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Transpiration by established trees could increase the efficiency of stormwater control measures

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ABSTRACT

Evapotranspiration is an important aspect of the hydrological cycle in natural landscapes. In cities, evapotranspiration is typically limited by reduced vegetation and extensive impervious surfaces. Stormwater control measures (SCMs) seek, among other objectives, to move the urban hydrological cycle towards pre-development conditions, promoting processes such as infiltration and evapotranspiration. Yet, evapotranspiration is generally assumed to play a minor role in the water balance of stormwater control measures. Since established urban trees can use large quantities of water, their inclusion with stormwater control measures could potentially substantially increase evapotranspiration. We installed infiltration trenches alongside established *Lophostemon confertus* trees in the grassed verges of a typical suburban street to assess 1) whether redirecting stormwater to trees could increase their transpiration and 2) the contribution of transpiration to the water balance of stormwater control measures. We measured stormwater retention and transpiration for two spring-summer periods and estimated an annual water balance for the infiltration trenches. Although redirecting stormwater to trees did not increase their transpiration, these trees did use large volumes of water (up to 96 L d^{-1}), corresponding to 3.4 mm d^{-1} per projected canopy area. Annually, stormwater retention was 24% of runoff and tree transpiration was equivalent to 17% of runoff. Our results suggest that streetscapes fitted with tree-based stormwater control measures, could increase the volumetric reduction of stormwater runoff by increasing the proportion of evapotranspiration in the water balance. Since public space is highly contested in cities and increasing canopy cover is a priority for many planners, integrating trees with stormwater control measures could provide dual benefits for a single management intervention, enabling a greater number of distributed stormwater control measures with smaller impervious catchments in the streetscape.

1. Introduction

In natural ecosystems, infiltration and evapotranspiration of rainfall are large components of the hydrological cycle. In urban landscapes, extensive impervious surfaces and densification disrupt infiltration and evapotranspiration. Instead, large volumes of rainfall are converted to stormwater runoff, causing flash flooding and degradation of urban waterways (Hatt et al., 2004; Walsh et al., 2005). Stormwater control measures (SCMs) seek to emulate pre-development hydrological processes, by reducing and slowing stormwater runoff through a combination of detention, infiltration, and retention (Paule-Mercado et al., 2017; Walsh et al., 2015). Biofilters and raingardens are commonly used SCMs that intercept runoff near its source, encouraging infiltration and evapotranspiration of stormwater flows, so that urban hydrological processes and the water balance are closer to their pre-development conditions (Burns et al., 2012; Eckart et al., 2018).

While impervious surfaces can create large volumes of stormwater runoff, they simultaneously reduce water availability for urban vegetation, such as street trees. The reduction in infiltration beneath impervious surfaces, combined with limited rooting volumes, soil compaction, and high evaporative demand in cities, means street trees are likely to experience drought stress (Martin et al., 2016; Mullaney et al., 2015), which could reduce the

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valuable ecosystem services that trees provide (Thom et al., 2016; Zhang et al., 2019a). Recognition of the ecosystem services that trees provide in cities, including urban cooling, pollution reduction, biodiversity habitat, and stormwater reduction has motivated municipalities to increase tree canopy cover (Cameron and Blanuša, 2016; Ordóñez et al., 2019). In the context of existing drought stress, however, which is likely to be exacerbated by warmer, drier climates under predicted climate change scenarios (Hoegh-Guldberg et al., 2019; Zhang et al., 2019b), such efforts may be unsuccessful if trees do not have adequate soil moisture (Gebert et al., 2019; Widney et al., 2016). To address the challenge of vegetation drought stress, and excessive stormwater runoff concurrently, researchers and practitioners are increasingly advocating the use of stormwater as a resource to passively irrigate vegetation in cities (Berland et al., 2017; Fenner, 2017; Scharenbroch et al., 2016).

Trees have the capacity to make use of large volumes of water through transpiration and therefore could improve the retention capacity of stormwater control measures (Nocco et al., 2016; Szota et al., 2017). Trees have been shown to use large volumes of water in cities (Litvak et al., 2012; Pataki et al., 2011; Wang et al., 2012), In temperate Beijing, Wang et al. (2012) measured maximum transpiration of 44 L day^{-1} for *Aesculus chinensis* trees. Even higher maximum water use was measured by Litvak et al. (2012) in arid Los Angeles, ranging from 70 to 250 L d^{-1} depending on species. However, few studies to date have measured transpiration from trees passively irrigated by stormwater control measures (Scharenbroch et al., 2016; Tirpak et al., 2019). Hence, our understanding of the volume of water that trees could transpire from SCMs, and therefore their potential to increase volumetric retention of stormwater, is limited.

Vegetation is generally considered to play a minor role in the water balance of small-scale SCMs such as bioretention systems, and therefore contribute little to the removal of stormwater inflows. Evapotranspiration from bioretention systems planted with sedges or rushes is typically 1–5% of stormwater runoff (Daly et al., 2012; Gao et al., 2018; Hoskins and Peterein, 2013). This is primarily because bioretention systems are generally small relative to the connected impervious catchment that drains into them (Payne et al., 2015), so evapotranspiration is a small proportion of the large volumes of stormwater runoff generated (de Macedo et al., 2019; Grey et al., 2018). For example, Braswell et al. (2018) estimated transpiration as the residual of inflows and outflows in a small tree-based SCM, calculating a mean contribution of 0.7%. Grey et al. (2018) modelled transpiration from reference evapotranspiration, estimating a higher contribution from establishing trees of up to 2.8%. Both these studies had small SCMs and tree canopy relative to the impervious catchment area, which meant the volume of stormwater runoff far exceeded transpiration. Conversely, Scharenbroch et al. (2016) suggested trees could play a much greater role in the water balance, estimating that trees could transpire up to 58% of stormwater runoff in bioswales fitted with an outlet control structure. When transpiration is high relative to the runoff received and retained by an SCM, evapotranspiration can play a greater role in the water balance of SCMs.

Established urban street trees have large projected canopy areas that may exceed the surface area of SCMs. So, even if transpiration rates are similar to other vegetation types (Szota et al., 2018; Tirpak et al., 2019) or young trees, they have the potential to transpire from a greater area than ground-level vegetation types planted into SCMs. Therefore, Berland et al. (2017) suggests trees can provide greater stormwater reduction than other vegetation because of the discrepancy between the size of the projected canopy and the footprint of a tree at ground level. Large projected canopy area means trees could have greater runoff reduction efficiency for a small ground-level footprint, relative to the ground-level footprint of other vegetation types. Hence, establishing trees with smaller canopy areas could contribute less (Tirpak et al., 2019) to the proportion of stormwater runoff transpired from SCMs than large established trees (Litvak et al., 2012). To the best of our knowledge, the contribution of established tree transpiration to the water balance of SCMs has not been reported, despite their potential.

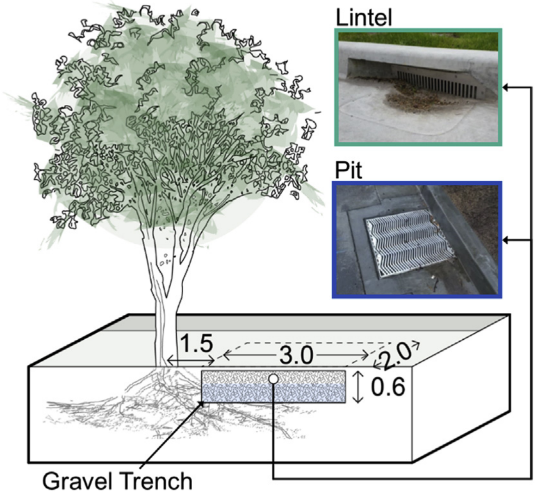

Fig. 1. Cross-section illustration of a gravel-filled infiltration trench installed alongside an established *Lophostemon confertus* tree. The inlet that conveys stormwater to the trench was either vertical (*lintel*) or horizontal (*pit*). The cross-section is cut at the centre of the trench showing dimensions relative to the tree in metres.

There remains a limited understanding of the potential contribution of established trees to the water balance of SCMs, and the co-benefits of integrating SCMs and trees, such as increased transpiration and reduced runoff from the street (Berland et al., 2017; Scharenbroch et al., 2016). Therefore, the primary aims of this study were to determine 1) whether redirecting stormwater to established trees could increase their transpiration, and 2) the potential contribution of transpiration to the water balance of stormwater control measures.

2. Materials and methods

2.1. Site description and experimental design

To assess the influence of SCMs on transpiration and the contribution of transpiration to the water balance, we installed 6 m^2 unlined infiltration trenches (sized from 2.4 to 4.6% of the connected impervious catchment) in the grassed verges of a low-density residential street in Melbourne, Australia (Fig. 1). Melbourne has a temperate climate (Peel et al., 2007), with mean annual temperature of 19.8 °C (1971–2019) and mean annual rainfall of 708 mm (1950–2019). Rainfall is relatively evenly distributed throughout the year, with long-term means ranging from 43.3 to 69.0 mm per month. Lowest rainfall generally occurs from January to March (BoM, 2019).

Nine established *Lophostemon confertus* trees (broadleaf, evergreen) were selected for the study, based on similarity in size and connected impervious catchment area (Table 1). Trees were allocated to one of three treatments 1) tree with no adjacent infiltration trench (*control*), 2) tree with an adjacent infiltration trench receiving stormwater through a vertical grated inlet (*lintel*), and 3) tree with an adjacent infiltration trench receiving stormwater through a horizontal grated inlet (*pit*). Fig. 1 illustrates a cross-section of trench dimensions and spacing relative to the trees. For further detail on the installation of infiltration trenches and

Table 1
Summary of mean treatment characteristics. Dbh is the stem diameter at breast height, sapwood area is the area of conducting wood where sap flow sensors are installed, PCA is the projected canopy area, SCM: catchment is the ratio of the surface area of the stormwater control measure to the impervious catchment area, and PCA: catchment is the ratio of projected canopy area to impervious catchment area. Values represent means (and standard error, n = 3).

Treatment	Dbh (cm)		Sapwood area (cm^2)		PCA (m^2)		Catchment area (m^2)		SCM: catchment (%)		PCA: catchment (%)	
Control	19.5	(1.8)	222.3	(47.2)	15.8	(1.1)	-		-		-	
Lintel	18.4	(1.4)	206.4	(18.8)	13.3	(1.8)	193.7	(33.8)	3.3	(0.6)	7.0	(0.4)
Pit	18.9	(2.7)	212.9	(70.4)	13.0	(1.7)	202.9	(28.7)	3.1	(0.4)	6.5	(0.6)

technical details of the inlet designs, see Szota et al. (2019).

2.2. Meteorological conditions

Meteorological conditions were monitored from October 2014 to April 2016 (Fig. 2). Two automatic weather stations were installed at each end of the street, which measured solar radiation (SP212, Apogee Instruments, Logan, USA), wind speed (014A, Met-One, Campbell Scientific, Garbutt, Australia), and air temperature and relative humidity (HMP155A, Vaisala, Melbourne, Australia) at 30-min intervals. Measurements from each station were averaged and used to calculate mean daily vapour pressure deficit (D) and mean daily Penman-Monteith reference evapotranspiration (ET_O) (Allen et al., 1998). Rainfall data from a rain gauge located 1.7 km from the study site were supplied by Melbourne Water (station: Oakleigh South) and aggregated into rainfall events using the

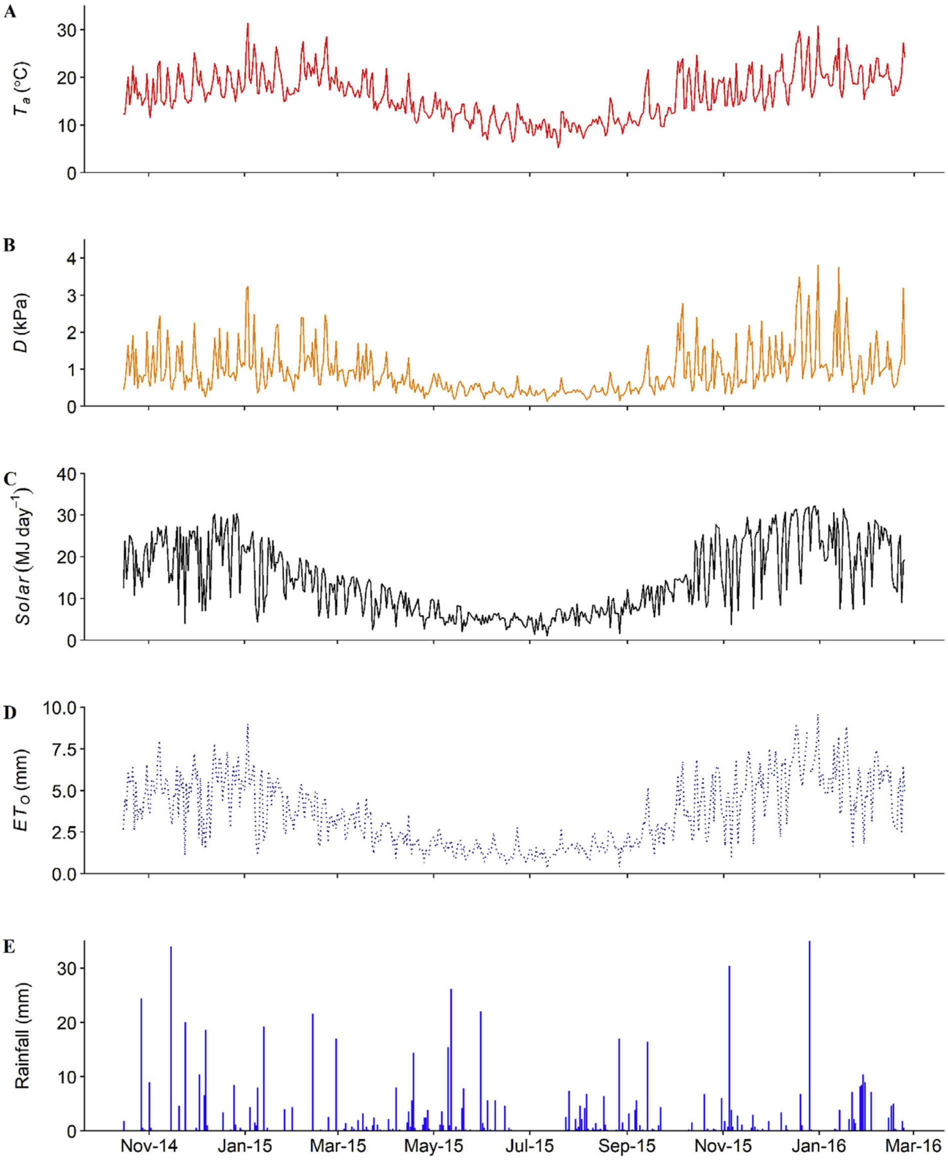

Fig. 2. Local environmental conditions during the two sap flow monitoring periods including mean daily A) air temperature (T_a), B) vapour pressure deficit (D), C) solar radiation ($Solar$), D) reference evapotranspiration (ET_O), and e) Rainfall.

hydromad package (Andrews et al., 2011) in R 3.4.2 (R Core Team, 2017). Events were distinguished by at least 6 hr without rainfall. Fig. 2 shows environmental conditions throughout the study.

2.3. Stormwater runoff and retention

Rainfall that generates stormwater runoff at this site (effective rainfall) was estimated by subtracting an initial loss of 0.5 mm from each rainfall event as calculated by Szota et al. (2019). Total stormwater runoff (Q_{Runoff}, m^3) was then estimated for each event by multiplying effective rainfall by the impervious catchment area (m^2) feeding into each infiltration trench. We assumed the grassed verge did not generate runoff because topsoil saturated hydraulic conductivity as measured at the site was 46.5 mm $hr^{-1}$and the maximum rainfall intensity during the study was 13.2 mm hr^{-1}. While runoff from saturation excess may occur when the permeable upper layers are full, this would be infrequent in this region (Hill et al., 1996). To determine stormwater retention ($Q_{Retention}$), Odyssey water level sensors (0.5 m, Dataflow Systems Ltd., Christchurch, NZ) were installed in each infiltration trench to measure depth of water (mm) at 6-min intervals. Stormwater retention (m^3) was then calculated as the sum of positive changes in water level (taking substrate porosity into account) during a stormwater runoff event, multiplied by the surface area of the trench:

$$Q_{Retention} = \left(SA_{trench} \times \sum \Delta WL\right) \times p \tag{1}$$

where SA_{trench} is the surface area of the trench (6 m^2, Fig. 1), ΔWL is positive changes in water level during a stormwater event, and p is the porosity of gravel in the trench. Infiltration trenches did not have an overflow outlet, so all retained stormwater was assumed to exfiltrate into surrounding soil. Once trenches were full, stormwater runoff could not enter the inlet, and therefore bypassed as discharge to stormwater networks.

2.4. Soil moisture

Two soil moisture sensors (Odyssey multi-profile soil moisture, Dataflow Systems Ltd, Christchurch, NZ) were installed 1 m from the base either side of each study tree, (parallel to the road). Soil moisture was monitored at 5 depths: 300, 500, 700, 900, and 1100 mm below the surface, representing the ‘total’ stored water in the soil profile (200–1200 mm). Average volumetric water content (VWC, %) was calculated for each depth class and averaged across the profile to get mean daily VWC. We used soil moisture data from the sensor located between the tree and infiltration trench. The second sensor was used to estimate soil moisture during periods when the first sensor had missing or sporadic data capture. During winter 2015, sensors were affected by preferential flow of water down the access tube causing malfunction, resulting in six weeks of missing data (Fig. 3).

2.5. Transpiration

Transpiration was estimated from sap flow sensors (SFM1, ICT international) utilising the heat ratio method measured at two depths, after Burgess et al. (2001). Two sap flow sensors were installed on the east and west side of each tree, approximately 1–2 m from the ground, during October to March (late spring to early autumn) from 2014 to 2016.

Sap flux (cm^3 cm^{-2} hr^{-1}) was calculated using a constant thermal diffusivity (Burgess et al., 2001) and specific sapwood properties (sapwood area, wood density, and moisture content) determined from tree cores (5 mm diameter) collected in April 2016. Data were corrected for an average wounding diameter of 1.8 mm. To correct for probe misalignment, climate data were filtered to identify periods where sap flux should equal zero as described in Pfautsch et al. (2010) and all data were linearly offset accordingly. Where a sensor thermistor failed, raw data from the opposite sensor was used to estimate sap flux from measured wood properties during that period. Sap flux was then multiplied by the cross-sectional area of sapwood surrounding each measurement depth (Hatton et al., 1990) to determine whole tree water use (sap flow, L).

To estimate transpiration (E_C, mm), east and west sap flow data were averaged, and divided by projected canopy area (m^2) for each study tree (Table 1).

2.6. Predicting annual transpiration

Since sap flow data were not available from April to September 2015, we estimated daily transpiration from environmental variables for each tree adjacent to an SCM (*pit* and *lintel* treatments). Estimated and measured transpiration were then combined to calculate an annual water balance for 2015. We assessed the relationship between transpiration and mean daily climate variables (air temperature, vapour pressure deficit solar radiation, and reference evapotranspiration), mean daily soil moisture (0–1200 mm profile), and mean daily water level for all SCM trees.

We compared all plausible combinations of these variables (excluding combinations of correlated variables) to select the model which explained the greatest variance in transpiration with the least explanatory variables. Both adjusted R^2 and Akaike information criterion (AIC) were used to select the best model for predicting transpiration. The model with high R^2 and low AIC was deemed most suitable.

2.7. The potential annual water balance

To assess the potential contribution of transpiration to the annual water balance of SCMs adjacent to established trees, we calculated a modified water balance for 2015.

The complete water balance is defined by (Eger et al., 2017) as:

$$R + P = Q + ET + I + \Delta S \tag{2}$$

where R is runoff from the impervious catchment area, P is direct precipitation on all surfaces in the catchment, Q is discharge to stormwater networks, ET is evapotranspiration, which includes transpiration from plants and evaporation from surfaces, I is infiltration, and ΔS is the change in stored water. In our study, we define a modified water balance relative to the impervious catchment only, that does not include P on the grassed verge, nor I from direct precipitation. Further, evaporation from surfaces (grassed verge, tree canopy) were not measured, so ET is comprised of tree transpiration only. Therefore, the modified water balance was calculated as:

$$Q_{Runoff} = Q_{Bypass} + Q_{Transpiration} + \Delta S \tag{3}$$

where Q_{Runoff} is the stormwater runoff generated by each impervious catchment area (Section 2.3) and does not include runoff from the grassed verge, Q_{Bypass} is the quantity of stormwater bypassing the SCM (i.e. discharge to stormwater networks) and is calculated as the difference between Q_{Runoff} and stormwater retention ($Q_{Retention}$, Eq. (1)). $Q_{Transpiration}$ is the transpiration from trees relative to the impervious catchment area, calculated by dividing sap flow (section 2.5) by the catchment area of each SCM

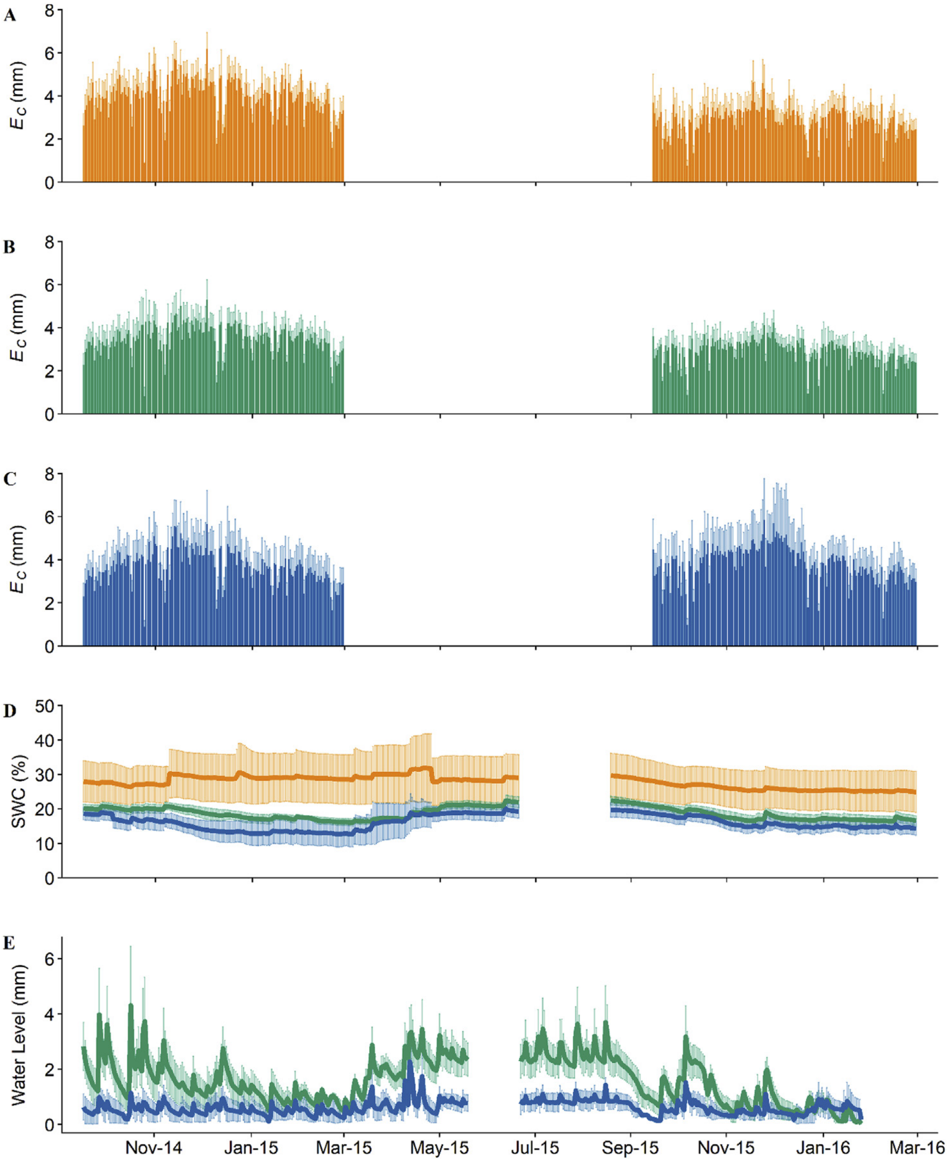

Fig. 3. Mean daily transpiration per projected canopy area (E_C, mm m^{-2}) of A) *control*, B) *lintel*, and C) *pit* trees were measured from October to April. D) Mean daily soil water content (SWC) and E) mean daily level of runoff retained were measured throughout the study and missing data was due to sensor maintenance. *Control* treatments are represented in orange, *lintel* treatments in green and *pit* treatments in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

tree. ΔS is the change in stored water, which could include deep percolation or a change in soil moisture, calculated as the residual of $Q_{Retention}$ and $Q_{Transpiration}$:

$$\Delta S = Q_{Retention} - Q_{Transpiration} \tag{4}$$

where $Q_{Retention}$ represents the infiltration of stormwater captured by the SCM.

2.8. Data and statistical analyses

To evaluate statistical differences between treatments, all variables were first assessed for normality and homogeneity to determine the most appropriate test. Where assumptions of normality and homogeneity were met (E_C), we used Tukey's HSD test. For non-homogenous variables (soil moisture) Welch's test was used, and for non-normal variables ($Q_{Retention}$) a Kruskal-Wallis test was used. R version 3.4.2 was used for all data processing and analysis (R Core Team, 2017).

3. Results

3.1. Treatment effects on transpiration, soil moisture, and water level

Trees used large quantities of water daily, ranging from 0.7 to 6.2 mm d^{-1} per projected canopy area (Fig. 3A, C), equivalent to 10.8 to 96.1 L d^{-1}. Mean daily soil moisture ranged from 12.7% to 31.9% (Fig. 3D) and mean daily water level retained at the catchment scale ranged from 0.03 to 4.3 mm d^{-1} (Fig. 3E).

We assessed the difference in treatment means for transpiration, soil moisture, and stormwater retention to evaluate whether redirecting stormwater to trees could increase transpiration. On average, trees transpired 3.5 mm d^{-1} (Fig. 4A), with no significant

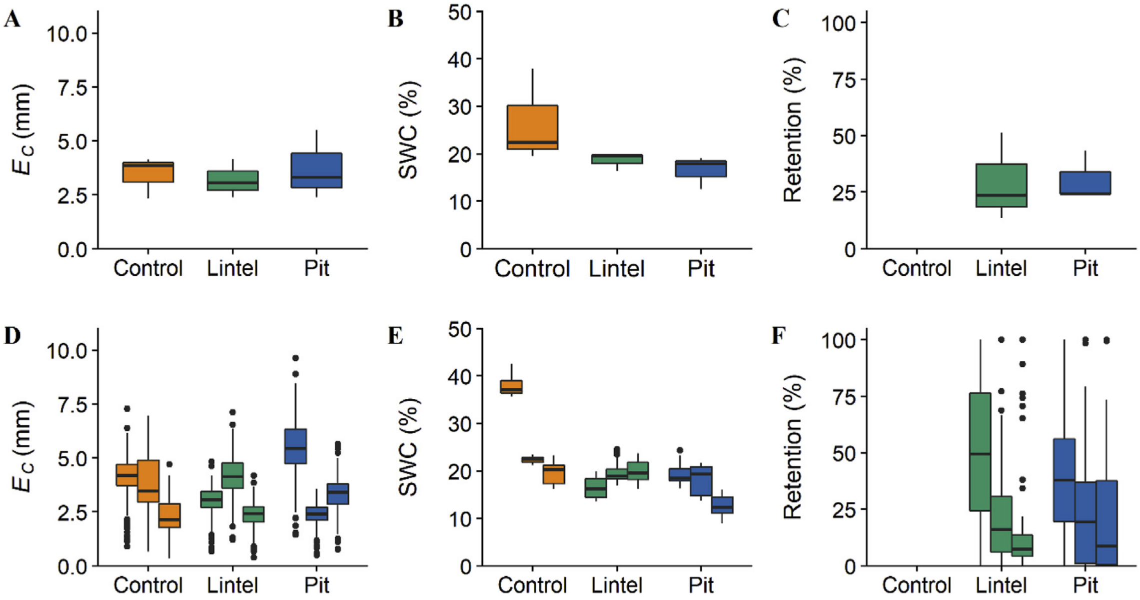

Fig. 4. Mean daily transpiration per projected canopy area (E_C, mm m^{-2}) (A and D), mean daily soil water content (B and E) and mean stormwater retention per rainfall event as a proportion of runoff (C and F). *Control* treatments are represented in orange, *lintel* treatments in green and *pit* treatments in blue. A-C show means per treatment and D-F show means per replicate. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

difference in transpiration per projected canopy area between treatments ($p = 0.86$). Mean daily soil moisture was 20.8% (Fig. 4B), with no significant difference between treatments ($p = 0.19$). There was large variation in the soil moisture of *control* trees, driven by a single replicate (Fig. 4E), which meant that soil moisture was often higher than *lintel* and *pit* treatments during the study (Fig. 3D). Mean stormwater retention per rainfall event was equivalent to 30% of runoff on average (Fig. 4C) and did not differ significantly between treatments ($p = 0.7$).

3.2. Predicting transpiration for calculation of an annual water balance

To evaluate the potential contribution of transpiration to the 2015 water balance, daily transpiration was modelled between April and September as sap flow was not measured in these months. Transpiration was positively correlated with natural log-transformed reference evapotranspiration, solar radiation, and vapour pressure deficit (Fig. 5A–C). Both air temperature and soil moisture (Fig. 5D–E) were weakly related to transpiration ($p < 0.05$, $R^2 < 0.05$) and there was no significant relationship between daily transpiration and mean daily water level in the trench on the same day (Fig. 5F). Since reference evapotranspiration had the highest R^2 and is calculated from other correlated climate variables, we predicted transpiration from reference evapotranspiration for each tree, which explained 82% of the variance in transpiration (Figure S1B).

3.3. The contribution of transpiration to the annual water balance

To assess the potential contribution of transpiration to the annual water balance of our SCMs, we calculated transpiration ($Q_{Transpiration}$) as a proportion of impervious catchment runoff (Q_{Runoff}). The residual difference between stormwater retention ($Q_{Retention}$) and transpiration was assumed to contribute to a change in soil water content (ΔS). Overall, transpiration was equivalent to 17% of total stormwater runoff generated by the connected impervious catchment in 2015. Stormwater retention was 24%, which exceeded transpiration overall. Therefore, on an annual basis, the potential change in stored water was equivalent to 7% of total runoff (Fig. 6). The partitioning of the water balance varied throughout the year. During warmer months (October–March), when transpiration was high, $Q_{Transpiration}$ (6–79%) was equivalent to, or exceeded $Q_{Retention}$ (10–40%), so the soil was often a source of water to trees, rather than a sink for stormwater (Fig. 7A). During cooler months (April–September), $Q_{Transpiration}$ was generally less then $Q_{Retention}$, because reference evapotranspiration was low during this period, so the soil was a sink for stormwater (Fig. 7A). Cumulatively, $Q_{Transpiration}$ decreased from 22% of Q_{Runoff} in warmer months to 12% of Q_{Runoff} in cooler months. Conversely, $Q_{Retention}$ increased from 20% in warmer months to 28% in cooler months. Therefore, $Q_{Transpiration}$ exceeded $Q_{Retention}$ in warmer months, while the reverse was true in cooler months.

4. Discussion

4.1. Does redirecting stormwater to established trees increase transpiration?

Our hypothesis that redirecting stormwater to established trees could increase transpiration relied on the assumption that these trees had limited access to water and are often drought stressed. However, there was no significant difference in mean transpiration per projected canopy area (3.5 mm d^{-1}) between SCM and control trees. As such, there was limited evidence to support our hypothesis. We suggest that redirecting stormwater did not increase transpiration in our study because trees already had access to enough water in the streetscape. Mean daily soil moisture in the roadside verge was 20.8% and did not differ between treatments, despite particularly high soil moisture for one *control* tree. The relationship between mean daily transpiration and soil moisture was weak, and there was no significant relationship between mean daily transpiration and water level within infiltration trenches, supporting our suggestion that water was not limiting in this study. Further, leaf water potential measurements demonstrated that these trees were not drought stressed throughout the two-year

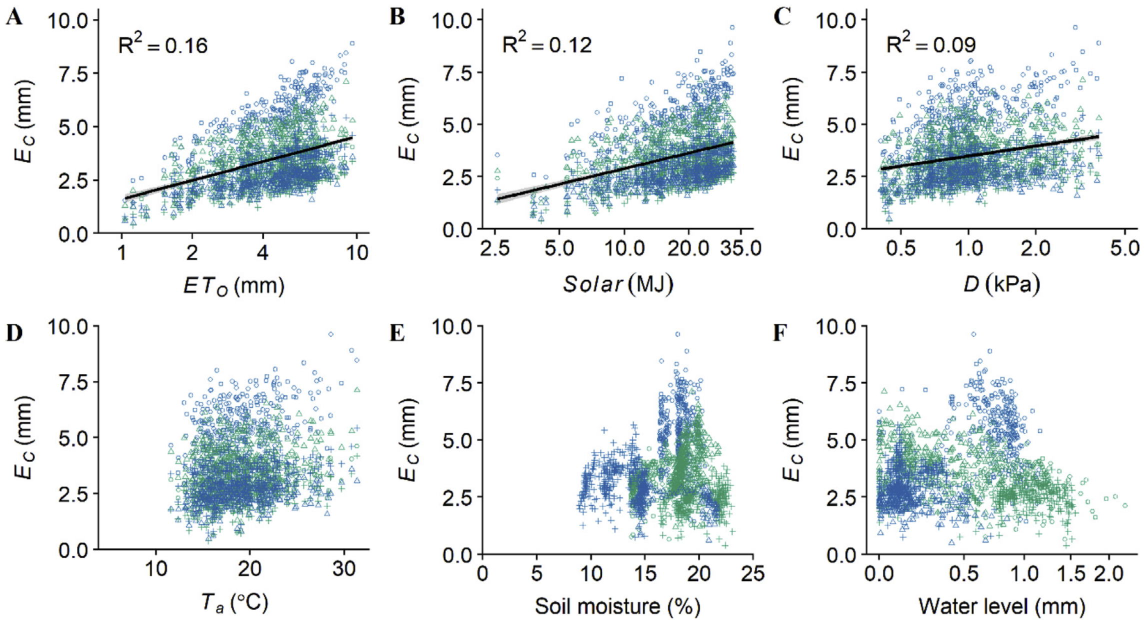

Fig. 5. Scatter plots of relationship between daily transpiration per projected canopy area (E_C, mm m^{-2}) and A) daily reference evapotranspiration (ET_O), B) mean daily solar radiation (*Solar*), C) mean daily vapour pressure deficit (D), D) mean daily air temperature (T_a), E) mean daily soil moisture, and F) mean daily depth of water retained (water level). *Lintel* treatments are represented in green and *pit* treatments in blue. Replicates 1–3 for each treatment are represented by circles, triangles, and crosses. Black lines represent significant relationships with $R^2 > 0.05$. Log transformations were applied to ET_O, D and water level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

study (Szota et al., 2019). High variability in soil moisture within our street road verges highlights the inherent heterogeneity of soil properties and soil moisture availability within urban landscapes (Ossola and Livesley, 2016). Many potential water sources exist within the urban landscape, such as leaky pipes (Bonneau et al., 2018) or verge irrigation (Marshall et al., 2019). Large established trees have been shown to extend roots toward such wet zones (Östberg et al., 2012; Čermák et al., 2000). Assuming that all urban trees are water limited may therefore be an oversimplification of the complex heterogeneity that exists in urban landscapes. Installing SCMs in dense urban areas that have less permeable surfaces and obvious limited soil moisture, vegetation drought stress, or hotter and drier climates, may result in a greater positive influence on the transpiration of adjacent trees. Additionally, installing SCMs with large storage, detention zones, and slower infiltration rates could extend the length of time water is available to adjacent trees, or contribute to greater soil moisture recharge, which can support the water requirements of trees beyond the immediate rainfall event (Symes and Connellan, 2013).

4.2. The contribution of transpiration to the water balance

Although we could not conclude that redirecting stormwater to trees increased transpiration, our data shows that established trees can use large volumes of water, which could improve the volume reduction efficiency of SCMs (Nocco et al., 2016). In our study, established trees used up to 96 L d^{-1}, in line with other studies on urban tree water use for a range of species and climates (Čermák

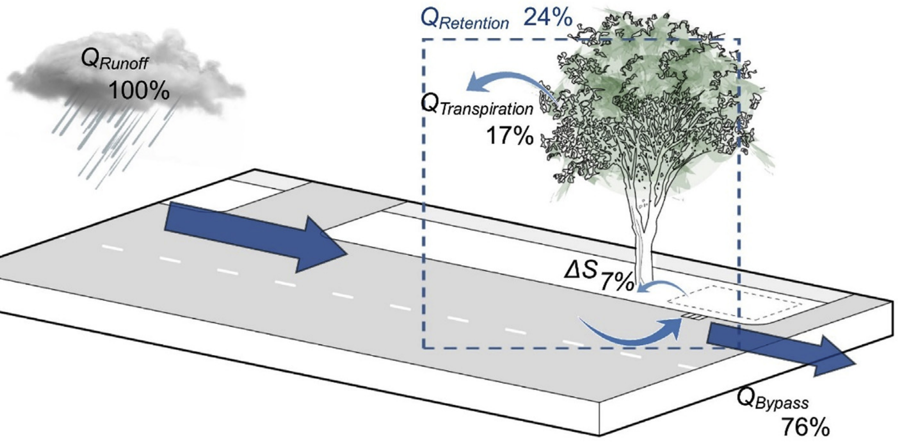

Fig. 6. The mean monthly water balance of stormwater control measures in this study (variables in black font). Total runoff (Q_{Runoff}, largest blue arrow) generated by the connected impervious catchment (grey shaded area) is partitioned into the quantity bypassed (Q_{Bypass}), the quantity transpired by the tree ($Q_{Transpiration}$) and the change in stored water (ΔS). The sum of $Q_{Transpiration}$ and ΔS represents the potential pathways of the quantity infiltrated into the soil by the infiltration trench ($Q_{Retention}$), highlighted by the dashed blue square. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

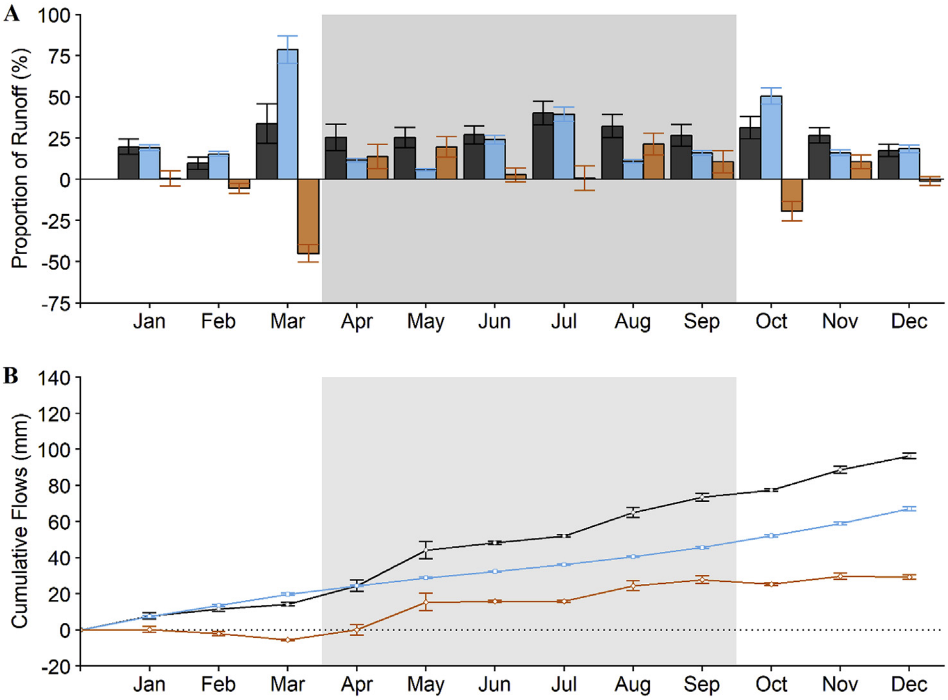

Fig. 7. The mean quantity transpired by the tree ($Q_{Transpiration}$, blue) and change in stored water (ΔS) per month as A) a proportion of stormwater runoff from the connected impervious catchment, and B) cumulative monthly flows (mm). The sum of $Q_{Transpiration}$ and ΔS represents the potential pathways of the quantity infiltrated into the soil by the infiltration trench ($Q_{Retention}$, black). Shaded areas indicate months where transpiration was predicted from reference evapotranspiration. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article).

et al., 2000; Litvak et al., 2012; Wang et al., 2012). Over a year, established tree transpiration was equivalent to 17% of total runoff from a 198 m^2 connected impervious catchment. Hence, evapotranspiration from SCMs sized from 2.4 to 4.6% of the connected impervious catchment in our study was much greater than is generally reported for small-scale SCMs (1–5% of the connected impervious catchment) such as biofiltration systems, which is generally less than 5% of stormwater runoff (Brown and Hunt, 2011; Daly et al., 2012; Winston et al., 2016). Established trees have the potential to transpire a much larger proportion of stormwater runoff in the water balance compared with standard biofiltration systems, increasing evapotranspiration toward pre-development proportions and reducing runoff volumes. We suggest this is due to several factors including 1) projected canopy area, 2) connected impervious catchment area, 3) system design, and 4) rainfall distribution.

Mean transpiration rates per projected canopy area of established trees in this study (3.5 mm d^{-1}) were within the range previously reported for SCMs (2.7–7.7 mm d^{-1}) planted with a variety of vegetation types (Denich and Bradford, 2010; Tirpak et al., 2019; Wadzuk et al., 2015). The key difference is that per unit SCM surface area, trees are much more efficient. For example, while established trees in our study transpired up to 6.2 mm d^{-1} per projected canopy area (13 m^2), transpiration per SCM area (6 m^2) was equivalent to 13.4 mm d^{-1}. Therefore, A tree-based SCM could be much more efficient than an equivalent SCM planted with sedges or rushes, because the canopy area providing the transpiration pathway in the water balance extends beyond the SCM ‘footprint’ at ground level (Berland et al., 2017). High transpiration rates relative to the SCM surface area could markedly increase volumetric reduction efficiency of SCMs by creating greater storage capacity between rainfall events (Nocco et al., 2016; Szota et al., 2017). While species differences would play a major role in transpiration rates, particularly during drought (Szota et al., 2018) and recovery from water deficit (Brodribb and McAdam, 2013), we propose projected canopy area would be an important point of difference between trees and other vegetation types influencing the proportion of stormwater runoff that could be transpired from SCMs. Of course, trees grow over time, so smaller trees would transpire less runoff initially when their projected canopy area is less than or equivalent to the SCM footprint at ground level. Grey et al. (2018) estimated evapotranspiration of young trees with a projected canopy area equal to the SCM footprint (0.72 m^2) in a dense streetscape, was up to 2.8% of total runoff, in line with standard biofiltration estimates (Brown and Hunt, 2011; Daly et al., 2012; Winston et al., 2016). However, as trees mature, extending their canopy area beyond the SCM, volumetric transpiration, and therefore volumetric reduction efficiency could increase. We therefore suggest that tree-based SCMs be designed to target a projected canopy area at maturity relative to the connected impervious catchment, in combination with appropriate SCM-to-catchment ratios, so that system retention and storage capacity can be matched with the potential water requirements of the mature canopy.

The surface area of small SCMs such as raingardens and biofiltration systems tends to be much smaller than the catchment (Payne et al., 2015), meaning they receive very large volumes of stormwater runoff (Gao et al., 2018; Hoskins and Peterein, 2013), and rendering the volume transpired comparatively small (Braswell et al., 2018; Grey et al., 2018). Since smaller catchments will generate lower runoff volumes, a greater proportion of that runoff could be transpired for the same projected canopy area. In our study, SCMs were spaced approximately three residential frontages apart, corresponding to a 198 m^2 connected impervious catchment area on average. The projected canopy area of SCM trees (13 m^2) was therefore equivalent to 7% of the catchment. If SCMs had been installed outside each house, the projected canopy area would be equivalent to 19% of the catchment (70 m^2), so transpiration could be equivalent to 50% of generated runoff, if the tree transpired an average of 3 mm m^{-2} of projected canopy d^{-1} throughout the year. Therefore, the volume of runoff a given canopy receives at ground level will markedly influence the potential contribution of transpiration to the water balance. In our study, rainfall was particularly low during March 2015, resulting in minimal stormwater runoff from the catchment. As such, transpiration was 79% of total runoff, emphasizing how the volume of runoff affects the relative proportion of flows that are transpired. Increasingly, studies have emphasised the role that evapotranspiration can play in the water balance of small-scale SCMs such as green roofs or biofiltration systems. A summary of evapotranspiration from SCMs was conducted by Eger et al. (2017) and Ebrahimian et al. (2019), who suggest 20–80% of the water balance can be evapotranspired. However, these studies often have small or no connected impervious catchment areas (Hess et al., 2017; Nocco et al., 2016). To increase volume reduction efficiency of tree-based SCMs compared with standard bioretention systems, we suggest that smaller connected impervious catchments, combined with larger projected tree canopy could be considered, thus increasing the proportion of runoff that is transpired. This greater SCM efficiency could also be achieved through a narrow, but continuous SCM trench that provides supplementary soil moisture to all the trees planted within the street. Tree plantings could include a combination of large mature trees or shrubs and other vegetation to maximise the projected canopy area transpiring from the SCM. However, if catchment sizes are decreased, larger storage volumes may be required to ensure the water requirements of trees are met.

The potential of established trees to transpire runoff retained by adjacent SCMs assumes the SCMs function efficiently and do not block or restrict water inflow. In our study, a large proportion of runoff (76%) bypassed the SCMs due to issues with inlet design, transmission efficiency, and blockages (Szota et al., 2019). These complications limited stormwater inflow and therefore retention, which meant that tree transpiration often exceeded runoff retention during summer months. Improving inlet efficiency could enable SCMs to meet water requirements of trees, even during periods of high transpiration. In addition to supplementing water requirements of adjacent trees, unlined SCMs can contribute to recharging soil moisture, when runoff retention exceeds transpiration in cooler months. Building up soil moisture storage in cooler months when tree water requirements are lower, also referred to as soil water banking (Symes and Connellan, 2013), could support higher tree transpiration in subsequent spring and summer months, especially for cities with reduced spring/summer rainfall. The variation in water balance partitioning at both the annual and monthly scales, will be further affected by the distribution of rainfall and leaf phenology. For deciduous trees, the contribution would be considerably lower or close to zero during winter months (Harper et al., 2015), contributing to greater soil water banking or groundwater recharge. Hence, the potential contribution of transpiration to the water balance reported here, would vary for similarly sized trees in cities with different rainfall distributions, hotter and drier climates that have greater reference evapotranspiration, or for deciduous trees.

5. Conclusions

Evapotranspiration from SCMs is increasingly recognised as an important aspect of the water balance, but is a small part relative to the large volume of stormwater runoff generated by connected impervious catchments. We found that established urban trees retrofitted with infiltration trenches transpired large volumes of water, equivalent to 17% of annual runoff generated. Established trees have the potential to transpire a greater proportion of runoff from small SCMs than other vegetation types, because their transpiring canopy area typically extends beyond the surface area of an SCM at ground level. To maximise the proportion of stormwater transpired from a street, planners could create minimum projected canopy area to impervious catchment ratios for SCMs. A combination of smaller impervious catchment areas, and large established trees, could increase the volumetric reduction of stormwater runoff in a street. While we could not conclude that redirecting stormwater to trees through SCMs increases transpiration rates of established trees in this study, we have shown that the large volume of annual transpiration means integrating trees with SCMs has the potential to markedly increase the proportion of evapotranspiration in the water balance of SCMs and therefore, volumetric reduction of stormwater runoff. Since public space is highly contested in cities and increasing canopy cover is a priority of many planners, integrating trees into SCMs could provide dual benefits for a single management intervention, and enable a greater number of distributed stormwater control measures with smaller impervious catchments in the streetscape, improving overall performance and benefits.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watres.2020.115597.

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