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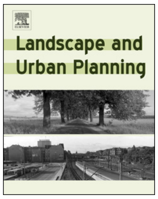

Research Paper

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

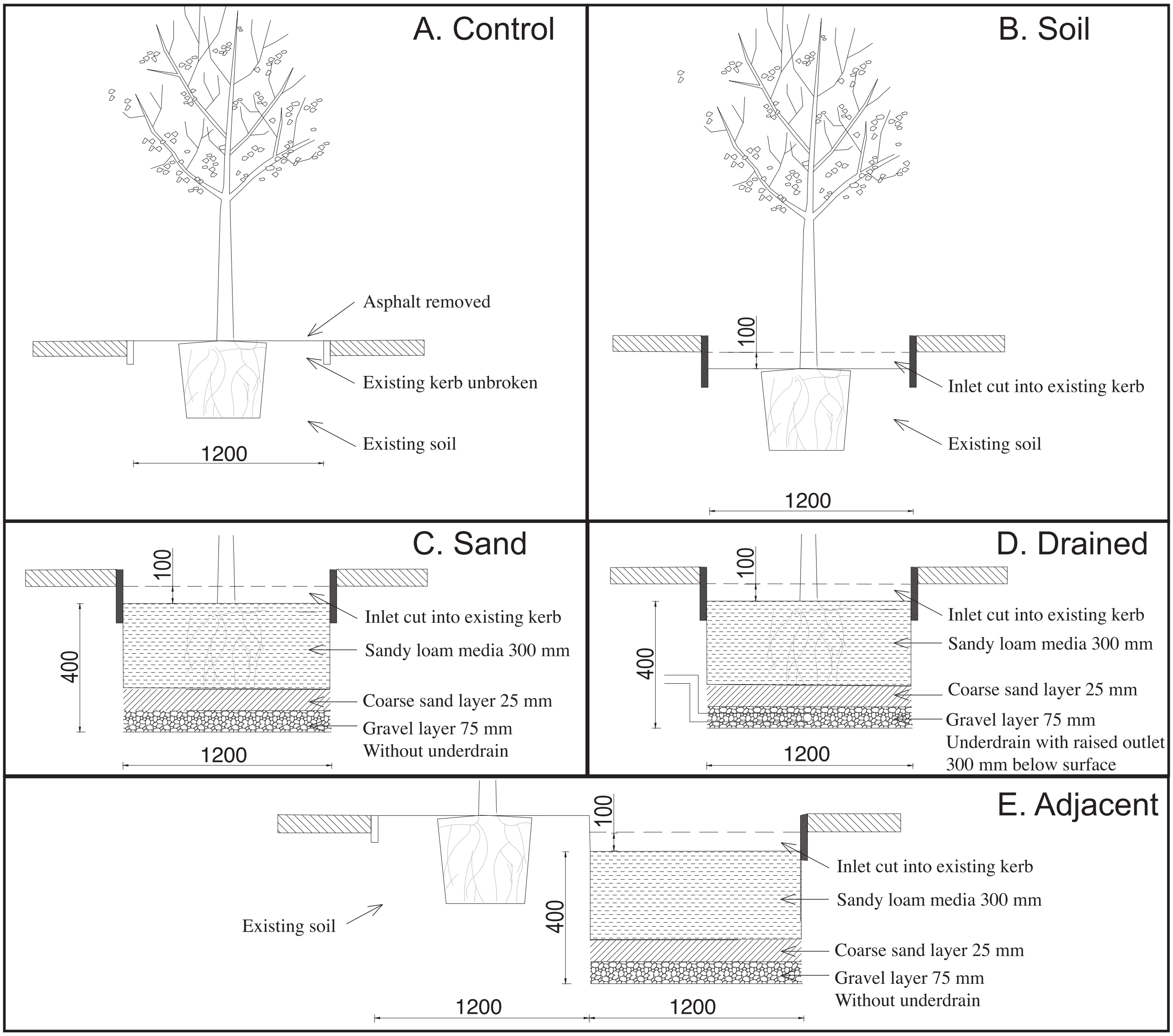

Fig. 1. . Cross section drawings of (A) Control, (B) Soil, (C) Sand, (D) Drained, (E) Adjacent treatments showing differences in inlet locations, soil/substrate types, drainage connections and tree locations. Dimensions shown are in mm.

within the street. The predominant soil type was classified as heavy clay from textural analysis of samples taken from site as per McDonald, Isbell, Speight, Walker, and Hopkins (1990). There were no vegetated verges or nature strips in the street, with an asphalt footpath (approx. width 2 m) extending from the property boundary to the road edge. The boundary between the road and footpath was a 150 mm high bluestone kerb.

Five replicates of five tree pit designs were constructed in winter (June) 2015. The treatments are described in Table 1 and Fig. 1. The 'Control' treatment was a standard method for planting new street trees into native soil using a 1.2 m × 0.6 m opening cut into the asphalt footpath. While the Control treatment only received rainfall input from directly above, i.e. it received no runoff from the road, the other four treatments (Soil, Sand, Adjacent and Drained) captured runoff from a larger catchment (median catchment area 390 m^2; range 180 m^2–1900 m^2) via a 1.2 m wide cut in the kerb. As per the Control, the 'Soil' treatment contained only native soil, however, the kerb was cut and an extended detention depth of 100 mm was excavated to capture runoff. The 'Sand' treatment was the same as the Soil treatment except, that the soil in the tree pit was removed to depth of 400 mm and replaced with (from bottom to top): 75 mm of gravel (drainage layer), 25 mm of coarse sand (transition layer) and 300 mm of sandy loam (filter media, as per Payne et al. (2015)). The 'Drained' treatment was identical to the Sand treatment, except the gravel base layer contained a perforated PVC underdrain with a raised outlet connected to the stormwater drainage system. The 'Adjacent' treatment differed from the other three treatments receiving runoff, in that it combined aspects of the Sand and Control treatments. That is, runoff was directed into pit identical to the Sand treatment except that the tree was planted into native soil adjacent to the pit, rather than planted into the sandy profile. This alternate tree location was adopted in order to avoid potential detrimental effects of runoff direct to the tree root ball, whilst still making runoff available to the tree. The pit surface area of all treatment replicates was < 0.4% of the impervious catchment area that supplied runoff water; and as a result all runoff treatments experienced similarly high and rapid inflows of water during rainfall events.

A deciduous exotic species, *Acer campestre* (L.), was planted into all treatments in a 350 mm diameter by 250 mm deep planting hole. At the time of planting, these trees had a stem diameter of between 22 and 25 mm when measured at 0.5 m above the soil/substrate surface.

2.2. Tree growth measures

2.2.1. Relative stem diameter growth

Stem diameter was measured every 4–6 weeks during the 'in leaf' period at 0.5 m above the soil/substrate surface. Measurements were taken both perpendicular and parallel to the road using Vernier calipers (accuracy ± 001 mm) and the mean recorded. If an unusual trunk characteristic was encountered (e.g. a branch stub) then measurements were taken at locations equidistant above and below the 0.5 m height and the mean recorded. For consistency, all measurements were taken by the same operator. The first measurement was taken on 15 September 2015 and the final measurement was taken on 7 March 2017, approximately 18 months later. As all replicates had similar initial stem diameters, the relative growth over the recorded period was calculated as a percentage of the initial diameter. For trees that died during the measurement period, the maximum recorded stem diameter was used as their final diameter measurement.

2.2.2. Relative leaf area growth

To quantify tree crown growth in response to the treatments, measurements of branch diameter were taken initially on 4 November 2015 and again on 7 March 2017. Allometric relationships of leaf area to branch diameter were calculated from four destructively sampled *Acer campestre* trees (number of branches = 242, $r^2 = 0.79$) using a LI-3100 leaf area meter (LI-COR Biosciences, Nebraska, USA), and applied to the field measurements to non-destructively calculate maximum leaf area. As noted by Nowak (1996), this method calculates the maximum possible leaf area for the tree and does not take into account leaf loss from factors such as leaf decline, pruning or vandalism. As all replicates had similar initial leaf areas, the relative growth over the recorded period was calculated as a percentage of the initial leaf area. Dead trees were excluded from relative leaf area growth estimates.

2.3. Water level measurements

To relate the depth of water in the tree pits to tree growth, water level sensors (Dataflow Systems Ltd., Christchurch, NZ) were installed in all treatment replicates except the Control, which did not receive runoff. The water level sensors were 0.5 m long and installed in PVC perforated access tubes. Water level was recorded on a six-minute time step.

2.3.1. Saturation water level regime

To summarize the saturation water level regime, median saturation water levels were determined from the water level sensors. To relate duration of saturation of the soil/substrate profile to tree growth, cumulative frequency distributions of the saturation water level were fitted. These analyses were undertaken over both growing seasons combined covering 1 September 2015–31 May 2016 for the first year of measurements and 1 September 2016–7 March 2017 for the second year. For treatments where the tree received runoff directly to the root ball; i.e. for the Soil, Sand and Drained treatments, saturation water level was compared against stem diameter growth. Adjacent treatments were not considered for this analysis, as the tree was not planted in the area of the pit directly receiving runoff.

2.3.2. Maximum exfiltration rates

To relate tree stem growth to how quickly water drained from the tree pits, exfiltration rates were determined from the water level sensors. Eight events were selected where the tree pits filled to capacity with runoff, then completely drained over a series of days free from any subsequent rainfall or runoff. We identified the maximum observed exfiltration rate from among these eight events for each pit. Maximum exfiltration rates were compared against stem diameter growth for each replicate tree. This analysis was performed only for the Soil and Sand treatments, where the tree was directly planted into the runoff-receiving pit. The Drained treatment was excluded due to the unrestricted nature of the underdrain exfiltration rate. Adjacent treatments were not considered as the tree was not planted directly within the saturation zone.

2.4. Soil moisture content

To quantify the soil moisture available to the trees, soil moisture probes (Dataflow Systems Ltd., Christchurch, NZ), with three sensor depths at 170, 270 and 370 mm below the soil/substrate surface, were installed in each tree pit. Soil moisture content was recorded on an hourly timestep. Two soil moisture probes were placed on either side of the tree, between 200 and 300 mm from the stem, parallel with the kerb. Each sensor on each probe was calibrated using a two-point linear calibration as recommended by the manufacturer. To do this, we used the supplied dry soil offset value and a soil/substrate sample extracted from each tree pit and depth when the soil/substrate was wet after recent rainfall. Soil samples at each of the three depths were extracted, wet mass determined immediately, then samples were oven-dried at 105 °C for one week before determining dry mass. Gravimetric water content (GWC) was calculated as the mass of water (mass wet sample − mass dry sample)/mass dry sample ($g\,100\,g^{-1}$). GWC was then multiplied by the bulk density of the soil/substrate to calculate volumetric water content (VWC). Bulk density samples were extracted from each pit as intact cores (7.4 cm diameter). Core samples were oven-dried at 105 °C for one week and dry bulk density calculated as mass of dry soil per unit volume ($g\,cm^{-3}$).

Textural analysis of native soil and the sandy substrate was used to classify the soil/substrate as 'heavy clay' and 'sandy loam' following the procedure set out in McDonald et al. (1990). Associated literature values for the field capacity (FC) and permanent wilting point (PWP) were identified as 27% and 41% for the native clay soil and 8% and 18% for the sandy substrate (Saxton & Rawls, 2006). These critical thresholds were used to relate the soil moisture content regime to tree growth.

2.5. Statistical analysis

One-way analysis of variance (ANOVA) was used to identify differences in stem diameter growth, median saturation water level, maximum exfiltration rates and median soil moisture among treatments and Tukey's post hoc tests were used to identify significant differences at the 95% confidence interval. Linear regression analysis was used to relate the saturation water level, maximum exfiltration rate and median soil moisture to stem diameter growth. One Drained replicate was compromised early in the study and as such was excluded (i.e., n = 24). R version 3.3.3 was used for all data analysis (R Core Team, 2017).

3. Results

3.1. Individual measures of tree growth, water level and soil moisture

Tree pits with an underdrain showed approximately double the increase in median stem diameter and leaf area compared with all other treatments over the course of the experiment (Figs. 2a and S1; $P < 0.01$). The Soil and Sand treatments experienced some tree mortality, with only two replicates surviving in the Sand treatments and three replicates surviving in Soil treatments. In the Soil, Sand and Adjacent treatments, tree growth was highly variable among replicates (Figs. 2a and S1). Leaf area growth (Fig. S2) and stem diameter increase were found to be strongly positively correlated ($r^2 = 0.9$, $P < 0.01$) and therefore we used stem diameter increase to represent overall tree growth.

There were no significant differences in median saturation water level among treatments, however, there was high variability among replicates (Fig. 2b). As expected, the Drained treatments had a median saturation water level at a greater depth than 300 mm in the profile. In

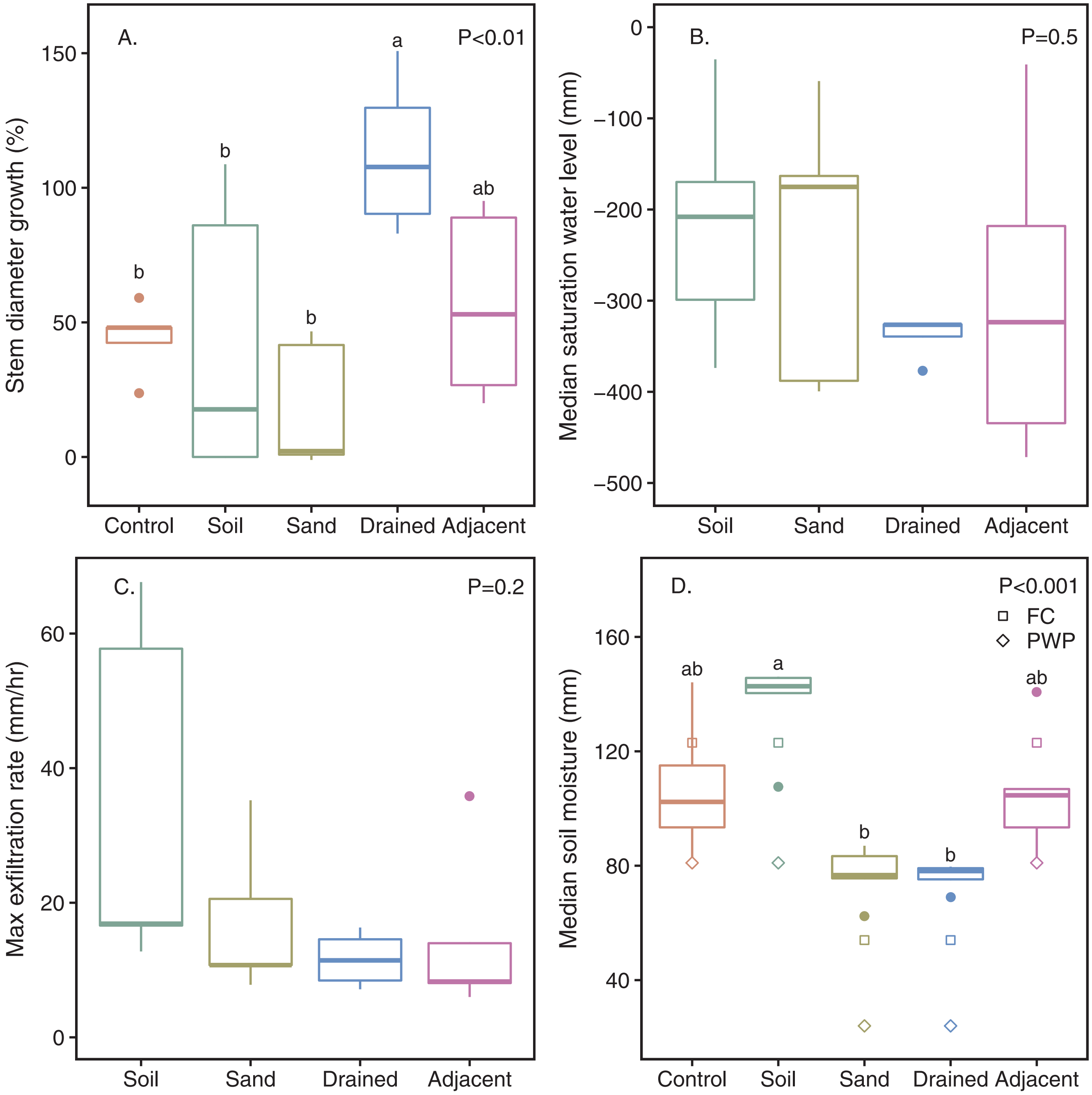

Fig. 2. Summary of measures showing differences between treatments over the course of the experiment for (A) stem diameter growth, (B) median water level within the soil/substrate profile, (C) maximum exfiltration rate from the pit, (D) median soil moisture at the tree root ball. P-values were derived from one-way ANOVA and different letters indicate significant differences among treatments.

treatments without an underdrain (Soil, Sand and Adjacent), saturation water levels were highly variable (Fig. S3) and included median saturation water levels for some replicates within the upper 100 mm of the profile (Fig. 2b).

There were no significant differences in the maximum exfiltration rate among treatments, however, it was highly variable among replicates (Fig. 2c). For Soil and Sand treatments, the maximum exfiltration rates ranged from 6.0 to 67.6 mm h^{-1}.

Median soil moisture content was above field capacity for Soil, Sand and Drained treatments (Fig. 2d). Other treatments (Control and Adjacent) experienced median soil moisture content below field capacity but above permanent wilting point. High variability of the soil moisture content in the soil/substrate profile was observed among replicates for the native soil (Control and Soil) treatments, with lower variability within the sandy substrate (Sand, Drained and Adjacent) treatments (Fig. S3).

3.2. Relationships between tree growth, water level and soil moisture

For Soil, Sand and Drained treatments there was a strong, positive relationship between stem diameter growth and saturation water level (Fig. 3a; $r^2 = 0.85$; $P < 0.001$). Stem diameter growth was higher where the saturation water level was > 170 mm below the soil/substrate surface, with replicates with a saturation water level below this threshold recording growth above the Control treatment, for which the median stem diameter growth was 48%. This 170 mm threshold depth

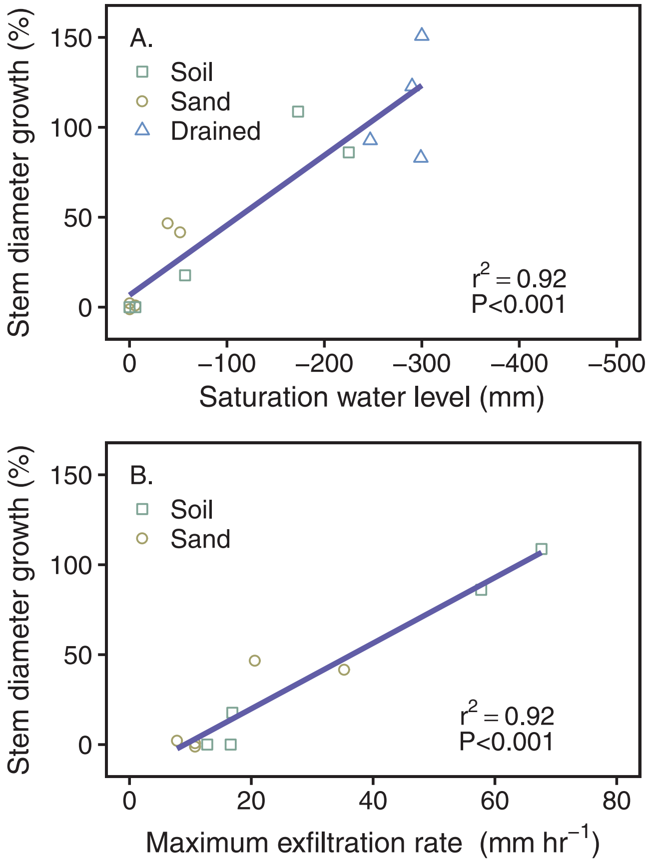

Fig. 3. Relationships between stem diameter growth and (A) water level depth exceeded for 10% of the growing season for each replicate of the Soil, Sand and Drained treatments and (B) maximum exfiltration rate for each replicate of the Soil and Sand treatments.

corresponds to approximately half the depth of the rootball at the time of planting.

Stem diameter growth for Soil and Sand treatments was positively related with the maximum exfiltration rate observed in each pit (Fig. 3b, $r^2 = 0.92$; $P < 0.001$). Replicates with a maximum exfiltration rate $> 58\ \mathrm{mm\,h^{-1}}$ showed growth equivalent to the Drained treatment ($> 85\%$), whereas those with $< 20\ \mathrm{mm\,h^{-1}}$ showed little or no growth ($< 20\%$).

There was no relationship between the median soil moisture content and stem diameter growth for trees growing in native soil or the sandy substrate (Fig. S4). Several replicates growing in native soil and all replicates growing in sandy substrate showed median soil moisture greater than field capacity. No treatments showed median soil moisture content below the permanent wilting point of the substrate.

4. Discussion

4.1. Can directing stormwater to tree pits improve tree growth during establishment?

Trees planted in pits with an underdrain showed double the growth of trees in the Control (non-SCM) street tree planting treatment (Figs. 2a and S2). This suggests that passively irrigating establishing trees with stormwater can be highly beneficial to their growth. Irrigating trees with stormwater pushed growth of the Drained treatment into the high growth range expected for trees in an urban setting, whereas the Control trees were in the slow-medium range (Lawrence, Escobedo, Staudhammer, & Zipperer, 2012; Nowak et al., 2008). While the concept of irrigating street trees with stormwater has been widely promoted (Berland et al., 2017), few have provided the quantitative data on potential growth benefits (Scharenbroch et al., 2015) which may assist in justifying their higher installation (Mell, Henneberry, Hehl-Lange, & Keskin, 2013). Here, we provide evidence of substantial tree growth benefits achieved via passive irrigation of street trees and suggest that canopy cover targets set to mitigate urban heat could be met sooner by directing stormwater to establishing trees.

4.2. What factors influence tree survival and growth?

The highest tree growth rates were achieved in tree pits that provided direct access to stormwater whilst avoiding waterlogging, whereas tree mortality was experienced in tree pits that experienced extended waterlogging conditions (Fig. 3a). Trees in pits with an underdrain showed the highest growth as they received direct access to stormwater whilst the underdrain prevented waterlogging. Trees in the Adjacent treatment also avoided waterlogging as the tree was planted outside of the water-receiving pit; however, they showed less growth than Drained trees as they likely had less direct access to captured stormwater. In contrast, several replicates in the Sand and Soil treatments showed poor growth or even died due to extended periods of waterlogging. Glenz, Schlaepfer, Iorgulescu, and Kienast (2006) suggested that whilst it is generally accepted that the maximum duration of (waterlogging) saturation a tree can survive is 40% of the growing season, this may vary widely among different tree species. Indeed, our study indicates that presence of waterlogging for as little as 10% of the growing season had a significant impact upon the growth of *Acer campestre* trees planted into the tree pits. *Acer campestre* is characterized as having intermediate waterlogging and drought tolerance (Glenz et al., 2006; Niinemets & Valladares, 2006; Sjöman, Hirons, & Bassuk, 2015), thus it is unsurprising that growth was impaired due to extended periods of waterlogging. Other tree species with higher waterlogging tolerance, such as *Tristaniopsis laurina* (Glenz et al., 2006; Melick, 1990) may have performed better.

Not all individuals in Sand and Soil treatments died as a result of waterlogging, with some replicates even showing growth equivalent to trees in the Drained treatments. Among these replicates, increased growth was correlated with the maximum exfiltration rate from the tree pit, where exfiltration rates $> 20\ \mathrm{mm\,h^{-1}}$ corresponded to higher tree growth (Fig. 3b). The saturated hydraulic conductivity of native soils surrounding SCMs are therefore a major consideration when trees are planted directly into the area of the pit receiving stormwater (Bartens et al., 2009; Mullaney et al., 2015). Where exfiltration rates are sufficiently high, Soil and Sand treatments may provide an alternate tool to increase urban street tree growth without the expense of installing an underdrain and connection to the stormwater system. It is worth noting that within the streetscape experimental area the exfiltration rates into the surrounding soil varied between $1\ \mathrm{mm\,h^{-1}}$ and $68\ \mathrm{mm\,h^{-1}}$. Whilst the dominant clay soil type remained constant, this is a highly disturbed, urban soil landscape (Ossola & Livesley, 2016) that can create preferential flow pathways or perched water tables that greatly impact the exfiltration rate experienced in that specific location of the street (Bonneau, Fletcher, Costelloe, & Burns, 2017; Kaushal & Belt, 2012). Thus, even in areas with a dominant clay soil, it may be possible to achieve sufficiently high exfiltration rates to allow the installation of Sand or Soil treatments (Winston, Dorsey, & Hunt, 2016). The installation of Adjacent treatments may also reliably avoid waterlogging conditions even when low exfiltration rates are present. Although no advantage in tree growth for the Adjacent treatment was found in this experiment, this treatment also achieves stormwater infiltration benefits and it is hypothesized that over a longer time period improved tree growth will occur as tree roots grow to take full advantage of access to stormwater.

In assessing the impact of water regime factors on tree growth it is important to note that the climate of Melbourne is described as temperate with relatively uniform rainfall distribution across the year

(Bureau of Meteorology, 2017a) and the soil type in which this experiment was conducted was a clay soil with low to moderate exfiltration rates. Within these climate and soil characteristics, waterlogging was found to be the dominant factor influencing tree growth in the first two years of establishment. However, in other climates with greater evaporation rates, smaller rainfall volumes or more seasonal distributions of rainfall, the dominant factor influencing tree growth may change. For example, in a Mediterranean climate, where rainfall is concentrated within the winter and there are hot, dry summers, we would expect drought to become more important and perhaps the dominant soil moisture condition influencing tree growth in these systems (Stovin, Poë, & Berretta, 2013).

Despite concerns about inducing drought conditions in treatments utilizing biofiltration sand, all replicates of the Sand and Drained treatments recorded median soil moisture greater than field capacity (Fig. S4). While the low exfiltration rates into the surrounding native soil led to waterlogging deaths of some Sand replicates, in the Drained treatment they created a reservoir below the underdrain sufficient to ensure high soil moisture was maintained within the sand profile. This finding is consistent with the current best practice design standards for biofiltration SCMs, where a submerged zone is encouraged to retain a reservoir of stormwater, providing plant access to water between rain events (NCDEQ, 2017; Payne et al., 2015) events. In contrast, the Control treatment experienced median soil moisture conditions between permanent wilting point and field capacity, indicating that whilst these trees did not suffer prolonged drought conditions, they were more water-limited than the trees in the Soil, Sand and Drained treatments.

Within Soil and Sand treatments, the maximum exfiltration rate into the surrounding soil was found to be the dominant factor influencing tree growth rather than the type of substrate that the tree is planted directly into (Fig. 3b). Tree pits installed in surrounding soil types with higher exfiltration rates (e.g. sandy or fluvio-glacial soils) will likely avoid waterlogging and in such soils tree growth in pits without underdrains will likely rival those of the Drained treatment. However, it would also be reasonable to expect that very high exfiltration rates would decrease available soil moisture to such an extent that drought stress, rather than waterlogging, becomes the dominant factor influencing tree growth. In this case, alternate tree pit designs such as a partially lined pit to provide an internal water storage may be required to maximize tree growth (Dasch Houdeshel, Pomeroy, & Hultine, 2012).

This study explored tree growth during the establishment period, however it remains unanswered if the advantages bestowed during the establishment period will continue over the longer term. Further work is also required to evaluate tree pits in alternate soil types and climates to ascertain under what scenarios the benefits to tree growth continue. The suitability of alternate tree species to the tree pit environment also remains to be explored. Additionally, if tree pits are to be employed as SCMs, monitoring and analysis of the impacts of tree pits on water quality and flow reduction is required.

5. Conclusions

This study has found that access to stormwater may double the growth of street trees compared to traditional street tree planting techniques during the establishment period. However, if not carefully managed, passive irrigation with stormwater may lead to reduced tree growth or even death. Waterlogging was identified as the dominant water stress condition within tree pits and thus avoidance of waterlogging conditions is required to stimulate increased tree growth. For a temperate climate and soils with low exfiltration rates, we found this may be reliably achieved through installation of an underdrain. In this same climate, we found soils with higher exfiltration rates may achieve similar high growth rates without the additional complication of installing an underdrain. We conclude that directing stormwater to street trees can be an important tool in improving tree growth, even where native soils have low exfiltration rates.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.landurbplan.2018.06.002.

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