on the spatial distribution of birds in suburbs and reserves', *Diversity and Distributions*, vol. 19, no. 3, pp. 294-306.

Jobbágy, EG & Jackson, RB 2001, 'The distribution of soil nutrients with depth: Global patterns and the imprint of plants', *Biogeochemistry*, vol. 53, pp. 51-77.

Johnson, T, Cameron, DA & Moore, GM 2011, 'Trees, stormwater, soil and civil infrastructure: synergies towards sustainable urban design for a changing climate', paper presented at the ISA International Conference and Tree Climbing Championships, Sydney, Australia.

Jones, EL & Leather, SR 2012, 'Invertebrates in urban areas: A review', *European Journal of Entomology*, vol.109, no. 4, pp. 463-478.

Kalmbach, KL & Kielbaso, JJ 1979, 'Resident attitudes toward selected characteristics of street trees plantings', *Journal of Arboriculture*, vol. 5, no. 6, pp. 124-129.

Kendal, D, Williams, NSG & Williams, KJH 2012, 'Drivers of diversity and tree cover in gardens, parks and streetscapes in an Australian city', *Urban Forestry and Urban Greening*, vol. 11, no. 3, pp.257-265.

Killicoat, P, Puzio, E & Stringer, R 2002, 'The economic value of trees in urban areas: estimating the benefits of Adelaide's street trees', paper presented at the 3rd National Street Tree Symposium, Adelaide, Australia.

Kirkpatrick, JB, Davison, A & Daniels, GD 2012, 'Resident attitudes towards trees influence the planting and removal of different types of trees in Australian cities', *Landscape and Urban Planning*, vol. 107, no. 2, pp.147-158.

Kjelgren, R & Clark, JR 1994, 'Urban microclimates and growth of sweet gum street trees', *Arboriculture Journal*, vol. 18, no. 4, pp. 401-417.

Konvicka, M & Kadlec, T 2011, 'How to increase the value of urban areas for butterfly conservation? A lesson from Prague nature reserves and parks', *European Journal of Entomology*, vol. 108, pp. 219-229.

Kristoffersen, P 1998, 'Designing urban pavement sub-bases to support trees', *Journal of Arboriculture*, vol. 24, no. 3, pp.121-126.

Kuo, FE & Sullivan, WC 2001, 'Environment and crime in the inner city: does vegetation reduce crime?', *Environment Behavior*, vol. 33, no. 3, pp. 343-367.

Lambert, MS, Massei, G, Bell, J, Berry, L, Haigh, C & Cowan, DP 2009, 'Reproductive success of rose-ringed parakeets Psittacula krameri in a captive UK population', *Pest Management Science*, vol. 65, no.11 , pp. 1215-1218.

Lee, JG & Heaney, JP 2003, 'Estimation of urban imperviousness and its impacts on storm water systems', *Journal of Water Resource Planning and Management,* vol. 129, no. 5, pp. 419-426.

Lesser, LM 2001, 'Hardscape damage by tree roots', *Journal of Arboriculture*, vol. 27, no. 5, pp. 272-276.

Li, H, Li, J, He, Y, Li, S, Liang, Z, Peng, C, Polle, A & Luo, Z-B, 2013, 'Changes in carbon, nutrients and stoichiometric relations under different soil depths, plant tissues and ages in black locust plantations', *Acta Physioligiae Plantarum*, vol. 35, no. 10, pp. 2951-2964.

Lindsey, P and Bassuk, N 1992, 'Redesigning the urban forest from the ground below: a new approach to specifying adequate soil volumes for street trees', *Arboriculture Journal*, vol. 16, no. 1, pp. 25-39.

Loh, FCW, Grabosky, JC & Bassuk, NL 2003, 'Growth response of Ficus benjamina to limited soil volume and soil dilution in a skeletal soil container study', *Urban Forestry and Urban Greening*, vol. 2, 53-62.

Lohr, VL, Pearson-Mims, CH, Tarnai, J & Dillman, A 2004, 'How urban residents rate and rank the benefits and problems associated with trees in cities', *Journal of Arboriculture*, vol. 30, no. 1, pp. 28-35.

Lu, JWT, Svendsen, ES, Campbell, LK, Greenfield, J, Braden, J, King, KL & Falxa-Raymond, N 2010, 'Biological, social, and urban design factors affecting young street tree mortality in New York City', *Cities and the Environment*, vol. 3, no. 1, pp. 1-15.

Lucke, T & Beecham, S 2011, 'Field investigations of clogging in a permeable pavement system', *Building Research and Information*, vol. 39, no. 6, pp. 603-615.

Lucke T, Johnson, T, Beecham, S, Cameron, D & Moore, G 2011, 'Using permeable paving to promote street tree health', paper presented at the 12th International Conference of Urban Drainage, Porto Alegre, Brazil, 10 - 15 September 2011.

Maco, SE & McPherson, EG 2003, 'A practical approach to assessing structure, function, and value of street tree populations in small communities', *Journal of Arboriculture*, vol. 29, no. 2, pp. 84-97.

McPherson, EG, Nowak, DJ & Rowntree, RA 1994, *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project.* USDA Forest Service Northeastern Forest Experiment Station General Technician Report. NE-186.

McPherson, EG & Peper, PJ 1996, ‘Costs of street tree damage to infrastructure’, *Arboriculture Journal*, vol. 20, 143-160.

McPherson, EG, Simpson, JR, Peper, PJ & Xiao, Q 1999, ‘Benefit cost analysis of Modesto’s municipal urban forest’, *Journal of Arboriculture*, vol. 25, no. 5, pp.235-248.

McPherson, EG 2000, ‘Expenditures associated with conflicts between street tree root growth and hardscape in California, United States’, *Journal of Arboriculture*, vol. 26, no.6, pp. 289-297.

McPherson, EG, Maco, SE, Simpson, JR, Peper, PJ, Xiao, Q, VanDerZanden, AM & Bell, N 2002, *Western Washington and Oregon community tree guide: benefits, costs and strategic planting*. International Society of Arboriculture, Pacific Northwest Chapter.

McPherson, EG, Simpson, JR, Peper, PJ, Maco, SE & Xiao, Q 2005, ‘Municipal forest benefits and costs in five U.S cities’, *Journal of Forestry*, vol. 103, no. 8, pp. 411-416.

McPherson, EG 2007, ‘Benefit-based tree valuation’, *Arboriculture and Urban Forestry*, vol. 33, no. 1, pp. 1-11.

McPherson, EG, Simpson, JR, Xiao, W & Wu, C 2011, ‘Million trees Los Angeles canopy cover and benefit assessment’, *Landscape and Urban Planning*, vol. 99, no. 1, pp. 40-50

Miller, JD, Kim, D, Kjeldsen, TR, Packman, J, Grebby, S & Dearden, R 2014, ‘Assessing the impact of urbanisation on storm runoff in a peri-urban catchment using historical change in impervious cover’, *Journal of Hydrology*, vol. 515, 59-70.

Moore, G 2009, ‘Urban trees: worth more than they cost’, in D Lawry, J Gardner, & M Bridget (eds), *Proceedings of the 10th National Street Tree Symposium*, Adelaide, South Australia: Adelaide University, pp. 7-14.

Morgenroth, J 2008, ‘A review of root barrier research’, *Arboriculture and Urban Forestry*, vol. 34, no. 2, pp. 84-88.

Morgenroth, JM & Buchan, GD 2009, ‘Soil moisture and aeration beneath pervious and impervious pavements’, *Arboriculture and Urban Forestry*, vol. 35, no. 3, pp. 135-141.

Morgenroth, J 2011, ‘Root growth response of *Platanus orientalis* to porous pavements’, *Arboriculture and Urban Forestry*, vol. 37, no. 2, pp. 45-50.

Morgenroth, J & Visser, R 2011, 'Aboveground growth response of *Platanus orientalis* to porous pavements', *Arboriculture and Urban Forestry*, vol. 37, no. 2, pp. 1-5.

Morgenroth, J, Buchan, G & Scharenbroch, BC 2013, 'Belowground effects of porous pavements – Soil moisture and chemical properties', *Ecological Engineering,* vol. 51, 221-228.

Moskell, C & Broussard Allred, S 2013, 'Residents' beliefs about responsibility for the stewardship of park trees and street trees in New York City', *Landscape and Urban Planning,* vol. 120, 85-95.

Mou, P, Jones, RH, Mitchell, RJ & Zutter, B 1995, 'Spatial distribution of roots in sweetgum and loblolly pine monocultures and relations with above-ground biomass and soil nutrients', *Functional Ecology*, vol. 9, no. 4, pp. 689-699.

Mullaney, J, Lucke, T, Johnson, T, Cameron, D & Moore, G 2012, 'Pervious paving systems: potential use for promoting street tree health, reducing pavement damage and reducing stormwater flows', paper presented at the SUDSnet International Conference 2012 "Multiple Benefits for Surface Water Management", Coventry, UK, 4 - 6 September 2012.

Mullaney, J & Lucke, T 2014, 'Practical review of pervious pavement designs', *Clean – Soil, Air, Water*, vol. 42, no.2, pp. 111-124.

Nowak, DJ, Kuroda, M & Crane, DE 2004, 'Tree mortality rates and tree population projects in Baltimore, Maryland, USA', *Urban Forestry and Urban Greening*, vol. 2, 139-147.

Nowak, DJ, Crane, DE and Stevens, JC 2006, 'Air pollution removal by urban trees and shrubs in the United States', *Urban Forestry and Urban Greening*, vol. 4, 115-123.

Pandit, R & Laband, DN 2010, 'Energy savings from tree shade', *Ecological Engineering*, vol. 69, 1324-1329.

Pandit, R, Polyakor, M & Sadler, R 2012, 'The importance of tree cover and neighbourhood parks in determining urban property values', paper presented at the 56th AARES Annual Conference, Fremantle, Western Australia, 7th - 10th February 2012.

Puhe, J 2003, 'Growth and development of the root system of Norway spruce *(Picea abies)* in forest stands – a review', *Forest Ecology and Management*, vol. 175, no. 1-3, pp. 253-273.

Randrup, TB, McPherson, EG & Costello, LR 2001, 'A review of tree root conflicts with sidewalks, curbs, and roads', *Urban Ecosystems*, vol. 5, 209-225.

Rhodes, JR, Ng, CF, de Villiers, DL, Preece, HJ, McAlpine, CA & Possingham, HP 2011, 'Using integrated population modelling to quantify the implications of multiple threatening processes for a rapidly declining population', *Biological Conservation*, vol. 144, 1081-1088.

Roman, LA & Scatena, FN 2011, 'Street tree survival rates: Meta-analysis of previous studies and application to a field survey in Philadelphia, PA, USA', *Urban Forestry and Urban Green*ing, vol. 10, 269-274.

Sander, H, Polasky, S & Haight, RC 2010, 'The value of urban tree cover: a hedonic property price model in Ramsey and Dakota Counties, Minnesota, USA', *Ecological Economics*, vol. 69, 1646-1656.

Savard, JPL, Clergeau, P & Mennechez, G 2000, 'Biodiversity concepts and urban ecosystems', *Landscape and Urban Planning*, vol. 48, no. 3-4, pp. 131-142.

Schroeder, H, Flannigan, J & Coles, R 2006, 'Residents' attitudes toward street trees in the UK and US communities', *Arboriculture and Urban Forestry*, vol. 32, no. 5, pp. 236-246.

Scott, KI, McPherson, EG & Simpson, JR 1998, 'Air pollution uptake by Sacramento's urban forest*', Journal of Arboric*ulture, vol. 24, no. 4, pp. 223-234.

Seamans, GS 2013, 'Mainstreaming the environmental benefits of street trees', *Urban Forestry and Urban Greening*, *vol.* 12, 2-11.

Seitz, J & Escobedo, F 2011, *Urban forests in Florida: trees control stormwater runoff and improve water quality*. University of Florida, Institute of Food and Agricultural Sciences. IFAS Extension Publication FOR184.

Shashua-Bar, L, Pearlmutter, D & Erell, E 2009, 'The cooling efficiency of urban landscape strategies in a hot dry climate', *Landscape and Urban Planning*, vol. 92, no. 3, pp. 179-186.

Skiera, B & Moll, H 1992, 'The sad state of city trees', *American Forests*, March/April, 61-64

Smiley, ET 2008, 'Comparison of methods to reduce sidewalk damage from tree roots', *Arboriculture and Urban Forestry*, vol. 34, no. 3, pp. 179-183.

Smiley, ET, Calfee, L, Fraedrich, BR & Smiley, EJ 2006, 'Comparison of structural and non-compacted soil for trees surrounded by pavement', *Arboriculture and Urban Forestry*, vol. 32, no. 4, pp. 164-169.

Soares, AL, Rego, FC, McPherson, EG, Simpson, JR, Peper, PJ & Xiao, Q 2011, 'Benefits and costs of street trees in Lisbon, Portugal', *Urban Forestry and Urban Greening*, vol. 10, no. 2, pp. 69-78.

Sommer, J & Summit, R 1999, 'Further study of preferred tree shapes', *Environment Behavior*, vol. 31, 550-576.

Sommer, R, Barker, PA, Guenther, H & Kuranik 1989, ‚Householder evaluation of two street tree species', *Journal of Arboriculture*, vol. 15, no. 4, pp. 99-103.

Sommer, R, Guenther, H, Bowker, PA & Swenson, JP 1993, 'Comparison of four methods of street tree assessment', *Journal of Arboriculture*, vol. 19, no. 1, pp. 27-34.

Summit, J & McPherson, EG 1998, 'Residential tree planting and care: a study of attitude and behaviour in Sacramento, California', *Journal of Arboriculture*, vol. 24, no. 2, pp. 89-96.

Sydnor, TD, Gamstelter, D, Nichols, J, Bishop, B, Favorite, J, Blazer, C & Turnip, L 2000, 'Trees are not the root of sidewalk problems', *Journal of Arboriculture*, vol. 26, no. 2, pp. 20-29.

Tallis, M, Taylor, G, Sinnett, D & Freer-Smith, P 2011, 'Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments', *Landscape and Urban Plan*ning, vol. 103, no.2, pp. 129-138.

Tarran, J 2009, 'People and trees, providing benefits, overcoming impediments', in D Lawry, J Gardner & M Bridget (eds), *Proceedings of the 10th National Street Tree Symposium,* Adelaide, South Australia, Adelaide University, pp. 63-82.

Thompson, RP 2006, *The State of Urban and Community Forestry in California*. Urban Forest Ecosystem Institute, San Luis Obispo, California. Technical Report 13.

Threlfall, CG, Law, B & Banks, PB 2012, 'Sensitivity of insectivorous bats to urbanization: Implications for suburban conservation planning', *Biological Conservation*, vol. 146, no.1, pp. 41-52.

Tracy, SR, Black, CR, Roberts, JA & Mooney, SJ 2011, 'Soil compaction: a review of past and present techniques for investigating effects on root growth', *Journal of the Science of Food and Agriculture*, vol. 91, no. 9, pp. 1528-1537.

Troy, A, Grove, JM & O'Neil-Dunne, J 2012, 'The relationship between tree canopy and crime rates across an urban-rural gradient in the greater Baltimore region', *Landscape and Urban Planning*, vol. 106, no. 3, pp. 262-270.

Van Dillen, SME, De Vries, S, Groenewegen, PP & Spreeuwenberg, P 2012, ‘Greenspace in urban neighbourhoods and residents health: adding quality to quantity’, *Journal of Epidemiology and Community Health*, vol. 66, no. 6, pp. e8.

Vergnes, A, Chantepie, S, Robert, A & Clergeau, P 2013, ‘Are urban spaces suitable for woodland carabids? First insights from a short-term experiment’, *Journal of Insect Conservation*, vol. 17, 671-679.

Viswanathan, B, Volder, A, Watson, WT & Aitkenhead-Peterson, JA 2011, ‘Impervious and pervious pavements increase soil CO_2 concentrations and reduce root production of American sweetgum *(Liquidambar styraciflua)*’, *Urban Forestry and Urban Greening*, vol. 10, no. 2, pp. 133-139.

Volder, A, Watson, WT & Viswanathan, B 2009, ‘Potential use of pervious concrete for maintaining existing mature trees during and after urban development’, *Urban Forestry and Urban Greening*, vol. 8, no. 4, pp. 249-256.

Wagar, JA & Barker, PA 1983, ‘Tree root damage to sidewalk and curbs’, *Journal of Arboriculture*, vol. 9, no. 7, pp. 177-181.

Williams, K 2002, ‘Exploring resident preferences for street trees in Melbourne, Australia’, *Journal of Arboriculture*, vol. 28, no. 4, pp. 161-170.

Wolf, KL 2005, ‘Trees in the small city retail business district: comparing resident and visitor perceptions’, *Journal of Forestry*, vol. 103, no. 8, pp. 390-395.

Xiao, Q & McPherson, EG 2002, ‘Rainfall interception by Santa Monica’s municipal urban forest’, *Urban Ecosystems*, vol. 6, no. 4, pp. 291-302.

Xiao, Q & McPherson, EG 2011, ‘Performance of engineered soil and trees in a parking lot bioswale’, *Urban Water Journal*, vol. 8, no. 4, pp. 241-253.

Young, KY, Daniels, CB & Johnston, G 2007, ‘Species of street tree is important for southern hemisphere bird trophic guilds’, *Austral Ecology*, vol. 32, no. 5, pp. 541-550.

Zhang, Y, Hussain, A, Deng, J & Letson, N 2007, ‚Public attitudes toward urban trees and supporting urban tree programs. *Environment Behavior*, vol. 39, no. 6, pp. 797-814.

TABLE 1– IMPACT OF TREE SIZE ON THE ECONOMIC BENEFIT OF STREET TREES.

Study	Method	Benefit (US$/tree/year)		
		Small	Medium	Large
McPherson et al. (1999)	Review of other studies	$10.97	--	$20.00
McPherson et al. (2002)	Itree	$5.22	$23.30	$46.82
Bonifaci (2010)	Itree	$38.79	--	$166.14

Table 2 – Cost – Benefit of Environmental, Social and Economic Benefits of Street Trees.

Economic value assigned to street tree benefit					
Study	Evaluation method	Tree population size	Annual cost value (US$tree/yr)	Estimated annual total benefit per tree population (US$/yr)	Volume removal benefit
Stormwater					
McPherson et al. (1999)	Direct estimation	91,379	$6.76	$616,139	3.2m^3/tree
Killicoat, Puzio and Stringer (2002)	Based on other studies	128,002	$6.85	$832,013	
Xiao and McPherson (2002)	Rainfall interception model	29,299	$3.80	$110,890	6.6m^3/tree
McPherson et al. (2005)	STRATUM	17,821	$27.836	$496,227	11.3m^3/tree
Bonifaci (2010)	Itree	91	$6.47	$588.75	
Soares et al. (2011)	Itree	41,288	$47.80	$1,973,613	4.5m^3/tree
McPherson et al. (2011)	Itree	444,889	$2.78	$1,236,791	5.6m^3/tree
		828,924	$4.37	$3,622,397	
Air pollution					
McPherson et al. (1999)	Direct estimation	91,379	$15.82	$1,442,036	7.2 t/yr
Killicoat, Puzio and Stringer (2002)	Based on other studies	128,002	$34.50	$4,416,069	
McPherson et al. (2005)	STRATUM	13,184	$0.28	$3,715	
Bonifaci (2010)	Itree	91	$6.07	$552.37	
McPherson et al. (2011)	Itree	444,889	$1.52	$676,231	
		828,924	$2.38	$1,972,839	
Soares et al. (2011)	Itree	41,288	$5.40	$222,738	25.6 t/yr
CO_2					

McPherson et al. (1999)	Direct estimation	91,379	$4.93	$449,445	
Killicoat, Puzio and Stringer (2002)	Based on other studies	128,002	$1.71	$21,888,342	
McPherson et al. (2005)	STRATUM	17,821	$1.53	$27,268	
Soares et al. (2011)	Itree	41,288	$0.33	$13,701	
Energy					
McPherson et al. (1999)	Direct estimation	91,379	$10.97	$1,000,560	
Killicoat, Puzio and Stringer (2002)	Based on other studies	128,002	$64.00	$8,192,128	
McPherson et al. (2005)	STRATUM	17,821	$31.03	$553,061	95kWh/tree
Moore (2009)		100,000			30kWh/tree
McPherson et al. (2011)	Itree	444,889	$2.16	$960,960	
		828,924	$3.35	$2,776,895	
Soares et al. (2011)	Itree	41,288	$6.16	$254,185	

TABLE 3 – OVERALL ECONOMIC BENEFITS OF STREET TREES.

Study	Method	Tree population size	Annual cost benefit (US$/tree/year)	Estimated annual total benefit (US$/tree population)	Notes
McPherson et al. (1999)	Direct estimation	91,379	$54.44	$4,963,816	
			$26.00	$2,340,000	Net
Killicoat, Puzio and Stringer (2002)	Based on research	128,002	$171.00	$21,888,342	
Maco and McPherson (2003)	Unspecified model	24,000	$52.43	$1,248,464	
McPherson et al. (2005)	STRATUM	8,907	$40.21	$358,133	Net
		16,409	$71.50	$1,173,161	Net
Moore (2009)		70,000		$14,000,000	
Bonifaci (2010)	Itree	91	$81.63	$7,429	
Faast and Cooling (2010)				$23,000,000	
McPherson et al. (2011)		444,889	$38.00	$16,905,782	High mortality
		828,942	$56.00	$46,420,752	Low mortality
Soares et al. (2011)	Itree	41,247	$159.00	$6,550,456	Net