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# Supporting growth and transpiration of newly planted street trees with passive irrigation systems

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## Key Points:

- Passive irrigation systems with a saturated zone and underdrain supported accelerated tree growth in initial years following planting.
- Accelerated growth was not sustained beyond two years. Despite this, trees with greater initial growth used more water in later years.
- Hence, passive irrigation systems may facilitate cooling and runoff reduction benefits through greater growth and transpiration.

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## Abstract

Solutions that use stormwater runoff to rapidly establish tree canopy cover in cities have received significant attention. Passive irrigation systems that direct stormwater to trees have the potential to increase growth and transpiration and may limit drought stress. However, little data from the field demonstrates this, and we lack robust and reliable designs which achieve it. Here, we quantified growth and transpiration for trees: i) in infiltration pits receiving stormwater, with a raised underdrain and internal water storage (*drained*), ii) next to infiltration pits receiving stormwater but without an underdrain and internal water storage (*adjacent*), and iii) planted in standard pits, not receiving stormwater (*control*). Trees in *drained* pits grew twice as fast as *control* trees in the first two years, but fast initial growth rates were not sustained in years three and four. Trees outgrowing the small infiltration pits, rather than a lack of water, was most likely responsible for growth rates slowing down. Despite this, rapid initial growth for trees in *drained* pits meant trees were larger by age three and transpired more than twice as much (5.1 L d<sup>-1</sup>) as trees *adjacent* to pits (2.4 L d<sup>-1</sup>) or *control* trees (2.3 L d<sup>-1</sup>). No trees showed drought stress during the study. However, some trees planted adjacent to infiltration pits showed waterlogging stress, suggesting caution installing infiltration pits adjacent to establishing trees in fine-textured soils. Overall, our results suggest passive irrigation systems can substantially increase initial tree growth, thereby facilitating greater cooling and runoff reduction through increased transpiration.

## 1 Introduction

Increasing tree canopy cover is being prioritised in cities due to the important ecosystem services that trees and vegetation provide (Endreny et al., 2017). A primary motivation for increasing canopy cover is to reduce urban heat, which is caused by higher absorption and emission of heat from impervious urban surfaces as compared to pervious, vegetated surfaces (Coutts et al., 2007; Rizwan et al., 2008). Trees can mitigate urban heat by reducing air temperatures through evapotranspiration and reducing radiant temperatures through the provision of shade during the day (Gillner et al., 2015; Guhathakurta & Gober, 2010; Konarska et al., 2016). These processes largely depend on both the size of trees and their transpiration rates (Rahman et al., 2020a; Tan et al., 2020). Yet, tree establishment and growth can be difficult in cities due to extensive impervious surfaces, compacted urban soils, conflicts with below-ground infrastructure restricting root development, and soil water

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availability (David et al., 2018; Jim, 2019; Somerville et al., 2018). For newly planted trees, low infiltration can be particularly problematic as establishing root systems require water to be available close to the root ball (Caplan et al., 2019; Vogt et al., 2015). Trees can be supported with irrigation to increase soil moisture and promote faster growth and canopy expansion (Montague & Bates, 2015). However, irrigating newly planted street trees is costly, requiring large potable water and labour resources (Pataki et al., 2011). For cities facing water scarcity and/or a hot and dry climate, active irrigation (regular, controlled moisture inputs) of street trees may not be feasible (Luketich et al., 2019). If ambitious canopy cover targets are to achieve urban cooling benefits, we need simple, robust methods to support the establishment and growth of newly planted trees.

While extensive impervious surfaces across urban landscapes restrict rainfall from infiltrating into the soil, they also generate large volumes of stormwater runoff, resulting in flash flooding and degradation of receiving waterways (Walsh et al., 2015). Stormwater control measures such as biofilters and infiltration trenches are used internationally to reduce the volume of stormwater runoff in urban areas through detention, infiltration, and evapotranspiration (Nocco et al., 2016; Yang & Chui, 2018). Yet, space constraints in cities can prevent the implementation of numerous or large stormwater control measures, when competing with other public space initiatives such as street trees (Berland et al., 2017). Hence, combining stormwater control measures and urban forest expansion strategies shows increasing promise (Carlyle-Moses et al., 2020; Scharenbroch et al., 2016). Many vegetated stormwater control measures are planted with shrubs and/or grasses, which typically evapotranspire less than 5% of runoff (Gao et al., 2018; Winston et al., 2016). Including trees that can intercept stormwater and transpire at high rates, could not only increase the number of stormwater control measures in public spaces, but also enable greater runoff reduction through evapotranspiration (Deutscher et al., 2019; Szota et al., 2018). At the same time, studies have demonstrated greater growth in trees irrigated with stormwater (Denman et al., 2016; Grey et al., 2018a; Scharenbroch et al., 2016). Hence, passively irrigating trees could contribute to faster expansion of urban forests, while also increasing the potential volume of stormwater that can be transpired from urban environments, thereby reducing the volume of runoff received by downstream waterways.

Directing stormwater runoff to irrigate vegetated landscapes in cities is often referred to as 'passive irrigation'. Passive irrigation systems planted with trees (e.g. raingardens, bioswales, or stormwater tree pits) simultaneously aim to i) support tree growth and transpiration by

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increasing soil moisture available to trees and ii) reduce the pollutant load and volume of stormwater runoff, with a spectrum of designs available to address these aims. The impact of passive irrigation systems on tree growth is highly variable (Caplan et al., 2019; Scharenbroch et al., 2016; Szota et al., 2019). To support tree growth and transpiration, passive irrigation systems must ensure trees have adequate soil moisture between rainfall events (Tu et al., 2020), while limiting waterlogging (Grey et al., 2018a). To minimise the risk of waterlogging, designs can include an underdrain, or trees can be planted adjacent to stormwater infiltration pits (Grey et al., 2018a; Szota et al., 2019; Thom et al., 2020b). However, such designs may limit soil moisture between rainfall events (Caplan et al., 2019; Tu et al., 2020). When waterlogging was avoided, Grey et al. (2018a) demonstrated that passive irrigation systems can double the growth of newly planted trees, relative to control trees in the first two years of establishment. Whether passive irrigation systems can support greater growth rates beyond establishment is unknown. While there have been multiple high-level planning documents released in recent years that guide design of passive irrigation systems to support tree growth and stormwater retention (e.g. E2DesignLab (2020), EPA (2013)), such documents are typically based on case studies, due to the limited availability of replicated experiments. Hence, to assess the success and trade-offs of passive irrigation designs to support trees, long-term monitoring of growth and an understanding of the water use of passively irrigated street trees is needed.

In this study, we designed, built, and monitored two different infiltration pit designs to determine the impact of passive irrigation systems on the water use and growth of newly planted *Acer campestre* (L.) saplings (stem diameter of 2.2 to 2.5 cm at 0.5 m when planted). We monitored stem diameter growth over four years and sap flow in the third year after planting. Specifically, we sought to determine whether passive irrigation systems i) support greater transpiration, and ii) sustain greater growth rates than control trees beyond the first two years of growth. Since transpiration and growth are good indicators of the success of passive irrigation systems, the results from this study can help inform design considerations for passive irrigation systems that can support faster tree growth and greater transpiration. Faster growth and higher transpiration could facilitate greater cooling benefits and greater retention of stormwater runoff in urban environments.

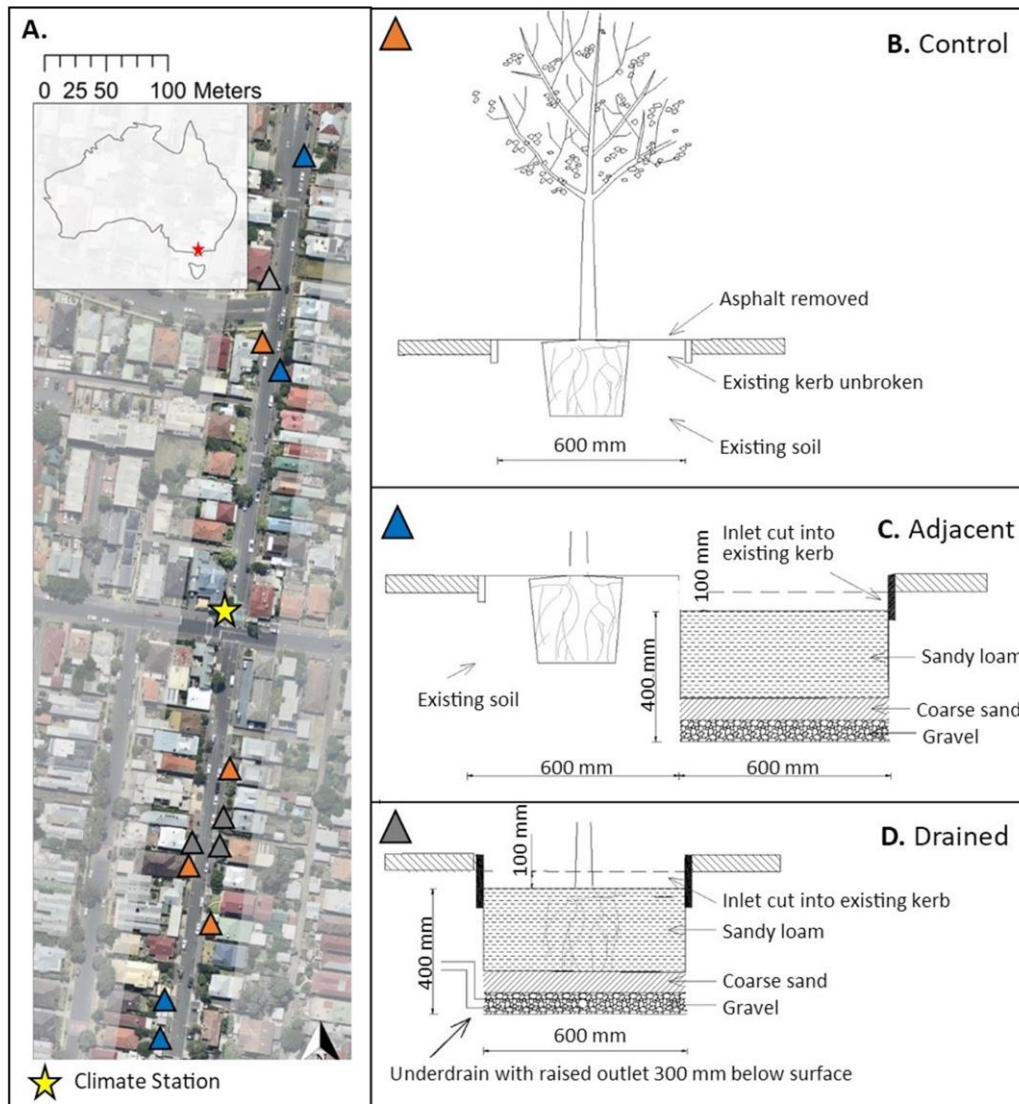
## 2 Materials and Methods

The setup of the experimental site is described in detail by (Grey et al., 2018a), who monitored tree growth (from stem diameter measurements) for 18 months from September 2015 to April 2017. We continued stem diameter measurements of two of the infiltration pit designs measured by (Grey et al., 2018a) as well as control trees until August 2019. The remaining two treatments in Grey et al (2018a) experienced waterlogging that caused tree mortality for some replicates and were not included in this study. We also monitored sap flow in the third growth year (August 2017 to 2018). The measurement periods for the two study questions were therefore:

- Stem diameter growth: Four growth years, September 2015 to August 2019.
- Transpiration and sap flow: The third growth year, August 2017 to August 2018.

### 2.1 Site description and experimental design

The study site was a north-south oriented residential street in a medium-density housing area of inner-north Melbourne, Australia (Figure 1A). This region of Melbourne has a temperate climate with mean maximum daily temperature of 20.2 °C and mean annual precipitation of 659.6 mm (BoM, 2020). Mean monthly rainfall ranges from 42.7 to 69.0 mm and is relatively evenly distributed throughout the year (BoM, 2020). The predominant soil type was classified as heavy clay from textural samples taken at the site (Grey et al., 2018a). The roadway was approximately 7 m wide, with no grassed verge, but with 2 m wide asphalt footpaths on either side. Since the street was narrow, space for tree planting was limited. The standard approach to tree planting in Melbourne (*control*) under this scenario is to cut approximately 1.2 m x 0.6 m from the road side of the asphalt footpath and to plant the tree into the heavy clay native soil (Grey et al., 2018a), with some minor irrigation during summer in the first growth year.



**Figure 1.** A) Map of tree locations at the study site (triangles) and sections of the three corresponding treatments. B) *control* trees, C) trees planted *adjacent* to undrained pits, and D) trees planted in *drained* tree pits. The surface area of the tree pits and asphalt cut-outs for *control* trees was 0.72m<sup>2</sup>.

To assess the effect of passive irrigation systems on the growth and water use of newly planted trees we studied three street tree treatments: 1) a tree in native soil (*control*; Figure 1B) ii) a tree planted in native soil adjacent to a passively irrigated undrained infiltration pit (*adjacent*, Figure 1C); and iii) a tree planted in an infiltration pit with a raised underdrain and internal water storage (saturated zone) at the base (*drained*, Figure 1D). Each treatment had five replicates, however, one *drained* replicate was compromised early in the study (Grey et al., 2018a). Hence, four replicates per treatment were instrumented with sap flow sensors to

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measure water use. Each treatment was planted with an *Acer campestre* (L.) tree (broadleaf, deciduous) in June 2015. At planting, tree stems (at 0.5 m) were between 2.2 and 2.5 cm diameter and tree height ranged from 2.8 to 3.8 m. All trees were planted into a 0.35 m diameter by 0.25 m deep planting hole (Grey et al., 2018a). The surface area of the infiltration pits was the same as the sidewalk cut-outs for *control* trees (1.2 m x 0.6 m; 0.72 m<sup>2</sup>). The average connected impervious catchment area that provided runoff to the infiltration pits was 356 m<sup>2</sup> (100 m<sup>2</sup> to 1000 m<sup>2</sup>). As such, the infiltration pit surface areas were on average 0.3% (0.1 to 0.7%) of their connected impervious catchment area. For *adjacent* and *drained* treatments, infiltration pits were excavated to a depth of 0.5 m below the road surface and backfilled with three substrate layers; sandy loam (0.3 m), coarse sand (0.025 m) and gravel (0.075 m) leaving a 0.1 m detention zone for standing runoff water at the top of the pit.

## 2.2 Environmental conditions

An automatic weather station (Campbell Scientific Australia Inc., Logan, Utah, USA) measured air temperature and relative humidity (HMP155A, Vaisale, Melbourne, Australia), solar radiation (SP212, Apogee Instruments, Logan, USA), and wind speed (014A, Met-One, Campbell Scientific, Garbutt, Australia) on site at an hourly time step (Thom 2020a). Rainfall was measured as the average of two tipping buckets (Davis Instruments, USA and Dataflow Systems Ltd., Auckland, NZ). From September 2017 to January 2018, the solar radiation (*slr*) sensor failed, therefore a relationship between measured *slr* and solar radiation data sourced from Melbourne Airport (BoM (2019); Station ID: 086282, 12 km from study site) was used to estimate *slr* during this time ( $slr = 0.92 * BoM$ ,  $R^2 = 0.92$ ). The rainfall gauge was offline from April to June 2018, so rainfall during this period was estimated from the average of two Melbourne Water rain gauges (Coburg, 2.3 km NNE and Northcote 2.6 km SE from the site). Vapour pressure deficit (*D*) and reference evapotranspiration (*ET<sub>0</sub>*) were calculated from measured climate variables following the FAO 56 Penman-Monteith equation (Allen et al., 1998). We installed 0.5 m Odyssey capacitance water level sensors (Dataflow Systems, Christchurch, NZ) within perforated PVC access tubes into the infiltration pits to measure the depth to water at a 6-minute timestep (Thom 2020a). The depth to water (measured from the ground surface) was averaged per day for each tree, then mean depth was calculated for pits *adjacent* to trees and *drained* pits with trees planted inside (Figure 2E). Soil moisture sensors

were installed at each treatment, however they failed during the study. Hence, depth to water was used as a proxy to understand water availability in *drained* and *adjacent* treatments.

### 2.3 Relative stem diameter growth

Stem diameter was measured in two axial directions (at 90°) at 0.5 m above the substrate surface using digital Vernier calipers ( $\pm 0.01$  mm) as per Grey et al. (2018a). Measurements were collected during the ‘in leaf’ period from September 2015 to September 2019 (Thom 2020a). To assess differences in relative stem diameter growth per growing season (September to March), relative growth was calculated as a percentage of the stem diameter at the start of the growing season (September) relative to the end of the growing season (March). To assess cumulative stem diameter growth over the four years, relative growth was calculated as a percentage of the initial diameter when trees were planted in 2015.

### 2.4 Sap flux, sap flow and transpiration

To estimate tree water use, sap flow sensors (SFM1, ICT International, Armidale, Australia) were installed into the North side of each tree stem at a height of approximately 0.2 m from the ground. SFM1 sensors utilise the heat ratio method developed by Burgess et al. (2001) to estimate sap flux ( $\text{cm}^3 \text{cm}^{-2} \text{hr}^{-1}$ ) from heat velocity ( $\text{cm hr}^{-1}$ ). SFM1 needles have two thermistors to estimate sap flux at ‘outer’ (close to the sapwood-phloem boundary) and ‘inner’ (15 mm toward heartwood from the outer thermistor) depths. The needles were installed so that the outer thermistor was positioned approximately 5 mm beneath the sapwood-phloem boundary of each tree (Burgess & Downey, 2014). Mean tree height was  $3.4 \text{ m} \pm 0.4 \text{ m}$  and mean height to the base of the canopy was  $0.8 \text{ m} \pm 0.1 \text{ m}$ . The low installation height avoided the stem diameter measurement point (0.5 m) and allowed the sensor and external battery to be concealed in a secure box at ground level to reduce the risk of vandalism. The installation site was covered in aluminium foil to mitigate the influence of radiation fluxes on measurements (Figure S4). Tree coring to determine the moisture content of sapwood was not feasible and trees could not be harvested, so sections cut approximately 0.1 m above the substrate of four *A. campestris* trees of comparable stem diameter grown under well-watered nursery conditions, were used to estimate mean fresh and dry weight of the sapwood (mean diameter of 3.7 cm compared with mean diameter of 3.9 cm for trees at the study site at the start of sap flow monitoring). Although differences in moisture content

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between our study trees and the nursery trees are a potential source of error, natural (diurnal to seasonal) variation in moisture content is a common source of error across all studies that use a single moisture content to calculate sap flux (López-Bernal et al., 2014). Sap flux was linearly offset for zero-flow conditions (low  $D$ , pre-dawn, following rainfall) as described in Pfautsch et al. (2010). Sap flow ( $L h^{-1}$ ) was then estimated by multiplying sap flux measured at the outer thermistor by daily sapwood area ( $cm^2$ ) of each tree (Thom et al. 2020a). Inner thermistor measurements were ignored as their positioning in the stem differed between trees (either in the middle or southern side of the tree) depending on stem diameter. Sapwood area was calculated from stem diameter measurements as

$$A = \pi \cdot (r_{EW} - B) \cdot (r_{NS} - B) \quad (1)$$

where  $A$  = area,  $r_{EW}$  = the east-west radius,  $r_{NS}$  = the north-south radius and  $B$  = bark depth (0.5 cm). Daily sapwood area ( $cm^2$ ) was estimated by linearly interpolating sapwood area calculated from each diameter measurement. All stemwood was assumed to be sapwood, based on the nursery trees with comparable stem diameter.

Equivalent transpiration per footprint at ground level ( $mm h^{-1}$ ) was then calculated by dividing sap flow by the surface area ( $0.72 m^2$ ) of the infiltration pit (*adjacent* and *drained* trees) and sidewalk cut-out (*control* trees). To assess differences among treatments, sap flux and sap flow data (and thus the equivalent transpiration rate) were summed to daily timesteps. We assessed differences for three periods: 1) spring (September-October), 2) summer, (November-March), 3) autumn (April-May). The periods were grouped by months with no significant difference in mean monthly air temperature (Table S1)

Sap flow sensors were periodically offline due to an internal battery issue. Therefore, periods where less than three replicates were available per treatment were excluded from analyses. This meant no sap flow data was available for one month between February and March.

## 2.5 Relative sap flow

Sap flow and thus transpiration are highly influenced by soil moisture, vapour pressure deficit, and solar radiation (Thomsen et al., 2020; Tirpak et al., 2018). Normalizing sap flow can provide insight to the relationship between one or more of these variables (Kunert et al., 2010; Thomsen et al., 2020). We normalised sap flow relative to climate conditions to give insight to the influence of soil moisture (e.g. waterlogging and drought) and therefore passive irrigation on tree water use. Sap flow was normalised by dividing daily sap flow by predicted

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daily maximum potential sap flow ( $S_{max}$ ) for each tree during summer to get relative sap flow ( $E_{rel}$ , % of  $S_{max}$ ).  $E_{rel}$  therefore represented the efficiency of water use on a given day. To determine  $S_{max}$  we binned daily sap flow during summer into classes of 0.5 mm  $ET_O$  (0 – 8.5 mm), and extracted the maximum daily sap flow per bin. We then estimated  $S_{max}$  from an asymptotic model of the relationship between  $ET_O$  and maximum daily sap flow per bin. Four models (linear, exponential, power, and asymptotic) of the relationship between  $ET_O$  and maximum daily sap flow per bin were assessed. The  $R^2$  for each non-linear model fit was calculated from a linear regression of predicted versus observed values of  $S_{max}$ .  $P$  values were then calculated by running an analysis of variance for the non-linear against a linear model. The asymptotic model was selected to estimate  $S_{max}$ , as it had the lowest Akaike information criterion (AIC) compared with the other model fits and highest  $R^2$  for all trees.

## 2.6 Statistical analyses

One-way ANOVA in combination with Tukey's honest significant difference test were used to assess differences in mean monthly air temperature to determine seasons (Table S1), as well as differences among treatments in mean relative stem diameter growth per replicate per year and per replicate after four years. The same analysis was used to determine if there were differences among treatments in mean daily sap flux density and sap flow per replicate per season identified (spring, summer, and autumn). Differences in  $E_{rel}$  among treatments were only assessed during summer, and we compared the probability of trees exceeding  $E_{rel}$  of *control* trees by calculating  $E_{rel}$  per treatment and ranking these values from 0 to 100 to create an exceedance curve. We used R version 3.4.2 for all data analysis (R Core Team, 2017).

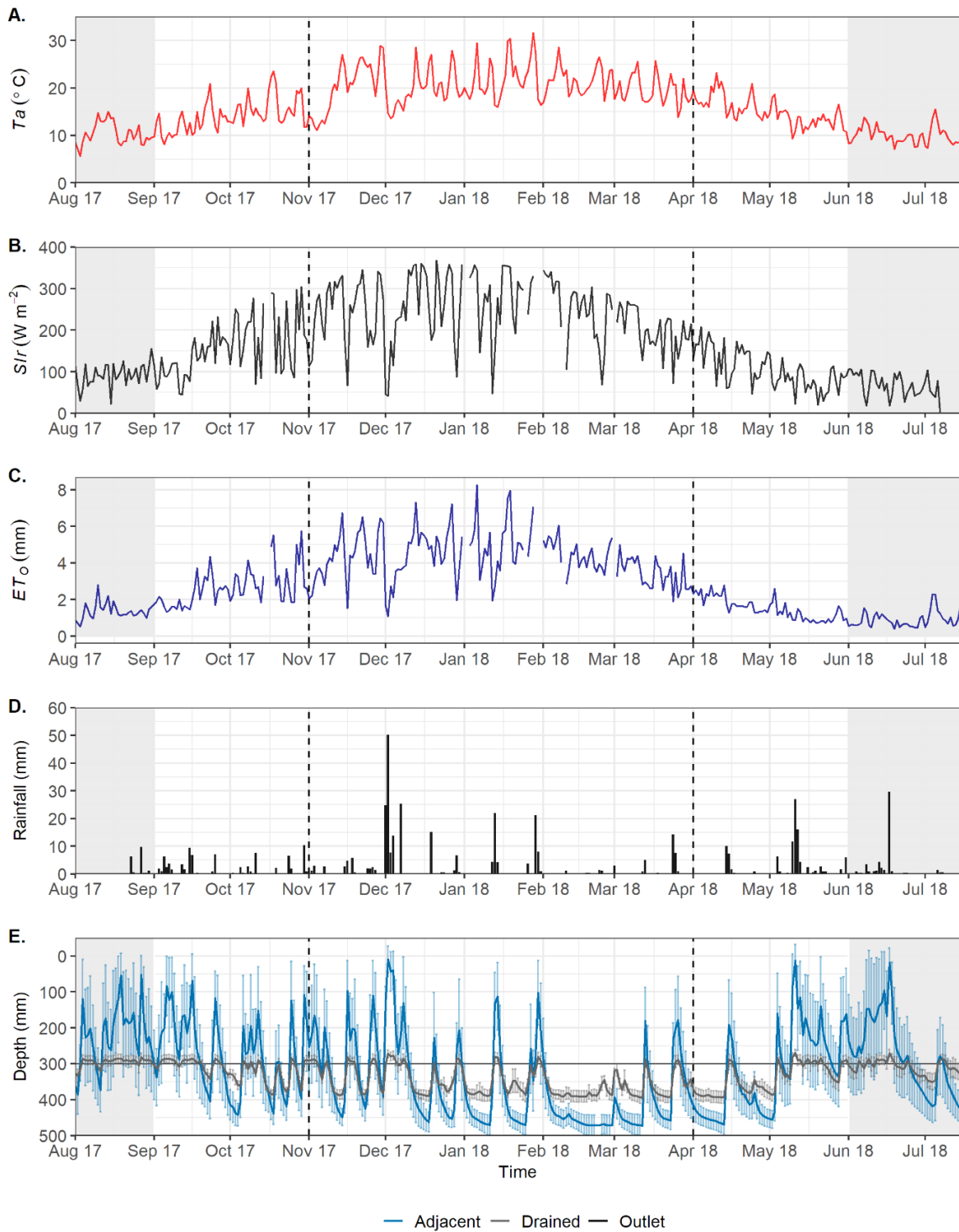
## 3 Results

### 3.1 Environmental conditions

Mean daily air temperature during sap flow monitoring (third growth year) ranged from 7.1 °C to 31.6 °C, with a mean of 17.2 °C (Figure 2A). Mean daily  $slr$  ranged from 18.0 W m<sup>-2</sup> in winter to a maximum of 367.9 W m<sup>-2</sup> in summer, with a mean of 180.1 W m<sup>-2</sup> (Figure 2B). Mean daily  $ET_O$  ranged from 0.4 mm d<sup>-1</sup> to 8.3 mm d<sup>-1</sup> with a mean of 2.8 mm d<sup>-1</sup> (Figure 2C). Total rainfall at the site was 552.2 mm, 120 mm less than the historical average (Table S1). Daily rainfall ranged from 0.2 mm to 50.1 mm, with a median of 1.4 mm (Figure 2D). The longest antecedent dry period during the third year (12 days) occurred in January, and

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was four times greater than the mean antecedent dry period (3 days) during summer. Lower than average rainfall was recorded for most months (Table S1) and was particularly low from February to April (11-38 mm less than average). The depth to water rarely dropped below 300 mm for *drained* pits (depth of the outlet), ranging from 270 mm to 395 mm, with a mean of 333 mm. The depth to water in pits *adjacent* to trees was more variable than *drained* pits, ranging from 9 mm to 472 mm with a mean of 318 mm. The greatest depth to water occurred from January to March (during summer) for all passively irrigated pits (Figure 2E).



**Figure 2.** Local environmental conditions throughout the study. The beginning and end of summer is indicated by the vertical dashed lines and the shaded area represents winter months. **A)** Mean daily air temperature ( $T_a$ ), **B)** mean daily solar radiation ( $Slr$ ), **C)** mean daily reference evapotranspiration ( $ET_o$ ), **D)** Total daily rainfall, and **E)** Mean daily depth of water in the substrate (Depth) per treatment ( $n = 4$ ). Error bars represent the standard error.

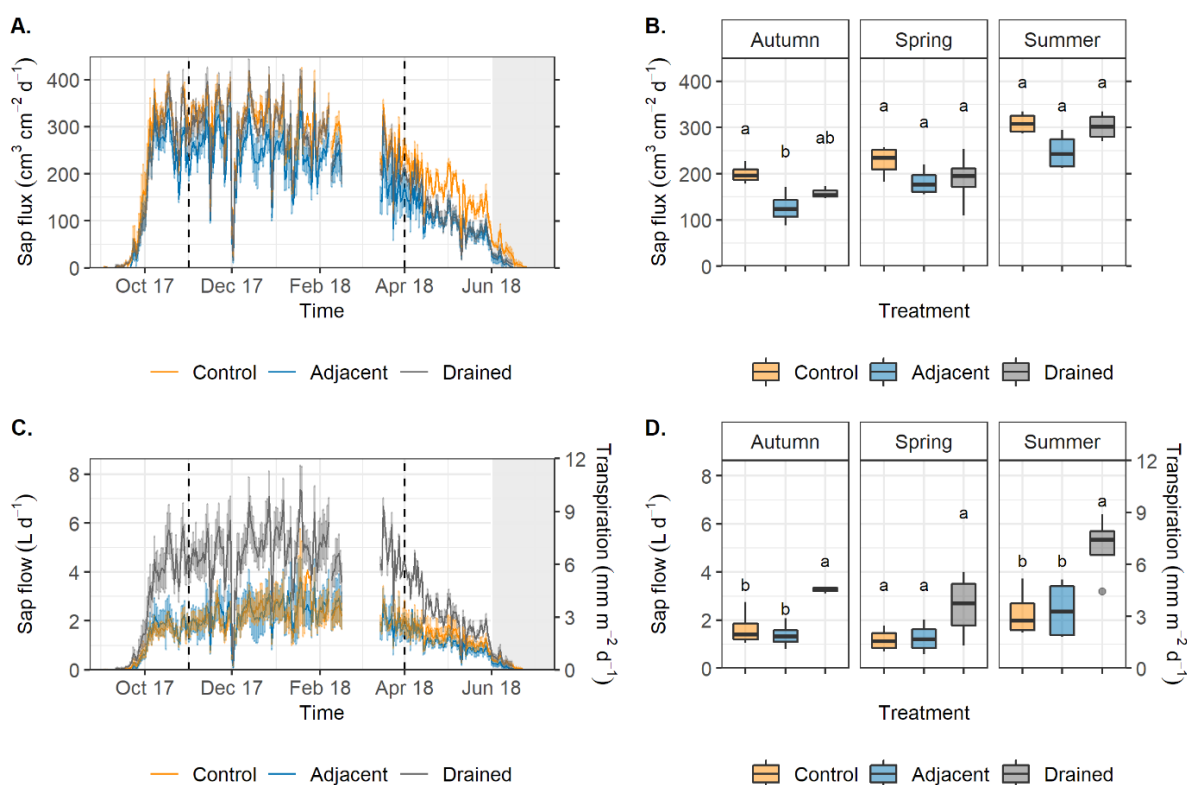
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### 3.2 Do passively irrigated trees transpire more than control trees?

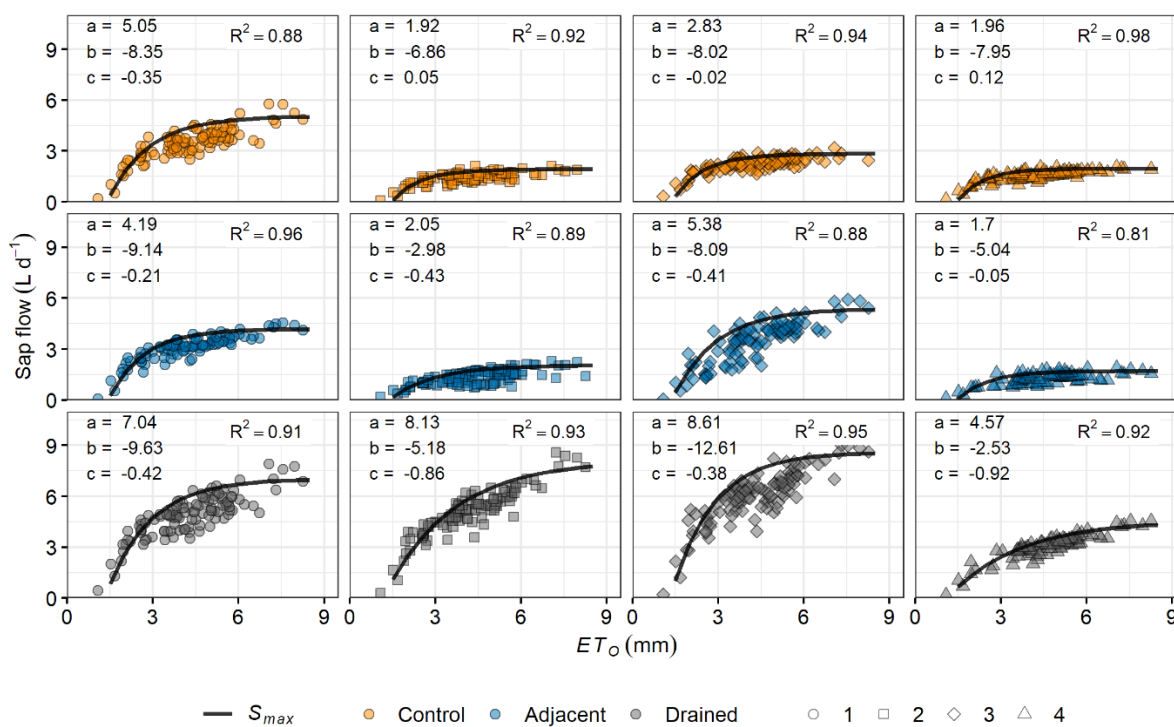
Mean daily sap flux (water transport per  $\text{cm}^2$  of sapwood area) ranged from 0 to  $420 \text{ cm}^3 \text{ cm}^{-2} \text{ d}^{-1}$  during the third year (Figure 3A). Mean daily sap flux during the third year was greater for *control* trees ( $199 \text{ cm}^3 \text{ cm}^{-2} \text{ d}^{-1}$ ) than trees *adjacent* to pits ( $148 \text{ cm}^3 \text{ cm}^{-2} \text{ d}^{-1}$ ;  $p = 0.01$ ), but did not differ from trees in *drained* pits ( $187 \text{ cm}^3 \text{ cm}^{-2} \text{ d}^{-1}$ ;  $p = 0.7$ ). Mean daily sap flux did not differ among treatments during summer ( $p = 0.05$ ), with a mean of  $270 \text{ cm}^3 \text{ cm}^{-2} \text{ d}^{-1}$  (Figure 3B).

Mean daily sap flow (total water transport per tree) of trees in *drained* pits ranged from 0 to  $7.4 \text{ L d}^{-1}$  (equivalent to  $10.3 \text{ mm d}^{-1}$  per pit surface area) during the third year (Figure 3C), with a mean of  $3.0 \text{ L d}^{-1}$  ( $4.2 \text{ mm d}^{-1}$ ), double that of trees *adjacent* to pits ( $1.4 \text{ L d}^{-1}$ ,  $p = 0.01$ ) and *control* trees ( $1.4 \text{ L d}^{-1}$ ,  $p = 0.02$ ). This meant that on average, annual sap flow of trees in *drained* pits ( $1301 \text{ L}$ ) was approximately twice that of *control* trees ( $675 \text{ L}$ ) or trees *adjacent* to pits ( $743 \text{ L}$ ). Mean daily sap flow of trees in *drained* pits ( $5.1 \text{ L d}^{-1}$ ;  $7.1 \text{ mm d}^{-1}$ ) was also twice that of trees *adjacent* to pits ( $2.4 \text{ L d}^{-1}$ ;  $p = 0.03$ ) and *control* trees ( $2.3 \text{ L d}^{-1}$ ;  $p = 0.03$ ) during summer, when there was no significant differences in sap flux (Figure 3D).

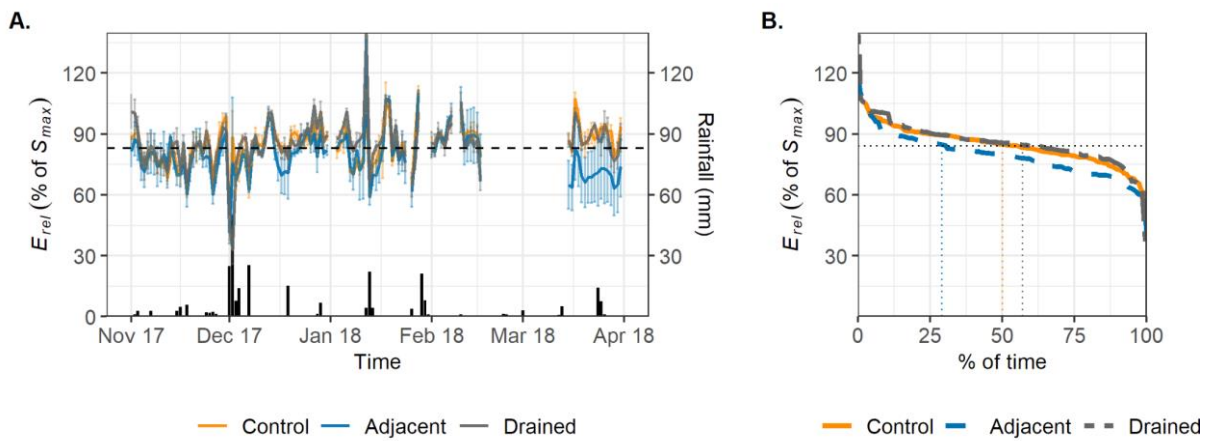


**Figure 3.** Mean daily sap flux are presented in **A)** for the third year and **B)** per season. Mean daily sap flow (sap flux scaled to the whole tree) and equivalent transpiration per treatment are presented in **C)** for the third year, and **D)** per season. Dotted lines in A and C represent the start and end of summer and the shaded area represents winter. Letters in B and D indicate significant differences among treatments per season ( $p < 0.05$ ,  $n = 4$ ). For interpretation of the references to colours in this figure legend, refer to the online version of this article.

Asymptotic model fits used to estimate potential sap flow from reference evapotranspiration were significant for each replicate ( $p < 0.05$ ), with  $R^2$  ranging from 0.81 to 0.97 (Figure 4). Relative sap flow (mean daily sap flow relative to maximum potential sap flow) was 83% for *control* trees and did not differ significantly among treatments ( $p = 0.1$ ; Figure 5A). Despite no difference among treatments in mean relative sap flow, trees *adjacent* to pits had a steeper exceedance curve for relative sap flow throughout the third year, representing greater variability among replicates than either *control* trees or trees in *drained* pits (Figure S3). Hence relative sap flow of trees *adjacent* to pits was below average for 71% of the study, compared with 50% for *control* trees and 43% for trees in *drained* pits (Figure 5B).



**Figure 4.** Potential sap flow ( $S_{max}$ ) predicted from the asymptotic relationship ( $S_{max} = a - be^{-cET_o}$ ) between daily sap flow and reference evapotranspiration ( $ET_o$ ) during summer for each tree replicate (1-4) per treatment. Top panels (orange) are *control* trees, middle panels (blue) are *adjacent* trees, and bottom panels (grey) are *drained* trees. Coefficients for each asymptotic model are presented in the top left corner and corresponding  $R^2$  in the top right corner. The  $a$  coefficient represents the asymptote for each fit.

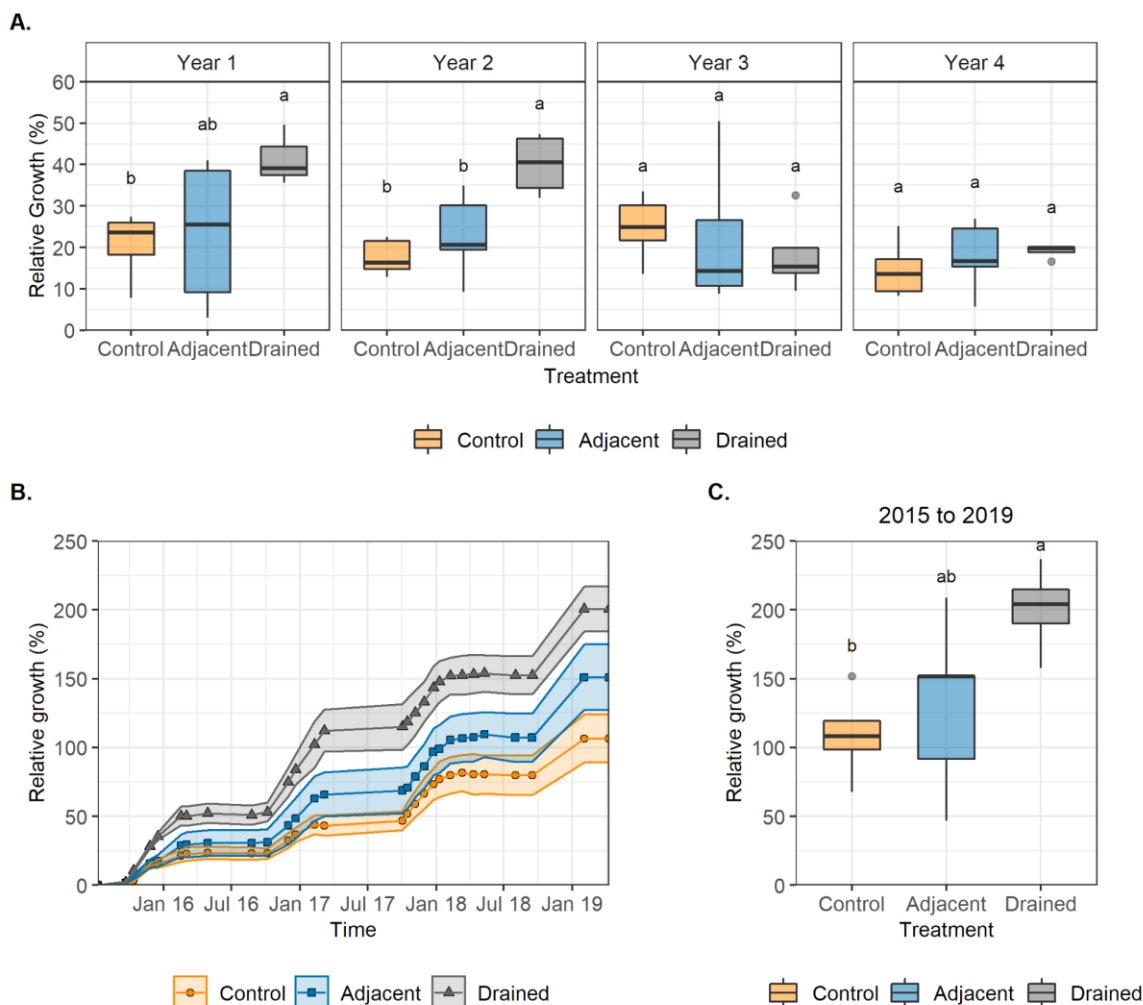


**Figure 5.** Mean daily relative sap flow ( $E_{rel}$ ) per replicate. A) Daily time series during summer, calculated as a proportion of potential sap flow ( $S_{max}$ ). B) the probability of exceeding  $E_{rel}$  during summer. The horizontal black dashed line indicates mean  $E_{rel}$  of *control* trees (83%). The coloured dashed lines represent the probability of exceeding the mean  $E_{rel}$  of *control* trees. For interpretation of the references to colours in this figure legend, refer to the online version of this article

### 3.3 Do passively irrigated trees sustain greater growth than control trees?

Trees planted in *drained* pits increased stem diameter twice as fast (+47% and +40%, respectively) as *control* trees (+21% and +18% respectively) in the first two years. Hence after two years of growth, the stem diameter of trees in *drained* pits had increased by 2.5 cm, whereas the stem diameter of *control* trees had increased by 1 cm. Greater relative annual growth rates were not sustained in the third or fourth year after planting (Figure 6A). Relative growth rates in the third and fourth year did not differ among treatments ( $p = 0.75$  and  $p = 0.59$ , respectively) because the annual growth rate of trees in *drained* pits decreased from an average of 44% in the first two years to 18% in the third and fourth years ( $p = 0.01$ ). Annual relative growth rate of trees *adjacent* to pits was more variable than *control* trees and trees in

*drained* pits (Figure S2) and only differed significantly from trees in *drained* pits in the second year ( $p = 0.02$ , Figure 6A). The greater relative growth rate of trees in *drained* pits in the first two years meant that cumulative stem diameter growth after four years (+201%, equivalent to 4.6 cm) was approximately double the cumulative stem diameter growth of *control* trees (+109%, equivalent to 2.5 cm) ( $p = 0.03$ ; Figure 6C).



**Figure 6.** Mean **A)** annual relative stem diameter growth from the beginning to the end of each growth year, **B)** cumulative relative stem diameter growth from planting in 2015 to 2019, and **C)** cumulative relative stem diameter growth in 2019. The shaded areas in **B** represent the standard error ( $n = 5$ ). Letters in **A** and **C** represent significant differences ( $p < 0.05$ ) among treatments within each year (**A**) and in 2019 (**C**).

## 4 Discussion

### 4.1 Passively irrigated trees can transpire more than control trees when they grow faster.

Trees in *drained* infiltration pits grew faster in the initial two years after planting and as such, transpired a greater volume of water than *control* trees in the third year. Mean sap flow of trees in *drained* pits during summer, when cooling benefits are needed most, was  $5.1 \text{ L d}^{-1}$ , double that of *control* trees and trees *adjacent* to infiltration pits. However, water use per  $\text{cm}^2$  of sapwood did not differ among treatments, indicating that differences in sap flow were due to the differences in tree size, rather than differences in water transport efficiency (Rahman, et al., 2020b). Nevertheless, trees in *drained* pits used larger volumes of water per day than *control* or *adjacent* treatments. Greater initial growth rates of trees in *drained* pits could also have enabled access to additional water in surrounding soil through root extension, which combined with stormwater, could support higher daily water use. Hence, if passive irrigation systems can be used to achieve early growth and establish trees in the urban landscape faster, the size advantage may not only provide more shade, but may also transpire a greater volume as compared with control trees. The larger volume of transpired water may deplete soil moisture in the pits faster, enabling greater retention of runoff from subsequent events, depending on the frequency and seasonality of rainfall relative to transpiration and evaporative demand (Szota et al., 2018; Thom et al., 2020b). Furthermore, greater transpiration may provide greater cooling benefits to urban populations through reduced air temperature via latent heat loss. (Gillner et al., 2015; Rahman et al., 2020a).

In addition to supporting the successful and rapid establishment of urban trees, passive irrigation systems seek to reduce the likelihood of drought stress during dry periods, by providing supplementary irrigation (Luketich et al., 2019). Hence, we expected sap flow normalised for climate (relative sap flow) to be greater for passively irrigated trees as compared with *control* trees, due to differences in water availability. However, mean relative sap flow (83%) did not differ significantly among treatments. Daily relative sap flow also showed minimal difference among treatments throughout summer, suggesting that no treatment trees were exposed to severe drought stress during the third year at the daily nor seasonal scale. Rainfall was relatively frequent during the third year, with an average antecedent dry period of 3 days and a maximum dry period of 12 days in summer. A combination of short dry periods and high supply of runoff owing to the small infiltration pits

relative to connected impervious catchments, meant the pits likely captured more than enough water to meet transpiration demand. The potential volume of water that could be stored in the substrate for each pit can be estimated as the surface area of the pit ( $0.72 \text{ m}^2$ ) multiplied by depth (300 mm to outlet for the *drained* pit, 350 mm to the gravel layer for the *adjacent* pit) and the water holding capacity (22%). The internal water storage of the *drained* pit (50 mm of sand with 30% porosity and 50 mm of gravel with 40% porosity) could store an additional 25 L of water, giving approximately 55 L of storage for *adjacent* pits and 73 L of storage for *drained* pits. Since trees *adjacent* to pits used  $2.4 \text{ L d}^{-1}$  and trees in *drained* pits used  $5.1 \text{ L d}^{-1}$  on average during summer, it would take approximately 26 days and 14 days respectively to deplete water storage following a rainfall event, assuming no exfiltration into the surrounding heavy clay soil. While exfiltration would contribute to faster depletion of water storage, it would likely take longer than the maximum antecedent dry period to deplete water storage. Hence, the volume of water captured by passively irrigated pits should have been sufficient to support tree water demand between rainfall events. On the other hand, it is also possible that even if trees did experience mild to moderate drought stress, it was not picked up in the sap flow signal (Luketich et al., 2019; Stratópoulos et al., 2018). Species differ in their regulation of transpiration during drought on a spectrum of strict (isohydric) to limited (anisohydric) control (Meinzer et al., 2016). Since *A. campestre* trees are more anisohydric (Li et al., 2016; Thom et al. 2021), *control* trees may have experienced mild to moderate drought stress that did not necessitate a decrease in transpiration.

While the volume of water storage for pits in our study is adequate to support the low water requirements of newly planted trees, it is likely that as trees grow and their water requirements increase, passive irrigation systems would provide supplementary irrigation to meet part of the water demand of trees (Thom et al. 2020b). For example, large *A. campestre* (40 cm diameter) can use up to  $140 \text{ L d}^{-1}$  (Čermák et al. (2000), which would exceed the amount of water stored in these small infiltration pits in less than one day. However, as trees mature and establish roots beyond the infiltration pit, they may not rely solely on passive irrigation to maintain transpiration and may access sufficient water resources beyond the passively irrigated pits, such as leaky water infrastructure (Bonneau et al., 2018; Szota et al., 2019; Thom et al., 2020b). Nonetheless, our results suggest that in cities such as Melbourne that have regular rainfall during summer, small infiltration pits with large catchments can support the water requirements of newly planted trees and may limit drought stress between rainfall events in the establishment years to support an expanding urban forest.

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While passive irrigation systems may reduce the likelihood of drought stress in drier summer months, it may also expose newly planted trees in small pits with large catchments to waterlogging stress following rainfall events when drainage from the pit is poor (Bartens et al., 2009; Grey et al., 2018a). Although we did not observe significant differences in mean relative sap flow among treatments, the steeper exceedance curve for trees *adjacent* to pits suggests sap flow was more variable for these trees than those in *drained* pits or *control* trees. Relative sap flow of trees *adjacent* to pits was below average more often (71% of the study) than other treatments. Since we have established that drought was probably not the cause (i.e. adequate storage and short antecedent dry period), it is likely this variance reflects that some trees *adjacent* to pits experienced extended waterlogging. Trees *adjacent* to pits were smaller than trees in *drained* pits, and as such would take twice as long to utilise the water stored in their *adjacent* pits, increasing the risk of waterlogging. Mean annual runoff per tree pit in the initial two years was 421,000 L per year, of which approximately 20,000 L was intercepted by the passive irrigation systems (Grey et al. 2018b). Hence, the volume of annual inflow was much greater than the 743 L transpired on average by trees *adjacent* to pits in the third year. Since pits adjacent to trees had no drainage, this likely contributed to waterlogging of some systems. Not only can waterlogging decrease transpiration of newly planted trees (Bartens et al., 2009), it also challenges the growth and survival of trees (Grey et al., 2018a) and therefore the success of canopy expansion programs. The risk of waterlogging could decrease as trees grow and water requirements increase.

#### 4.2 Passively irrigated trees may not sustain greater growth rates beyond establishment

Passive irrigation of trees in *drained* pits with an internal water storage doubled stem diameter growth in the first two years as compared with *control* trees (Grey et al., 2018a); however, greater growth rates were not sustained thereafter. The annual growth rates of trees in *drained* pits decreased from +44% year<sup>-1</sup> in the first two years, to +18% year<sup>-1</sup> in the third and fourth years, which was similar to the growth rates of trees *adjacent* to pits and *control* trees throughout the study. The decrease could be attributable to a change in the timing and volume of runoff received by passively irrigated pits (Taguchi et al., 2020; Tu et al., 2020). For example, July (winter) rainfall at our site from the third year was half that of the first two years (BoM, 2020), which may reduce growth rates in *A. campestre* (Rozas and Olano, 2017). Since the larger trees in *drained* pits used a greater volume of water than other

treatments, their growth may have been more affected by changing rainfall patterns. However, water level data shows the *drained* pits were almost always at capacity during winter months and never completely drained during summer, even during the longest dry spell. Hence, we hypothesise that actual water content would have been close to or above field capacity and therefore the reduction in growth rate from the third year was likely not due to a lack of water.

Alternatively, the decrease in annual stem diameter growth may be explained by a change in root growth due to below-ground conditions (Vidal-Beaudet et al., 2018). Trees in *drained* pits were planted in sandy loam filter media to promote surface infiltration of stormwater, and included an internal water storage to support root growth and exfiltration into surrounding soil (Glaister et al., 2017; Payne et al., 2014). In comparison, trees *adjacent* to pits and *control* trees were grown in native soil, a heavy clay with low saturated hydraulic conductivity (Grey et al., 2018b). Replacing compacted urban soils with less compacted media can support root exploration and therefore increase overall tree growth (Layman et al., 2016; Somerville et al., 2018). Since the native clay soils were beneath pavement prior to tree planting, it is likely they were heavily compacted. Hence, replacing clay with less compacted sandy loam, in conjunction with passive irrigation, may have contributed to faster root establishment and therefore greater growth of trees in *drained* pits in the first two years. However, it is important to note that two passively irrigated trees in native clay soil that did not have an underdrain, achieved similar growth rates (> 85%) to trees in drained pits in the first two years at the same site (Grey et al. 2018a). The greater growth of those trees was due to fast exfiltration rates (> 58 mm hr<sup>-1</sup>) that meant those trees were well drained. So, although a change in substrate may have contributed to greater growth, the combination of components in the drained passive irrigation system (change in substrate, internal water storage, and an underdrain) likely resulted in greater initial growth for all trees planted in that system. The decrease in growth rate in the third and fourth years could be due to complete colonisation of the sandy loam substrate and the beginning of root extension into compacted native soil impeding growth (David et al., 2018). Alternatively, the decrease in growth could be due to the internal water storage restricting vertical root exploration below 300 mm, since *A. campestris* are sensitive to waterlogging conditions (Grey et al., 2018a; Niinemets & Valladares, 2006). Although we cannot separate the effects of passive irrigation and change in substrate, the most likely reason trees in *drained* pits did not sustain greater growth was due to the trees 'outgrowing' their small pit of imported biofilter sand. Hence, we suggest

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passive irrigation systems that are larger pits or a continuous trench and therefore replace a greater volume of native soil, with high infiltration substrates (particularly when the native soil is clay dominated) may be preferable to small pits with regard to sustaining greater annual growth rates for longer (Jim, 2019) and retaining greater volumes of stormwater (Tu et al., 2020).

Growth of trees *adjacent* to pits was variable among the four replicates, suggesting variability in the ability to retain or release received stormwater. Some trees *adjacent* to pits grew faster than *control* trees, which likely reflects the benefit of passive irrigation alone, considering trees *adjacent* to pits were planted in the same native soil as *control* trees. However, some trees grew slower than *control* trees, which, in combination with the relative sap flow exceedance curve, suggests that waterlogging impeded growth and transpiration of some trees (Bartens et al., 2009; Grey et al., 2018a). We expected that planting trees *adjacent* to infiltration pits would be a simple, and low-cost option to limit the risk of waterlogging from passive irrigation. However, without an underdrain, stormwater could only exfiltrate slowly into the surrounding heavy clay. There is a high likelihood of preferential flow paths in disturbed urban soils (e.g. root channels, and gravel construction layers, (Di Prima et al., 2020)). Since the native clay soil had a very low soil hydraulic conductivity ( $< 5 \text{ mm h}^{-1}$ ; Grey et al., 2018b), it is likely such flow paths moved water toward the planting hole and waterlogged the soil around some, but not all, trees *adjacent* to pits. Our results suggest that planting trees *adjacent* to infiltration pits may not safeguard trees from waterlogging in areas with heavy clay soils, particularly for newly planted trees with low water requirements relative to the volume of stormwater retained by pits. It is important to note however, that results may vary across different climate conditions (precipitation, temperature and evaporative demand), species, tree age, or treatment design. The most appropriate distance of an *adjacent* pit from a passively irrigated tree therefore requires further consideration and will likely depend on site conditions such as *in situ* soil as well as tree species and age. Increasing the distance between newly planted trees and an *adjacent* pit in fine-textured soils to greater than 300 mm could reduce the risk of waterlogging while they establish, but may increase the risk of drought stress (Caplan et al., 2019). Alternatively, *adjacent* pit designs could be reserved for installation *adjacent* to larger trees that have higher water requirements (Thom et al., 2020b). In many climates and soil types, waterlogging remains a significant issue that should be avoided through design (Grey et al., 2018a) or selecting species that are flood tolerant (Bartens et al., 2009).

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## 5 Conclusions

We assessed the influence of tree pit design on the transpiration and growth of newly planted street trees to assess whether passive irrigation systems can support greater transpiration and sustain greater growth rates beyond establishment. The combined influence of passive irrigation, a change in substrate, internal water storage, and an underdrain supported greater growth rates of trees in *drained* pits initially, but the growth advantage was likely limited to the first two years of growth due to trees outgrowing the small infiltration pits. Nonetheless, fast initial growth meant trees in *drained* pits were double the size of *control* trees after four years of growth, which could lead to greater tree size at maturity. Future research should seek to assess the long-term impact of passive irrigation on the growth rates of trees and size at maturity as well as how this relates to size of infiltration pits. The faster growth of trees in *drained* pits supported greater transpiration than *control* trees, indicating passive irrigation systems could support greater cooling and runoff reduction benefits in urban environments. No trees were exposed to drought stress during this study, due to high supply of water from the catchment, short antecedent dry periods, and low water requirements of newly planted trees. However, some trees planted *adjacent* to infiltration pits showed poor growth and low transpiration, indicating the need for drainage or other design interventions to avoid waterlogging in fine-textured soils. To capture the ecohydrological benefits of passive irrigation including faster tree establishment and greater transpiration, we need to create context-specific systems that consider the volume and placement of infiltrated stormwater with respect to local climate and soil conditions. Further, consideration should be given to the size, drought or waterlogging tolerance, and species traits influencing transpiration dynamics of trees, to identify those that are best suited to passive irrigation systems.

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