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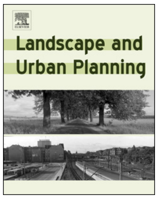

Research Paper

Establishing street trees in stormwater control measures can double tree growth when extended waterlogging is avoided

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ABSTRACT

Cities around the world are embracing stormwater control measures (SCMs) to reduce the environmental damage caused by impervious runoff. At the same time, there is a push to increase tree canopy cover to green neighborhoods and mitigate urban heat. Establishing SCMs that include trees may achieve these two objectives, but it is important to understand which design characteristics promote or reduce tree health and growth. We therefore undertook an 18-month streetscape experiment comparing four tree pit SCM designs, along with a control (non-SCM) street tree planting, to identify design characteristics influencing the water balance and growth of newly planted trees (*Acer campestre* (L.)) in an established urban area dominated by clay soils. Trees in pits with an underdrain showed double the growth of conventionally planted street trees receiving no stormwater. However, the low exfiltration rates of some non-drained tree pits resulted in some tree pits experiencing waterlogging and subsequent poor tree growth or even death. In other non-drained tree pits, the heterogeneity of urban soils resulted in sufficiently high exfiltration rates to avoid waterlogging and promote increased tree growth, even in these heavy clay soils. Our results suggest that establishing tree growth can be substantially increased by directing stormwater into tree pits, however, waterlogging conditions should be avoided via an underdrain or limiting installation to soils with a sufficiently high exfiltration rate.

1. Introduction

Street trees provide a wide range of environmental benefits such as mitigation of the urban heat island effect (McPherson et al., 1997; Norton et al., 2015) and improved air quality (Livesley, McPherson, & Calfapietra, 2016; McPherson, Simpson, Peper, Maco, & Xiao, 2005). They are also highly valued by the community, as demonstrated in community surveys (Ordóñez, Duinker, Sinclair, Beckley, & Diduck, 2016; Schroeder, Flannigan, & Coles, 2006) and linked to increasing house prices (Donovan & Butry, 2010; Pandit, Polyakov, Tapsuwan, & Moran, 2013; Plant, Rambaldi, & Sipe, 2017; Sander, Polasky, & Haight, 2010). These demonstrated benefits have encouraged municipal managers to increase street tree planting and canopy cover, as evidenced by the development of programs such as the London Tree Partnership, New York City's "Million Trees NYC" initiative, and urban forest strategies designed by the cities of Melbourne (City of Melbourne, 2014) and Vancouver (City of Vancouver, 2014).

Maintaining or increasing an urban forest requires the provision of favorable growing conditions likely to result in street trees reaching their full potential (Dobbertin, 2005; Jacqueline et al., 2010; Pedersen, 1998). Providing good growing conditions can result in higher tree growth rates and associated ecosystem benefits in a faster timeframe (Rahman, Armson, & Ennos, 2015). Conversely, urban tree growth and ecosystem service benefits may be negatively impacted by the stressful conditions of the urban environment (Cregg & Dix, 2001; Jutras, Prasher, & Mehuys, 2010; Nowak, Kuroda, & Crane, 2004). Limited access to water is a common stress for street trees, resulting in poor growth and mortality (Beatty & Heckman, 1981; Gilbertson & Bradshaw, 1990; Smith, May, & Moore, 2001). Developing healthy tree crowns and substantial urban forest canopies will thus require addressing the causes of urban tree stress, including the provision of suitable soil water conditions (Dale & Frank, 2017).

Increased impervious surface cover and hydraulically efficient drainage systems which characterize urbanization lead to a major disturbance of the water cycle, decreasing infiltration, increasing surface runoff and mobilizing and transporting pollutants to receiving waters. This combination of stressors can lead to 'the urban stream syndrome' involving the degradation of urban waterway ecological processes and benefits (Booth, Roy, Smith, & Capps, 2015; Hatt, Fletcher, Walsh, & Taylor, 2004; Walsh, Fletcher, & Ladson, 2005). As understanding of

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Table 1
Description of the five tree pit treatments installed. Pit dimension depths are relative to the existing surface (i.e., the invert of the kerb). In all instances, systems were built, then a 350 mm diameter × 250 mm deep hole was excavated to plant the tree. No systems were lined and only the Drained treatment was connected via a raised outlet to the stormwater drainage network.

	Control	Soil	Sand	Drained	Adjacent
Description	Standard tree planting method with tree planted into native soil at footpath surface level. Tree receives no runoff	Kerb cut directs stormwater to tree which is planted into native soil	Kerb cut directs runoff to tree which is planted in sandy substrate	Kerb cut directs runoff to tree which is planted in sandy substrate with underdrain	Kerb cut directs runoff to new pit containing sandy substrate. Tree planted as per Control directly adjacent to new pit
Treatment dimensions (m)	Width: 0.6 Length: 1.2 Depth: –	Width: 0.6 Length: 1.2 Depth: –	Width: 0.6 Length: 1.2 Depth: 0.65	Width: 0.6 Length: 1.2 Depth: 0.65	Width: 0.6 Length: 2.4 Depth: 0.65 (pit only)
Inlet	None	1.2 m kerb cut	1.2 m kerb cut	1.2 m kerb cut	1.2 m kerb cut in front of pit only
Soil surface level	Top of kerb	100 mm below invert of kerb	100 mm below invert of kerb	100 mm below invert of kerb	Pit surface 100 mm below invert of kerb
Extended detention depth (mm)	None	100	100	100	100
Substrate tree planted into (mm)	Clay	Clay	Sandy loam: 300	Sandy loam: 300	Clay
Drainage layers (mm)	None	None	Coarse sand: 25 Fine gravel: 75	Coarse sand: 25 Fine gravel: 75	Coarse sand: 25 Fine gravel: 75
Underdrain outlet	None	None	None	50 mm perforated PVC outlet to stormwater drain at 0.4 m depth	None
Substrate adjacent to tree	Clay	Clay	Clay	Clay	Sandy loam on one side; clay on remaining sides

this issue grows, and urban streams become more valued, mitigation of the negative impacts of stormwater runoff water entering urban streams is becoming increasingly important. Stormwater control measures (SCMs), such as constructed wetlands and biofiltration systems that capture and treat stormwater runoff, are now being installed throughout urban catchments (AECOM et al., 2016; Li et al., 2009; Melbourne Water, 2005).

Combining tree planting in streets with SCMs may provide an opportunity to both reduce the impact of urban stormwater runoff and increase tree growth, through the redirection of stormwater into a pit planted with a street tree to create "tree pits". The tree pit may contain native soil or have a specific biofiltration sand media profile (Cappiella, Schueler, & Wright, 2005; Center for Watershed Protection, 2012). Pits can either involve an underdrain connected to the stormwater system or rely on exfiltration into the surrounding soil as the primary means of dissipating collected stormwater (Payne et al., 2015).

Previous studies on the effect of directing stormwater to trees have identified mixed results. Several studies have suggested that directing stormwater to trees can increase tree growth (Denman, May, & Breen, 2006; Mullaney, Lucke, & Trueman, 2015; Scharenbroch, Morgenroth, & Maule, 2015; Xiao & McPherson, 2011). However, the nursery study by Bartens, Day, Harris, Wynn, and Dove (2009) showed that trees receiving stormwater in low exfiltration environments had reduced tree growth. These contrasting results suggest that the hydrology of a tree pit may present a stressful environment for street trees, particularly during the establishment period. Drought conditions may be experienced due to the presence of an underdrain coupled with the high hydraulic conductivity of the biofiltration media (Payne et al., 2014). Alternatively, tree pits without underdrains and with low exfiltration rates into surrounding soils may experience waterlogged conditions (GVSDD, 2012). As such, an improved understanding of the tree pit environment is required to ensure successful establishment and rapid tree growth, and to ensure trees can perform key functions in removing pollutants from stormwater and creating storage capacity for runoff retention via evapotranspiration (Denman, May, & Moore, 2016; Payne et al., 2014; Read, Wevill, Fletcher, & Deletic, 2008; Scharenbroch et al., 2015). There is currently a lack of quantitative data regarding what effect these systems may have on tree growth, and in particular, how to ensure an appropriate water balance during establishment when the tree is arguably most vulnerable (Gilbertson & Bradshaw, 1990; Roman, Battles, & McBride, 2014). In addition, there is currently a more general lack of field data available on urban tree growth with the need for further studies to better understand the relationships between water regimes and tree outcomes in urban areas (Jacqueline et al., 2010; McPherson & Peper, 2012; Vogt, Watkins, Mincey, Patterson, & Fischer, 2015).

In this study, we investigated the effect of different water regimes within tree pits on establishing tree growth over 18 months. We compared four tree pit designs, along with a traditional (non-SCM) tree planting to identify design characteristics that influence the establishment of newly planted trees (*Acer campestre* (L.)) in an urban area dominated by clay soils. Our aim was to identify whether directing stormwater to tree pits can increase tree growth during the establishment period, and which key design principles are required to maximize tree growth.

2. Materials and methods

2.1. Study site and experimental design

The study site was a 500 m long section of a north/south orientated residential street in the inner north region of Melbourne, Australia. The climate is temperate with an average annual rainfall of 587 mm year^{-1}, relatively evenly distributed across the year (Bureau of Meteorology, 2017b). Individual rainfall events were identified using a self-emptying tipping bucket (Dataflow Systems Ltd., Christchurch, NZ) positioned