



Mechanistic insights into water use strategies and heat tolerance of Australian native trees in saline soils: Implications for phytoremediation under climate change

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Abstract

Aims This study evaluates the water use strategies and physiological resilience of three Australian native tree species in saline soils to assess their potential for phytoremediation under climate change. We hypothesise that species with high water demand and delayed stomatal closure under aridity can enhance

soil salinity mitigation through sustained transpiration and groundwater regulation.

Methods Continuous sap flow measurements were recorded over 12 months on nine trees (three per species) from three species across three moderately saline sites in Melbourne, Australia. Detailed analyses of morphological traits, sapwood properties, and soil profiles (including texture and water content) were conducted. Diurnal sap flow patterns, peak flow timing, and physiological responses to temperature and vapour pressure deficit (VPD) were evaluated to determine species-specific thresholds for heat and drought tolerance.

Results *Melaleuca styphelioides* exhibited the highest water use, consuming 128% and 97% more water monthly than *Lophostemon confertus* and *Corymbia maculata*, respectively. Its peak sap flow occurred later in the day (15:00–17:00), coinciding with sustained stomatal conductance under high VPD (1.9–2.0 kPa) and extreme temperatures (41 °C). Optimal physiological performance for this species occurred at higher temperatures (32.2–33.4 °C) and VPD (1.9–2.0 kPa).

Conclusions *Melaleuca styphelioides* may warrant further investigation as a potential candidate for water management in saline environments, given its higher water consumption and ability to maintain sap flow under elevated temperature and VPD conditions. These findings suggest that additional research, incorporating larger sample sizes and direct measurements of soil salinity changes, would be valuable to evaluate

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the suitability of this species for phytoremediation applications in aridifying regions.

Keywords Climate change adaptation · Heat resilience · Phytoremediation · Plant-soil-climate feedbacks · Saline soil remediation · Sap flow

Introduction

In the twenty-first century, the world is facing a notable rise in environmental issues, prominently including water scarcity and the escalating salinisation of soil and water. These challenges are primarily a result of several factors, such as climate change, excessive utilisation of natural resources, and unsustainable development practices. Currently, approximately 20% of the world's cultivated agricultural land is affected by salinity (Shrivastava and Kumar 2015), with coastal regions particularly vulnerable due to climate change-induced sea level rise, which has increased soil salinity by 32% over 25 years (Rahman et al. 2018). This situation is especially critical in Australia, where the combination of arid climate and highly weathered landscape (Sun et al. 2023a) contributes to elevated salt levels in soils and groundwater. Studies conducted in 2000 identified 5.7 million hectares of Australian land as having high salinity potential (3,000–35,000 mg/L), with projections indicating potential expansion to 17 million hectares by 2050 without effective intervention (ABS 2010). This increasing salinity threatens soil quality, agricultural productivity, and economic returns (Hu and Schmidhalter 2002), while also posing significant risks to urban ecosystem health and vegetation (Boulton et al. 2014).

Trees offer a promising solution for soil remediation through multiple physiological mechanisms. They enhance soil water retention by incorporating organic matter and contribute to salinity reduction through transpiration, which facilitates the removal of dissolved salts from the soil, leading to long-term improvements in soil conditions. The strategic planting of trees on saline soil represents an effective approach to land amelioration while providing economic and ecological benefits to local communities (Bell 1999; Wicke et al. 2011). Species with high growth rates and substantial water requirements are particularly valuable for lowering groundwater levels,

facilitating faster rehabilitation of salinity-degraded land (Qadir et al. 2008). It is widely recognised that plants exhibiting peak sap flow later in the day tend to achieve higher growth rates (Ismanov et al. 2019). This phenomenon is attributed to the prolonged opening of stomata, which enhances carbon dioxide uptake and extends the duration of photosynthetic activity (Richards 2000). However, selecting the right species is critical: deep-rooted trees such as *Eucalyptus camaldulensis* and *Acacia nilotica* have been shown to draw significant volumes of saline groundwater, lowering water tables and preventing salt accumulation in the root zone (Minhas and Dagar 2016). Conversely, replacing deep-rooted perennials with shallow-rooted plants can increase recharge, raise the saline water table, and exacerbate surface salinisation (Clarke et al. 2002). Capillary rise from a shallow saline water table can mobilise salts into the root zone, offsetting transpiration benefits and leading to increased soil salinity (Jorenush and Sepaskhah 2003). Therefore, species selection must carefully consider rooting depth, overall water-use rates, and local hydrogeological conditions. Species such as saltbush (*Atriplex spp.*), although highly salt-tolerant, often possess shallow root systems that may not effectively lower water tables, potentially resulting in salt build-up near the soil surface (Barrett-Lennard 2002).

Understanding plant water relations through sap flow dynamics is crucial for evaluating physiological responses to environmental stresses. Sap, a nutrient-rich fluid containing water, minerals, sugars, and hormones, is essential for photosynthesis, growth, and reproduction. Its movement through the plant's vascular system is primarily governed by transpiration, which creates negative pressure through stomatal water loss, driving water uptake from roots through xylem vessels. Sap flow measurements provide a continuous, quantitative assessment of the volumetric flux of water through the xylem, offering direct insights into a plant's ability to transport water from roots to leaves under field conditions (Sun et al. 2022, 2024). Advanced techniques such as the heat ratio method and thermal dissipation probes enable high-resolution monitoring of sap flow velocity, integrating dynamic processes such as root water uptake, xylem hydraulic conductance, and stomatal regulation to characterise transpiration dynamics (Kumar et al. 2022). Normalising sap flow data by sapwood cross-sectional area further allows the calculation

of sapwood-specific hydraulic conductivity, a critical metric for evaluating a tree's capacity to sustain efficient water transport under environmental stress (Steppe et al. 2015). Continuous diurnal monitoring reveals species that maintain elevated transpiration rates at high vapour pressure deficits and temperatures, traits linked to deep rooting and a high potential for groundwater extraction, which are essential for lowering saline water tables (Tie et al. 2017). Comparative analysis of cumulative sap flow across species facilitates ranking based on total water use, thereby informing the selection of trees with high groundwater drawdown and salt-removal capabilities. Integrating sap flow data with soil moisture and groundwater models further refines species selection by predicting local hydrogeological impacts and ensuring effective salinity mitigation (Kim et al. 2014). In this way, sap flow provides an empirical framework to identify the ideal candidate for phytoremediation by quantifying hydraulic traits, water-use rates, and environmental resilience.

Soil salinisation poses a significant threat to urban green infrastructure by degrading soil productivity and hindering tree establishment, yet urban landscapes often exhibit highly heterogeneous salinity patterns that complicate remediation efforts (Singh 2021). Concurrently, urban climate change, driven by both global warming and the urban heat island effect, has increased the frequency and intensity of heatwaves and drought in cities, exacerbating soil moisture deficits and amplifying aridity (IPCC 2021). These stressors interact synergistically with soil salinity to impair tree hydraulic functioning: elevated vapour pressure deficit (VPD) and extreme temperatures can reduce sap flow and transpiration, limiting a tree's capacity to extract and transport saline groundwater (Muhammad et al. 2024). Despite recognising trees as agents for soil salinity mitigation, few studies have concurrently evaluated salt stress tolerance alongside heat/drought resilience when assessing species suitability for urban phytoremediation (Tang et al. 2024). Critical knowledge gaps remain in understanding (1) how combined salinity and heat/drought stress shape diurnal and seasonal tree water use strategies; (2) the thresholds of sap flow resilience under simultaneous soil salinity and arid conditions; and (3) practical guidelines for matching species' rooting depth, hydraulic conductance, and heat tolerance to heterogeneous urban hydrogeology. Addressing

these gaps is essential for selecting species capable of sustaining high hydraulic conductivity and groundwater uptake in saline, arid urban soils. To this end, our study employs continuous sap flow monitoring of three Australian native species across saline urban sites, linking hydraulic traits to heat and drought tolerance to inform species selection frameworks for urban salinity management.

This study investigates nine Australian native trees from three species to identify which has a better phytoremediation potential in saline soils. Continuous sap flow monitoring is employed to: (1) infer relative growth capacity based on the timing and magnitude of peak sap flow in relation to daily maximum VPD; (2) identify each species' optimal temperature and VPD thresholds for sustaining high transpiration; and (3) quantify cumulative monthly water use over a 12-month period as a proxy for groundwater extraction potential. We hypothesise that species with high water demand and delayed stomatal closure under elevated temperature and VPD, particularly *Melaleuca styphelioides*, will exhibit a greater potential to lower saline groundwater levels and mitigate soil salinity compared to species that close their stomata earlier, such as *Corymbia maculata*.

Materials and Methods

Experimental sites and species description

Continuous sap flow measurement of three Australian tree species (Fig. 1) was conducted over a 12-month period (September 2018–August 2019) on three Australian tree species: (a) *Corymbia maculata* (Hook) K.D Hill & L.A.S Johnson, (b) *Lophostemon confertus* (R.Br.) Peter G. Wilson & J. T. Waterh. and (c) *Melaleuca styphelioides* Sm., located at Bayswater (37°50'24"S, 145°16'14"E), Rowville (37°55'31"S, 145°13'50"E), and Boronia (37°51'35"S, 145°16'47"E), respectively, in Melbourne, Australia. Three specimens, including 'single' trees (S), individuals isolated from other trees, and 'group' trees (G) located within clusters of 3–5 conspecifics, from each species were selected for sap flow monitoring. All selected trees were mature and healthy, each with a single stem and a well-developed canopy. This experimental design allowed for the evaluation of how planting density and microclimatic competition

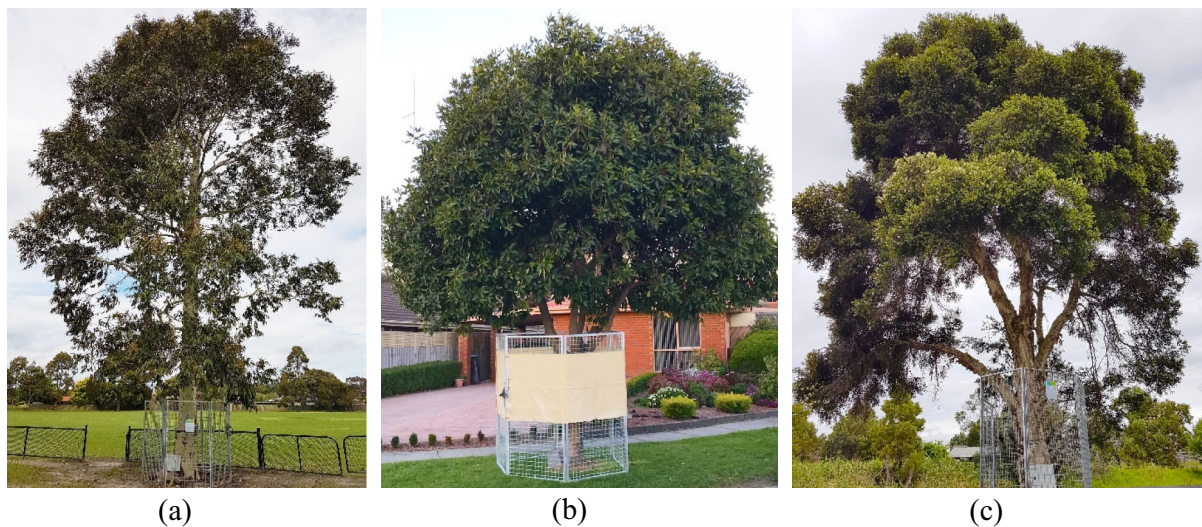


Fig. 1 Three tree species used in the study (a) *C. maculata* (b) *L. confertus* (c) *M. styphelioides*

influence sap flow dynamics. The differences in sap flow between single and group trees were subsequently compared, and potential underlying causes were analysed. These species are mainly distributed along the eastern coast of Australia, from east Victoria to central Queensland and from Nowra in New South Wales to Cape York Peninsula in Queensland. All three species are commonly used in landscaping and as street trees in urban settings. The average groundwater salinity at the monitoring field sites is approximately 2250 mg/L (VVG 2023), indicating a moderate soil salinity (Mayer et al. 2005). The experimental sites have relatively mild temperatures with distinct seasons and are located in a Temperate Climate Zone 3 (Li and Sun 2015). The mean annual temperature, rainfall, and solar exposure are 14.7 °C, 853 mm, and 14.6 MJ/m², respectively (BOM 2022).

Tree structures

The morphological characteristics of all the monitored trees, including the diameter at breast height (DBH), height of the tree, crown height, and crown diameter, were obtained using the photogrammetry technique (Mcpherson and Rowntree 1988; Sun and Li 2024). Photographs were taken at different orientations of the tree while a measuring pole with a known length was placed close to the tree trunk. AutoCAD software (Autodesk Inc., USA) was used to determine

the scale after these images were imported into it, allowing the physical tree height, crown height, crown diameter, and DBH to be estimated. The values reported are the mean obtained from these images. Below-canopy photographs were taken using a fish-eye lens to include the whole crown silhouette. The mean crown diameter was calculated by taking the longest and shortest crown spread determined by AutoCAD.

The live crown ratio (LCR) represents the proportion of a tree's height covered by live branches and foliage and is a ratio of crown height to the total tree height (Sun and Li 2024). It assesses the health and vigour of a tree (Stăncioiu et al. 2021). The Leaf area index (LAI) is the ratio of the total one-sided area of leaves to the ground they cover (Jonckheere et al. 2004). A larger LAI indicates a denser and more complex plant structure, which increases the interception of solar radiation, leading to higher rates of transpiration (Niu et al. 2019). The LAI was measured in different seasons using the Digital Plant Canopy Imager CI-110 (CID Bio-Science, Inc., USA), and the mean was reported.

Wood characteristics

Accurate estimation of whole-tree water use from sap flow measurements using the Heat Ratio Method (HRM) requires two key sapwood parameters. First,

sapwood depth, obtained from core samples, is used to calculate the sapwood cross-sectional area (A_s), which, when multiplied by the measured sap velocity (v), yields the volumetric flow rate ($Q = A_s \cdot v$). Second, sapwood thermal diffusivity (k), estimated from sapwood thermal conductivity, density, and specific heat capacity, is a critical input in the HRM algorithm for converting temperature-ratio signals into precise sap flow velocities (Burgess et al. 2001). Two core samples were extracted from the trunk of each tree at breast height using a Jim-Gem increment borer with a length of 400 mm and a diameter of 5 mm (Fig. 2a). One core sample was used to determine sapwood depth by applying a methyl orange indicator along the core body (Sun et al. 2022). The sapwood portion subsequently turned yellow, while the red colour appeared in the heartwood portion (Fig. 2b). The depth of the sapwood was measured by using a digital vernier calliper. A depth gauge was used to measure the bark thickness at three different locations of the trunk at the breast height, and the mean was adopted. The sapwood percentage was calculated by dividing the sapwood area by the tree basal area (TBA), which is the trunk's cross-sectional area at breast height.

The other core sample was used to measure sapwood density ρ , specific heat capacity c , and thermal conductivity K needed for determining thermal diffusivity k using Eq. 1.

$$k = \frac{K}{\rho c} \quad (1)$$

The c and K are calculated following Edwards and Warwick (1984) and Hogg et al. (1997).

$$c = \frac{w_d c_w + c_s (w_f - w_d)}{w_f} \quad (2)$$

$$K = K_s m_c \frac{\rho_b}{\rho_s} + K_w (1 - m_c \frac{\rho_b}{\rho_s}) \quad (3)$$

where w_d is the sapwood mass following oven drying; w_f is the fresh sapwood mass; c_w and c_s are the specific heat capacity of the wood matrix and water; K_s represents the thermal conductivity of water, while m_c indicates the water level present in sapwood; ρ_b and ρ_s present the density of wood and water; K_w expresses the thermal conductivity of dry wood matrix and is determined following Swanson (1983):

$$K_w = 0.04182 \times (21 - 20 \times (1 - \rho_b(0.667 + m_c))) \quad (4)$$

Soil measurements

Boreholes were drilled to a depth of 4 m at each study site. Samples obtained at every 0.25 m were marked and sealed in plastic zip lock bags, which were stored in thermally insulated containers and transported to the laboratory for establishing soil profiles and performing water content tests using the oven-drying method (AS 1289 1992). The water content values reported in this study are the mean of three



Fig. 2 Identification of sapwood and heartwood depths using an indicator dye (a) core sample after extraction from the tree trunk (b) colour change observed after applying methyl orange indicator dye

subsamples at each depth. Atterberg limits tests (AS 1289 (2009a, b)) were also conducted to determine soil plasticity at various depths. Soil plasticity refers to the range of water content between the liquid limit (above which soil behaves as a viscous fluid) and the plastic limit (below which it becomes a brittle solid). A higher plasticity index indicates a greater clay content, which enhances water-holding capacity but also leads to significant shrink-swell behaviour and reduced permeability. Measuring plasticity at depth provides insights into the soil's capacity to store and release water to tree roots, directly impacting sap flow rates.

Sap flow instrument

While various sap flow measurement techniques exist, including trunk injection methods (Kozlowski and Winget 1963; Sachs et al. 1977; Berger and Laurent 2019) and spontaneous electric potential (Fensom 1963; Gibert et al. 2006), the heat pulse velocity method has emerged as a preferred approach due to its reliability and capacity for continuous monitoring (Green et al. 1997; Li and Guo 2017; Sun et al. 2021, 2025). Specifically, the sap flow meter SFM1 (ICT International, Armidale, Australia), programmed with the Heat Ratio Method (HRM), offers precise measurements in measuring slow and reverse sap flow across varied field conditions (Burgess et al. 2001). It is a dependable and low-maintenance device utilised for quantifying sap velocity and flow rate in plants by many researchers (Bleby et al. 2004; Li et al. 2014; Sun and Li 2023a, b). The SFM1 consists of three needles made of stainless steel—one needle that generates heat and two needles that measure temperature changes. Each needle is 35 mm long and has a diameter of 1.3 mm. These needles are individually connected to the main device using a cable. The temperature needles measure heat propagation in the sapwood subsequent to the application of a heat pulse by the heater needle. The ratio of the temperature changes downstream to the changes upstream is computed, allowing the determination of heat pulse velocity and the subsequent sap velocity calculation by the Sap Flow Tool software. The SFM1 sensors operate within a range spanning from -100 cm/h to 100 cm/h. To ensure accurate sap velocity measurements, potential sources of error, such as probe misalignment and xylem tissue damage during installation, were carefully considered

and addressed. Probe misalignment was minimised by using a custom installation guide (e.g. an alignment jig), which ensured the heater and temperature needles remained co-planar and enabled parallel drilling at a fixed spacing. After installation, each sap flow record was validated by monitoring daily peak flow. A decline exceeding 10% over three consecutive days, indicative of xylem wounding or probe displacement, triggered probe removal. Re-boring was then performed at least 20 mm above the affected area, followed by sensor reinstallation. These measures help ensure reliable sap flow velocity data under field conditions. The SFM1 operates using an internal 4.2 V lithium polymer battery; however, to enable continuous data logging, this was connected to external 12 V lead-acid batteries that were replaced every 20 days. The bark was detached at breast height to allow installation of the SFM1 directly on the bare trunk of every measured tree. The data logger was set to collect sap flow data at intervals of 30 min during the monitoring period. One SFM1 was installed at breast height on the north-facing side of the trunk to collect data on tree water use.

It has been reported that Australia experienced its highest temperatures in 2019, exceeding the long-term average by 1.52 °C (BOM 2022). To assess the impact of extreme weather on sap flow, daily maximum temperature, VPD, and total daily solar radiation were analysed in relation to the sap flow rate. The growth rates of the three tree species were assessed by analysing the timing of daily peak sap flow in relation to the daily maximum VPD. A 12-month (September 2018– August 2019) study was conducted to monitor the daily water use of nine individual trees to evaluate the physiological responses of three species to projected temperature increases under climate change. This extended monitoring period generated a robust dataset for assessing the species' resilience to rising temperatures and their potential role in groundwater regulation within saline environments. Optimal physiological performance was defined as the environmental conditions under which each species achieved its maximal water transport capacity. To identify these conditions, we extracted the top five per cent of half-hourly sap flow measurements (95th percentile) recorded over the 12-month monitoring period. This percentile-based approach captures peak sap flow events, which reflect maximum water transport and metabolic activity.

Data Analysis

All data processing and statistical analyses were conducted in Microsoft Excel (Microsoft Corporation, WA, USA) with the Real Statistics add-in.

- *Descriptive statistics and between-species comparisons*: Means and standard deviations ($\pm$ SD) were calculated for tree morphological traits (e.g. DBH, tree height, mean crown diameter, LCR, LAI), sapwood properties (e.g. sapwood percentage, TBA, thermal diffusivity), and soil water content to summarise variation across species, sites, and depths. One-way ANOVA was then applied to each morphological trait to test for overall differences among the three species. Post-hoc pairwise comparisons were conducted via Tukey's honestly-significant-difference (HSD) test at $\alpha=0.05$. The HSD critical value was determined and any absolute pairwise mean difference (Δ) exceeding this threshold was deemed statistically significant.
- *Linear regression*: Simple linear regressions were fitted in Excel to explore relationships between mean sapwood area and each morphological trait (mean DBH, mean crown diameter, mean LAI). The coefficient of determination (R^2) was computed as a descriptive metric of explained variance, and scatter plots were generated to verify linearity. Given the small sample size, these regressions are presented as preliminary observations and are not used for statistical inference.
- *Sap flow volume*: Sap flow data were processed using the Sap Flow Tool, which converted raw heat pulse velocity measurements into sap velocity and volumetric flow rates. Daily and monthly sap flow volumes were calculated by integrating the 30-min interval flow rates.
- *Diurnal peak sap flow statistics*: For each day during the summer months, the time of peak sap flow was identified and matched to meteorological records of daily maximum VPD. A frequency distribution of these peak times was then established to quantify how often each species reached maximum flow at different hours of the day. This analysis enabled the characterisation of stomatal behaviour and hydraulic resilience under varying atmospheric demands. To compare species, the daily peak sap flow values from the three sampled trees were averaged to yield species means. A one-

way ANOVA was conducted to test for overall differences among species, followed by Tukey's HSD post-hoc test ($\alpha=0.05$) to identify significant differences between species pairs. The HSD threshold was calculated using the studentised range statistic and the within-group mean square; any absolute pairwise mean difference exceeding this threshold was considered statistically significant.

- *Optimal performance thresholds*: The top five per cent of the 12-month half-hourly flow dataset was extracted to isolate true peak events. The corresponding temperature and VPD values for these peak events were retrieved via timestamp matching, allowing determination of each species' adaptive thresholds.

Results

Tree morphological traits

Table 1 presents the measured properties for the nine trees from three species employed in the study. A one-way ANOVA revealed significant differences in tree height among the three species ($p=0.00032$). Tukey's HSD post-hoc test ($HSD=3.20$) indicated that *C. maculata* was significantly taller than *L. confertus* ($\Delta=8.77>3.20$) and *M. styphelioides* ($\Delta=7.37>3.20$), whereas the latter two did not differ significantly ($\Delta=1.4<3.20$). *C. maculata* also exhibited significantly larger canopy dimensions than the other species. Mean crown height (12.73 ± 1.73 m) differed overall among species ($p=0.0063$), and Tukey's HSD ($HSD=4.31$ m) confirmed that *C. maculata* exceeded *L. confertus* (6.10 ± 1.39 m; $\Delta=6.63$ m >4.31 m) and *M. styphelioides* (6.90 ± 0.99 m; $\Delta=5.83$ m >4.31 m). Similarly, mean crown diameter varied by species ($p=0.0073$), and post-hoc comparisons ($HSD=2.73$ m) showed *C. maculata* (10.53 ± 1.02 m) exceeded *L. confertus* (6.30 ± 0.78 m; $\Delta=4.23$ m >2.73 m) and *M. styphelioides* (7.27 ± 0.85 m; $\Delta=3.26$ m >2.73 m). *L. confertus* has the smallest mean DBH and mean crown diameter among the three species, although maintained a consistently high LCR (mean: 0.8–0.85). The mean LAI for this species ranged from 2.60 ± 0.02 to 2.90 ± 0.02 , the highest compared to the other species and indicating a larger leaf surface area. The single trees possess a larger crown height and DBH than

Table 1 Morphological characteristics of the sampled trees in this study

Species	Site	Mean tree height (m)	Mean DBH (m)	Mean crown height (m)	Mean LCR	Mean crown diameter (m)	Mean LAI
<i>C. maculata</i>	Bays. (S1)	14.80 ± 0.07	0.410 ± 0.014	12.10 ± 0.10	0.820 ± 0.011	11.80 ± 0.05	1.50 ± 0.02
	Bays. (S2)	16.90 ± 0.06	0.460 ± 0.008	15.10 ± 0.07	0.900 ± 0.005	10.50 ± 0.08	1.70 ± 0.02
	Bays. (G)	17.10 ± 0.05	0.350 ± 0.011	11.00 ± 0.05	0.640 ± 0.004	9.30 ± 0.07	1.30 ± 0.01
<i>L. confertus</i>	Row. (S1)	9.50 ± 0.03	0.400 ± 0.007	8.00 ± 0.04	0.850 ± 0.001	7.20 ± 0.08	2.90 ± 0.02
	Row. (S2)	7.00 ± 0.04	0.260 ± 0.009	5.60 ± 0.04	0.810 ± 0.005	5.30 ± 0.06	2.60 ± 0.02
	Row. (S3)	6.00 ± 0.06	0.290 ± 0.006	4.70 ± 0.03	0.800 ± 0.008	6.40 ± 0.08	2.80 ± 0.01
<i>M. styphelioides</i>	Boro. (S1)	9.00 ± 0.04	0.610 ± 0.008	7.50 ± 0.04	0.840 ± 0.002	7.60 ± 0.05	2.30 ± 0.02
	Boro. (S2)	8.70 ± 0.05	0.470 ± 0.014	7.70 ± 0.06	0.880 ± 0.008	8.10 ± 0.07	2.10 ± 0.01
	Boro. (G)	9.00 ± 0.05	0.310 ± 0.006	5.50 ± 0.06	0.610 ± 0.007	6.10 ± 0.07	1.50 ± 0.01

The ‘Site’ column uses abbreviations that indicate both the location and planting arrangement. The site locations are abbreviated as follows: Bays. = Bayswater, Row. = Rowville, and Boro. = Boronia. The planting arrangements are denoted by: (S1), (S2), (S3) = single trees (numbered 1–3), and (G) = a tree growing within a group of trees. For example, “Bays. (G)” refers to a tree growing within a group at the Bayswater site, while “Row. (S3)” indicates a single tree #3 located at Rowville

the trees in a group for *C. maculata* and *M. styphelioides*, despite a relatively smaller tree height for single trees. The mean LCR of approximately 0.6 was determined for the trees in a group, which was considerably smaller than the ratio of single trees, ranging from 0.8 to 0.9. This indicates that single trees are generally considered to be healthier and more structurally stable and subjected to a low risk of failure or mortality compared to trees in a group. The observations show that *C. maculata* may have better overall growth and crown development than *L. confertus* and *M. styphelioides*.

Wood characteristics

Table 2 presents the wood attributes for the nine experimental trees. The measurement results show significant diversity in the sapwood area among individual trees. *M. styphelioides* exhibits the highest bark depth and proportion of bark among the three species. The mean sapwood percentage for this species ranges from 19.3% ± 0.7% to 29.3% ± 0.8%, the lowest compared to the other two species, indicating a smaller proportion of sapwood in the total wood volume. It is noteworthy that sapwood accounts for over 50% and 60% of the TBA in the single *C. maculata* (S1) at Bayswater and *L. confertus* (S1 and S3) at Rowville. The mean sapwood depth of the *C. maculata* and *M. styphelioides* in groups is respectively 40%–45% and 37%–44%

smaller than the single trees grown in the same site. The measured mean thermal diffusivity in sapwood for all the trees ranged from 0.00230 ± 0.00004 to 0.00290 ± 0.00005 mm²/s. The exploratory linear regressions between mean sapwood area and each morphological trait (mean DBH, mean crown diameter, mean LAI) are summarised in Fig. 3. The mean DBH and mean LAI explained 87%–98% and 80%–87% of the variation in mean sapwood area for all three tree species. In contrast, the sapwood area-crown diameter relationship was highly species-specific: *L. confertus* exhibited a very strong fit ($R^2=0.93$), *C. maculata* showed a moderate fit ($R^2=0.63$), and *M. styphelioides* displayed poor concordance ($R^2=0.34$), indicating that crown diameter is not a reliable predictor of sapwood area in the latter two species.

Soil profiles and soil water content

The soil profiles and soil water content test results for the three experimental sites are presented in Fig. 4. Each data point represents the mean soil water content (±SD) of three independent subsamples collected at 0.25 m depth increments from 0–4 m. Error bars have been added to illustrate the observed variance. No groundwater was encountered in the soil boreholes at any of the experimental sites. The Bayswater site was covered with a 1.7 m fill consisting of a 0.15 m thick topsoil and a layer

Table 2 Wood attributes of the sampled trees in this study

Species	Site	Mean bark depth (mm)	Mean sapwood depth (mm)	Mean heartwood depth (mm)	Mean TBA (cm ²)	Mean sapwood area (cm ²)	Mean sapwood Pct (%)	Mean thermal diffusivity (mm ² /s)
<i>C. maculata</i>	Bays. (S1)	2.5 ± 0.1	67.10 ± 0.03	135.70 ± 0.02	1324.3 ± 87.4	713.4 ± 0.5	54.1 ± 3.7	0.00270 ± 0.00002
	Bays. (S2)	3.6 ± 0.1	61.70 ± 0.01	165.50 ± 0.03	1673.1 ± 60.9	761.3 ± 0.3	45.6 ± 1.7	0.00250 ± 0.00003
	Bays. (G)	3.4 ± 0.1	36.90 ± 0.02	134.90 ± 0.02	962.9 ± 61.4	355.6 ± 0.2	37.1 ± 2.4	0.00260 ± 0.00002
<i>L. confertus</i>	Row. (S1)	5.6 ± 0.1	79.30 ± 0.03	115.30 ± 0.01	1263.3 ± 44.2	771.9 ± 0.4	61.2 ± 2.2	0.00250 ± 0.00002
	Row. (S2)	5.4 ± 0.1	36.70 ± 0.01	86.80 ± 0.02	522.1 ± 36.4	242.5 ± 0.1	46.7 ± 3.1	0.00260 ± 0.00004
	Row. (S3)	5.2 ± 0.1	62.00 ± 0.03	77.70 ± 0.02	659.1 ± 25.7	423.5 ± 0.3	64.4 ± 2.5	0.00230 ± 0.00004
<i>M. styphelioides</i>	Boro. (S1)	21.5 ± 1.1	53.00 ± 0.02	231.00 ± 0.05	2933.2 ± 77.6	857.6 ± 0.4	29.3 ± 0.8	0.00230 ± 0.00004
	Boro. (S2)	22.6 ± 1.0	31.10 ± 0.04	181.50 ± 0.04	1743.1 ± 102.0	385.0 ± 0.5	22.2 ± 1.3	0.00290 ± 0.00005
	Boro. (G)	15.3 ± 0.8	17.30 ± 0.01	123.70 ± 0.02	746.3 ± 27.7	143.9 ± 0.1	19.3 ± 0.7	0.00280 ± 0.00003

of 1.55 m thick intermediate-plasticity silty clay (CI). The soil became high-plasticity (CH) from 1.7 m to 4.0 m. The soil water content was below 20% within the top 1.25 m, followed by a gradual increase to $26.21\% \pm 0.74\%$ at a depth of 1.75 m. A slight variation (approximately 4%) in water content was observed from 2.0 m to the full depth of measurement. At the Rowville site, high-plasticity silty clay (CH) was encountered from 0.2 m to 3.2 m, with the soil water content ranging from $12.45\% \pm 1.02\%$ to $16.67\% \pm 0.63\%$. A gradual water content rise to $20.46\% \pm 1.05\%$ occurred at 3.25 m depth, which remained almost constant over a layer of 0.75 m thick intermediate-plasticity silty clay (CI) from 3.25 m to 4.0 m. High-plasticity silty clay (CH) was found between 0.4 m and 4.0 m at the Boronia site. Soil water content increased progressively from $20.66\% \pm 0.72\%$ at 0.25 m to $30.56\% \pm 1.07\%$ at 1.5 m. This is followed by a gradual decrease to $26.32\% \pm 0.50\%$ at 2.5 m, which fluctuated around 28% between 2.75 m and 4.0 m. The Rowville site generally experienced soil desiccation, with the lowest water content of $12.45\% \pm 1.02\%$ observed at a depth of 2.25 m. In contrast, the Boronia site had the highest soil moisture content, although the variation

in soil water content was less than 10% across the investigated depths for all three experimental sites.

Tree sap flow

The comparison of the daily sap flow rate for nine trees at three sites over 21 days in the summer of 2019 is presented in Fig. 5. Common to all trees, the diurnal sap flow showed a ‘bell-shaped’ pattern, with a marked sap flow rise occurring in the morning and peaking in the early afternoon. A gradual decline in sap flow was observed in the late afternoon, approaching zero around midnight. Nocturnal sap flow was also observed throughout the monitoring period, averaging approximately 91%–97% lower than daytime sap flow rates. The maximum sap flow rates in *L. confertus* ranged from 4 L/h to 13 L/h, the lowest among the three tree species. In contrast, on average, the daily peak sap flow in the *M. styphelioides* at Boronia reached 28 L/h, 128% higher than the peak flow in the two single *C. maculata* at Bayswater. The maximum sap flow rate in the single *C. maculata* is 76%–81% higher than the tree in a group at the same site. When daily peak sap flow values were averaged across the three trees per species

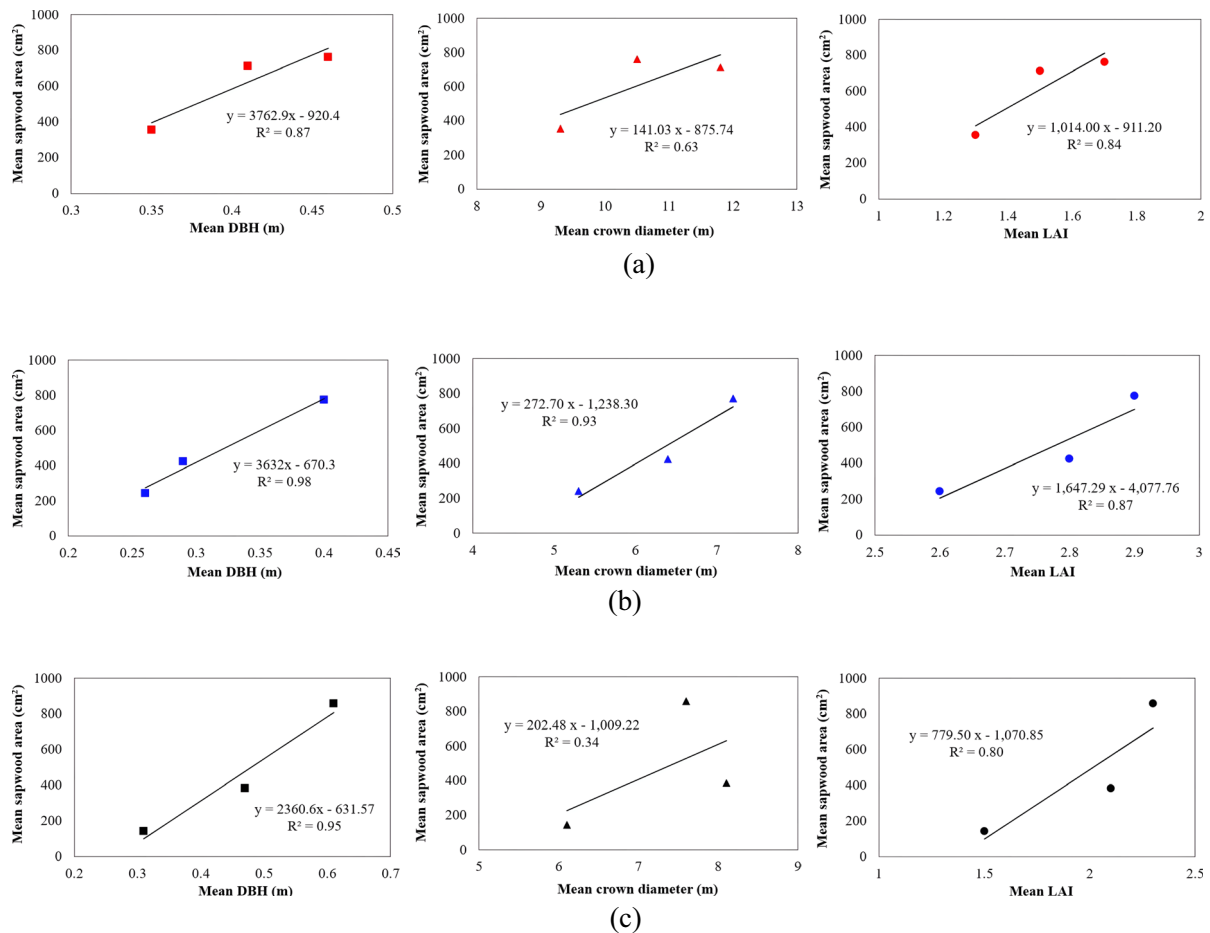


Fig. 3 Correlations between mean sapwood area, mean DBH, mean crown diameter and mean LAI (a) *C. maculata* (b) *L. confertus* (c) *M. styphelioides*

($n=21$ species-means), significant interspecific differences emerged (one-way ANOVA, $p < 0.0001$). Tukey's HSD (HSD=0.39 L/h) revealed that *M. styphelioides* (12.99 ± 0.64 L/h) had significantly higher daily peaks than *C. maculata* (8.71 ± 0.42 L/h; $\Delta = 4.28$ L/h) and *L. confertus* (6.85 ± 0.45 L/h; $\Delta = 6.13$ L/h), and *C. maculata* also exceeded *L. confertus* ($\Delta = 1.85$ L/h; all $p < 0.001$).

As shown in Fig. 5, there were four days with high temperatures exceeding 40 °C during the study period. During the heatwave days, mean daily sap flow volume decreased relative to the previous day's values by 11.7 ± 2.1 L in *C. maculata*, 8.9 ± 1.8 L in *L. confertus*, and only 2.1 ± 0.6 L in *M. styphelioides*. The smaller reduction in *M. styphelioides* highlights

its superior ability to sustain transpiration under extreme heat. On the 18th of January, all trees exhibited the lowest sap flow, which can be attributed to the significantly reduced total solar radiation of only 6 MJ/m². This value was 76% lower than the daily average solar radiation of 25 MJ/m². VPD exhibited patterns similar to sap flow rates. Across all nine trees, VPD explained between 58 and 69% of the variation in sap-flow ($p < 0.001$; R^2 range=0.58–0.69), indicating a moderate effect of atmospheric demand on transpiration under high temperature conditions.

Figure 6 presents the comparison of monthly tree water usage among nine trees from three species from September 2018 to August 2019. The data reveals substantial variation in the amount of water extracted

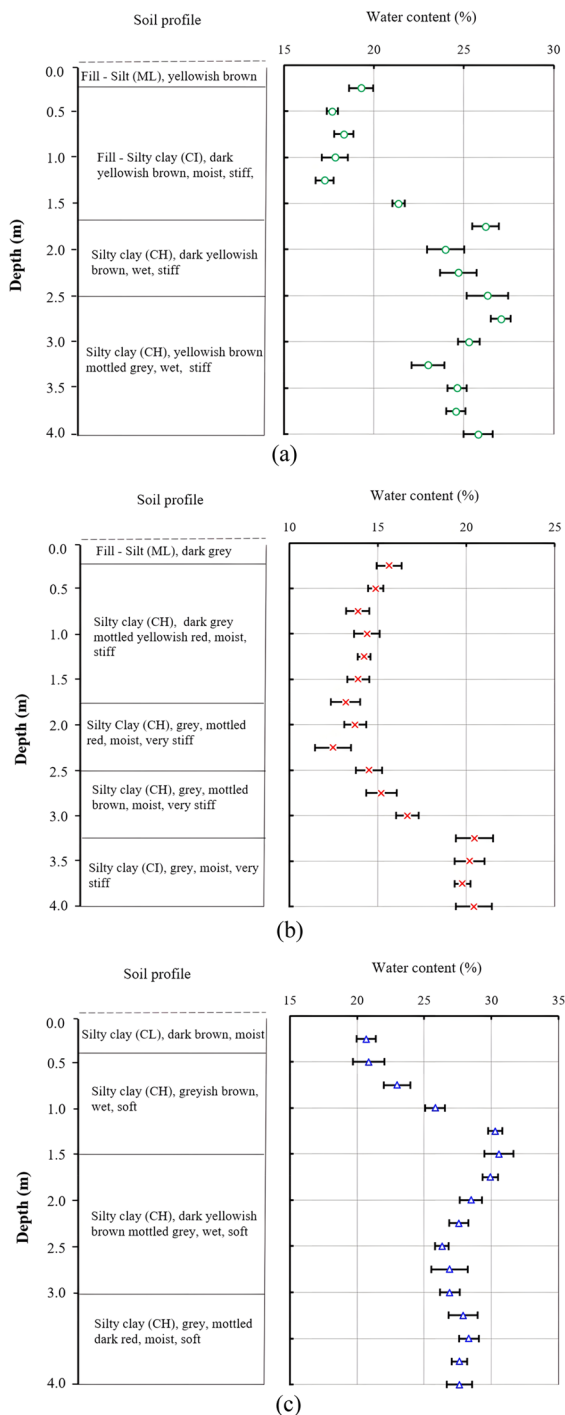


Fig. 4 Soil and water content profiles developed across the study sites (a) Bayswater (b) Rowville (c) Boronia

by trees throughout the seasons, with peak transpiration occurring predominantly during the summer months. Notably, the maximum monthly transpiration for *L. confertus* occurred in December, while for *C. maculata* and *M. styphelioides*, it occurred in January. The lowest tree water usage takes place from June to August for all three species.

The monthly water consumption ranged from 2.36 kL to 7.56 kL for the single *M. styphelioides* (S1) at Boronia, with an average monthly usage of 4.44 kL. This is 733% greater than the monthly mean water usage for the tree in a group at the same site, requiring only 193 L of water to survive in a winter month. Similarly, the mean monthly water consumption for the two single *C. maculata* at Bayswater varied from 1.95 kL to 2.25 kL, 120%–155% higher than the tree within a group (G). The *M. styphelioides* (S1) at Boronia utilised 53.27 kL of water over 12 months, which is only 6% less than the sum of total water usage of all three *L. confertus* over the same period.

Seasonal water use trends showed a consistent pattern across all species, exhibiting a notable increase from spring to early summer, followed by a gradual decline during autumn, and a slight increase in winter. The *C. maculata* (S2), *L. confertus* (S1), and *M. styphelioides* (S1) consumed the maximum mean monthly water of 2.25 kL, 1.95 kL, and 4.44 kL, respectively, over the 12-month monitoring period. On average, the *M. styphelioides* used 128% and 97% more water than the *L. confertus* and *C. maculata*, respectively. It is worth mentioning that the summer water use of *L. confertus* contributed to 40% of the total annual water consumption.

Resilience in hot and arid weather

To explore the species' patterns of water transport activity throughout the day under varying atmospheric demand, the timing of peak sap flow was plotted against the daily maximum VPD in Fig. 7. The data reveal that *C. maculata* most frequently reached peak sap flow between 9:00 am and 12:00 pm on days with high VPD during the summer months, suggesting earlier stomatal regulation compared to the other species. In contrast,

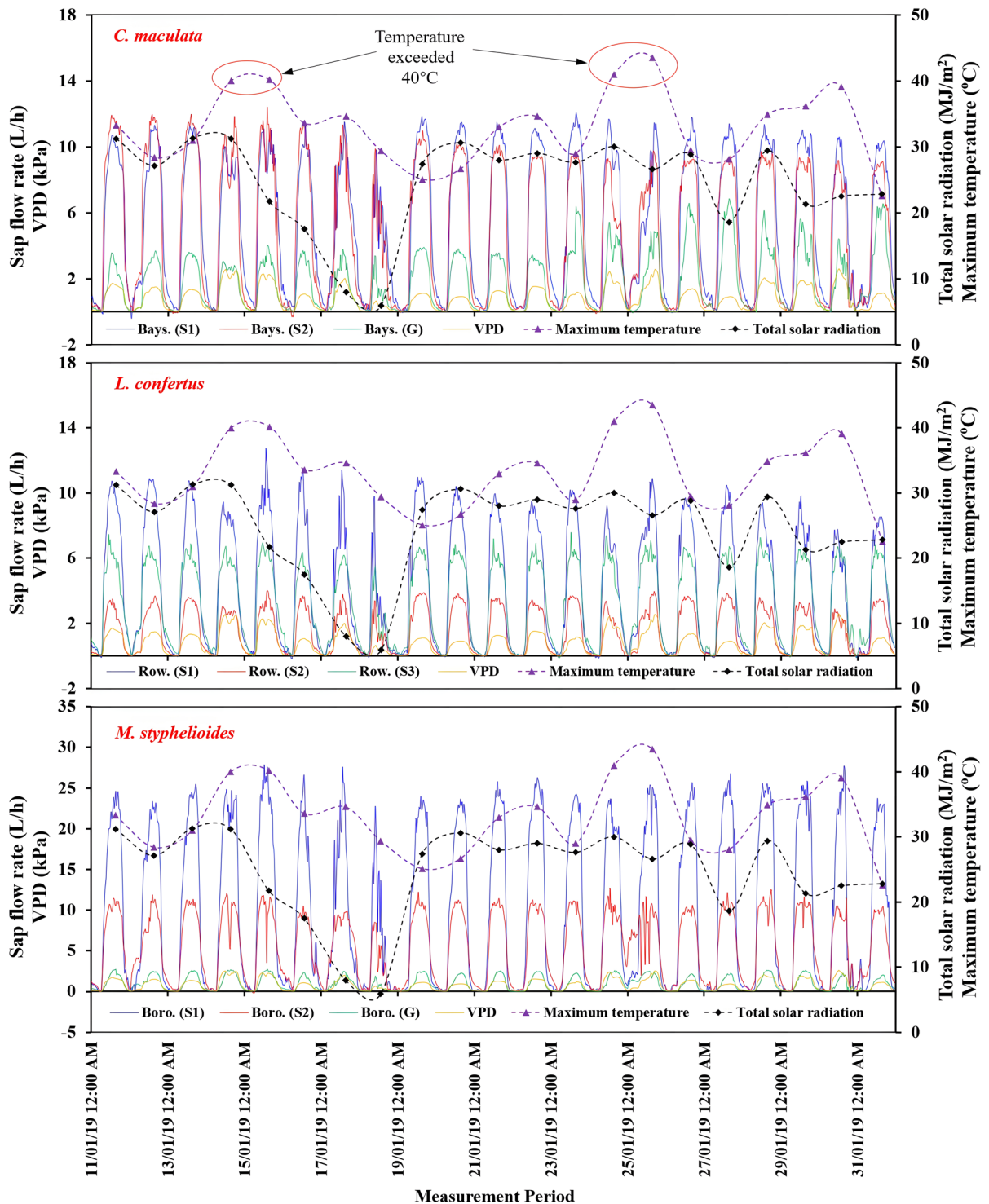


Fig. 5 Diurnal variation in sap flow rates for three tree species over 21 days

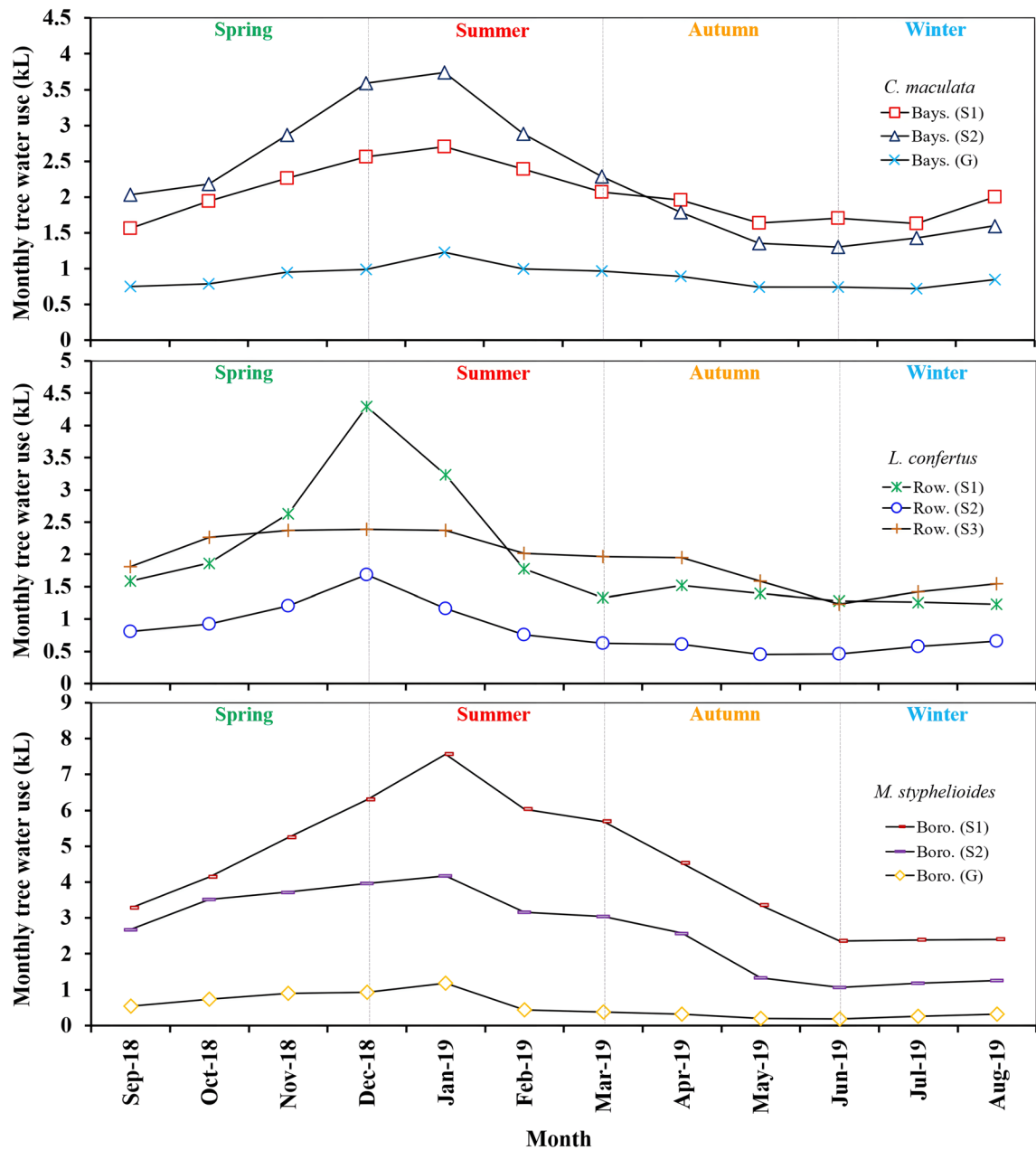


Fig. 6 The comparison of monthly tree water use among three species over 12 months

L. confertus typically peaked later, from 1:00 pm to 2:00 pm, at daily peak VPD levels of 5–7 kPa. Notably, the measured *M. styphelioides* specimens demonstrated the ability to maintain open stomata and sustain maximum sap flow into the late afternoon, indicating a distinct stomatal strategy adapted to arid conditions.

Figure 8 reveals the frequency distribution of the timing of the peak sap flow over the day for the sampled trees over the summer months. The peak sap flow for the single *C. maculata* (S1) occurred most frequently between 12:00 and 13:00, while the other two trees occurred between 13:00 and 14:00 on 33% (S2) and 29% (G) of days over the study period. The most

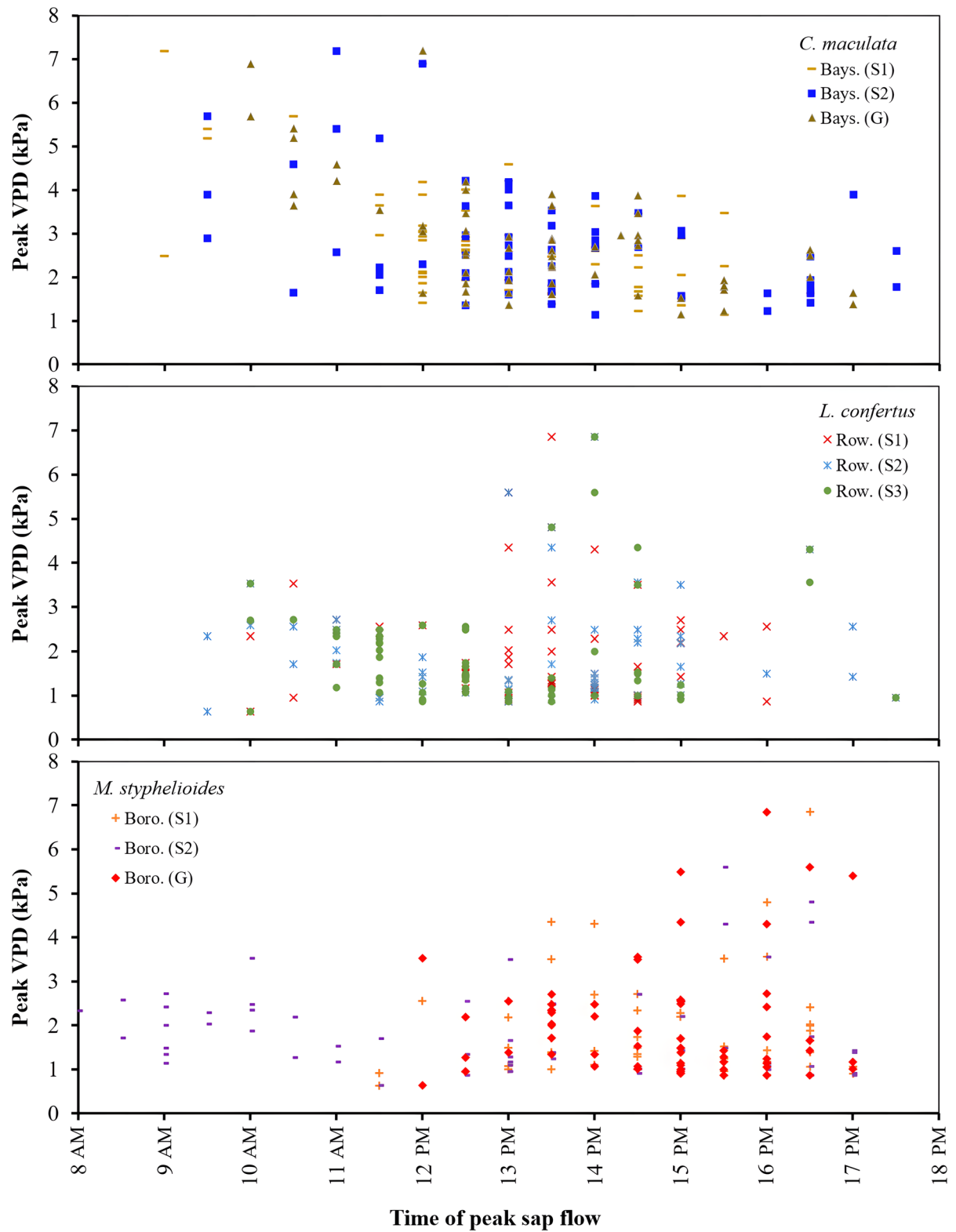
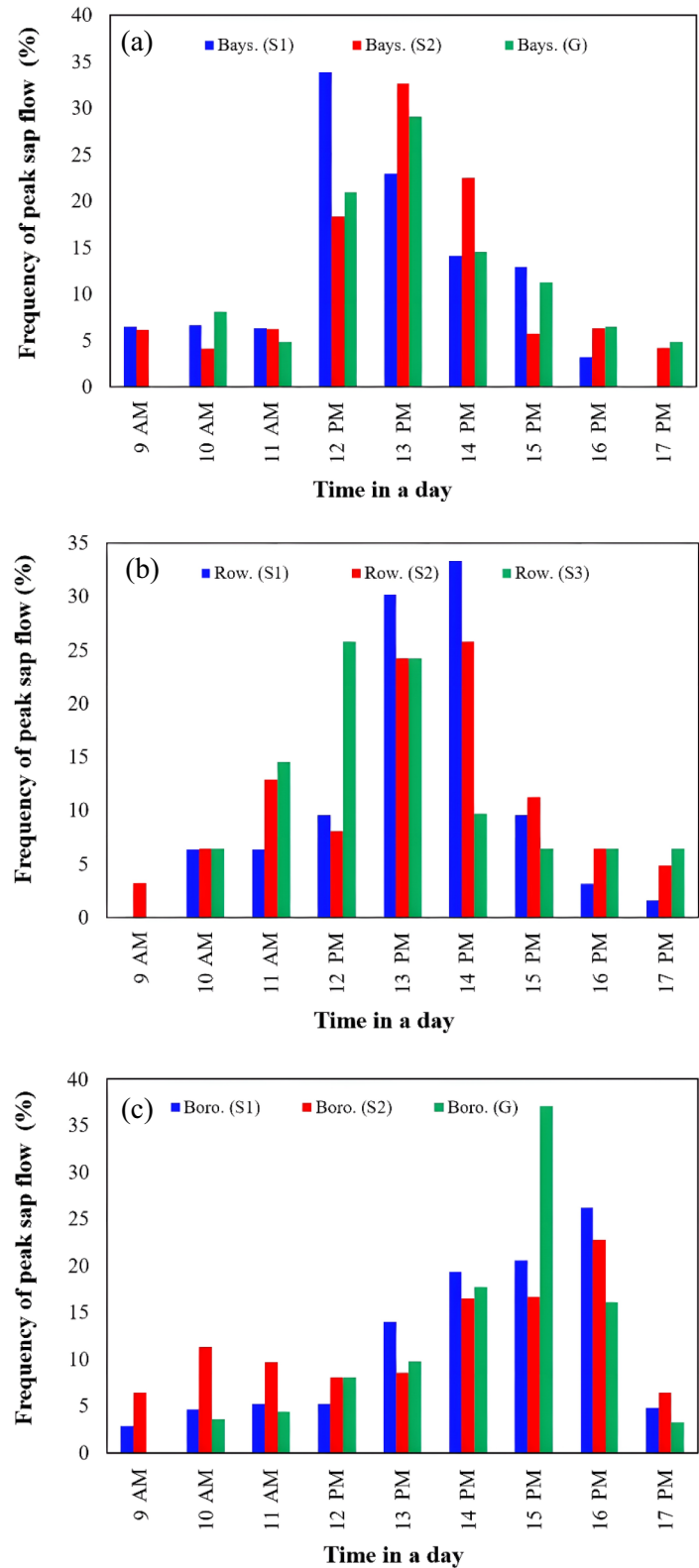


Fig. 7 Time of daily peak sap flow versus daily peak VPD for three tree species over summer months

Fig. 8 The occurrence frequency of peak sap flow timing across three tree species over summer months (a) *C. maculata* (b) *L. confertus* (c) *M. styphelioides*

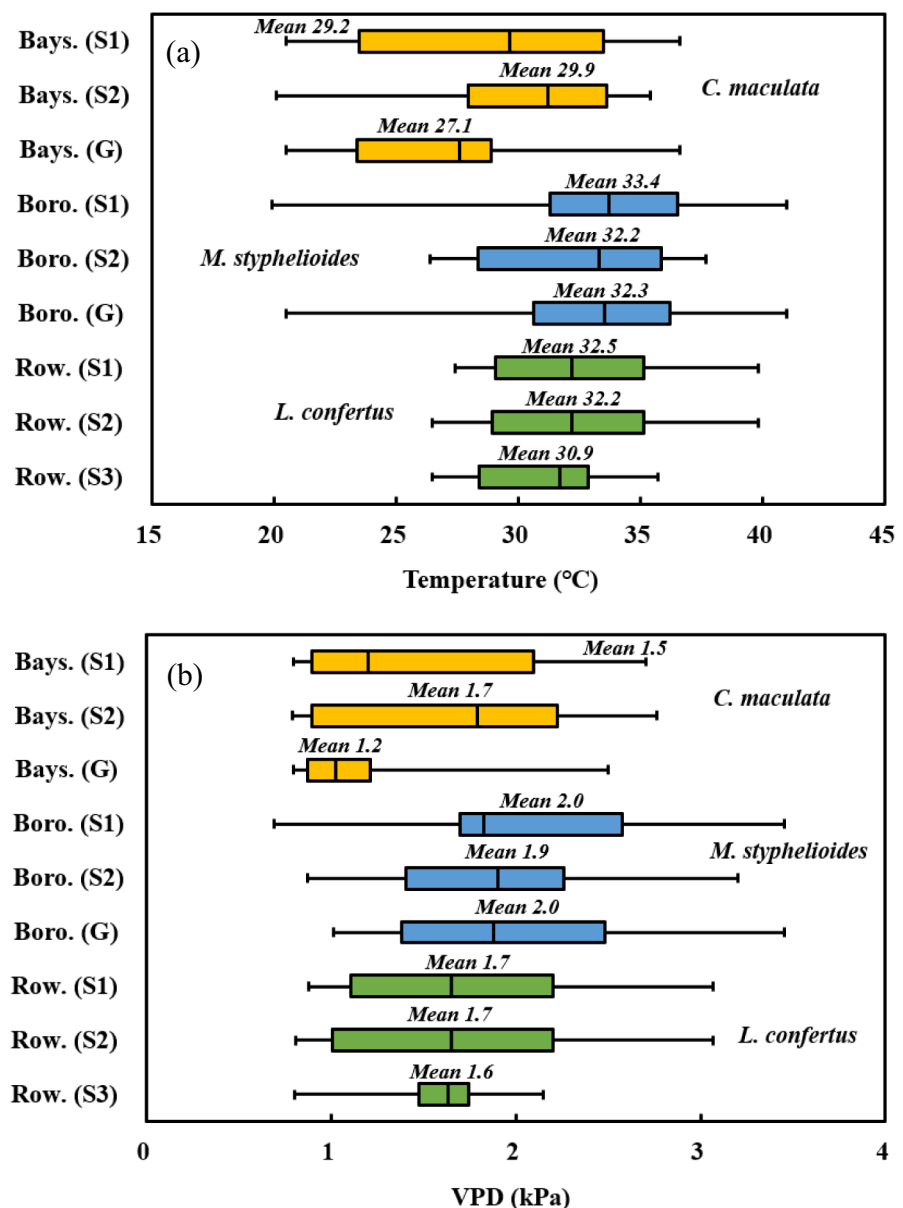


common time for peak sap flow for *L. confertus* was 12:00–15:00, occurring on 26% (S1), 33% (S2), and 26% (S3) of days. In contrast, the peak sap flow for *M. styphelioides* occurred between 15:00 and 17:00 in the late afternoon, with the maximum sap flow in the tree within the group (G) most frequently happening during 15:00–16:00 on 37% of the summer days.

The temperature and VPD optima for peak sap flow were evaluated and compared across the three tree species, with the results presented in Fig. 9. *C. maculata* specimens reached peak flow at mean

temperatures of 27.1–29.9 °C (± 4.3 –5.4 °C). In contrast, the *M. styphelioides* specimens exhibited peak sap flow at the highest mean temperatures of 32.2–33.4 °C (± 4.0 –5.9 °C). *L. confertus* displayed intermediate temperature optima, with peak sap flow occurring at 30.9–32.5 °C (± 2.9 –4.0 °C). In terms of VPD, *C. maculata* specimens maintained peak sap flow at lower VPD levels compared to *M. styphelioides* and *L. confertus*, with mean optimal VPD values ranging from 1.2–1.7 kPa (± 0.5 –0.7 kPa) associated with maximum flow rates. The difference

Fig. 9 Temperature and VPD optima associated with peak sap flow in three tree species (a) temperature optima (b) VPD optima



in the mean VPD of 0.1 kPa was observed among the three experimental trees for *L. confertus* and *M. styphelioides*. The *M. styphelioides* specimens exhibited peak sap flow at the highest mean VPD values of 1.9–2.0 kPa (± 0.7 – 0.8 kPa) compared to the other two species.

Discussion

Although the grouped specimens of *C. maculata* and *M. styphelioides* exhibited lower mean DBH, smaller mean crown diameter, and reduced mean LAI compared to the isolated trees, these observations are based on only one grouped individual per species and should therefore be considered as preliminary. A larger and more balanced sample is required to draw robust conclusions regarding the effects of planting density on morphological traits.

The observed variation in sapwood area among trees of the same species is consistent with findings by Espinosa Bancalari et al. (1987), who also reported a progressive reduction in sapwood area with increasing tree height. However, our study did not observe a similar trend, suggesting that factors beyond height, such as site conditions or species-specific physiological adaptations, may influence sapwood area distribution. A strong positive correlation between sapwood area, DBH, and LAI across all three species supports the model proposed by Hatton and Wu (1995). This relationship indicates sapwood area as a key determinant of leaf area potential, explaining 85%–95% of leaf area variability, as observed in *Pseudotsuga menziesii* (Espinosa Bancalari et al. 1987). The strong positive relationships between sapwood area and morphological traits are critical because the sapwood cross-section determines the maximum conductive pathway for water flow, while tree architecture (e.g. trunk girth) reflects the transpirational demand that the sapwood must supply. In other words, the reliable prediction of greater sapwood area from larger DBH or crown girth allows us to estimate a tree's water-transport capacity non-destructively, avoiding the need for invasive sampling.

The diurnal patterns of sap flow in all studied trees were characterised by a 'bell-shaped' curve, with sap flow peaking in the afternoon, which is consistent with studies on *C. ficifolia* (Li et al. 2014) and *C. maculata* (Sun and Li 2023c; Sun et al. 2023b). Days

with significantly reduced total solar radiation (e.g., 6 MJ/m^2) led to the lowest sap flow rates, corroborating previous findings that solar radiation accounts for 53% of sap flow variation (Sun et al. 2021).

Further analysis of the frequency distribution of peak sap flow timing among the three tree species during the summer revealed that *M. styphelioides* consistently maintained its highest sap flow rates later in the day, between 15:00 and 17:00, compared to *C. maculata* and *L. confertus*. This pattern suggests that *M. styphelioides* optimises photosynthetic activity in the afternoon, potentially enhancing its overall carbon assimilation efficiency. Figure 7 confirms that all three *M. styphelioides* trees sustained open stomata and maintained peak sap flow during the late afternoon. By shifting its maximum transpiration closer to sunset, *M. styphelioides* may exploit favourable late-afternoon light conditions, thereby maximising CO_2 uptake and carbon gain. This extended photosynthetic window could potentially confer a competitive growth advantage over *C. maculata* and *L. confertus*, which exhibited peak transpiration earlier in the day. However, we did not directly measure photosynthetic rates or biomass growth in this study. Future work combining sap flow monitoring with gas exchange and growth assessments is needed to validate these hypothesised carbon-gain benefits.

While late-day peaks in sap flow may indicate prolonged stomatal opening and extended opportunities for carbon gain under high VPD, this strategy can also increase vulnerability to xylem embolism and hydraulic failure if soil moisture becomes limiting (Brodribb and Cochard 2009). Conversely, species that close stomata earlier, such as *C. maculata* in this study, exhibit a more conservative water use strategy that reduces transpirational water loss and lowers the risk of dehydration. Although these species may invest less in photosynthesis during the hottest hours, they can still maintain growth and survival by optimising carbon fixation when atmospheric conditions are milder (Oren et al. 1999). Therefore, selecting "right trees" for phytoremediation requires matching species' water use strategies to site-specific soil moisture availability and drought risk.

Preliminary observations revealed that the grouped *M. styphelioides* (G) specimen transpired less water ($\sim 200 \text{ L}$) to survive in winter, which aligns with Sun et al. (2022) who reported lower winter water

use (325 L) for clustered *M. styphelioides*. However, these findings are based on a grouped individual and must be regarded as tentative. In contrast, the higher water consumption observed in the single *M. styphelioides* trees suggests a greater potential for groundwater uptake. To robustly evaluate the influence of planting density on water use and phytoremediation capacity, a larger and more balanced sample of both grouped and isolated specimens is required.

Variability in water use among conspecific trees at the same sites can be attributed to multiple factors, including xylem anatomy, planting density, tree height, canopy size, and the extent of solar radiation interception (Meinzer et al. 2001; Francescantonio et al. 2018). Among trees of the same species, those with the highest water demand were typically characterised by larger sapwood areas and greater height, indicating that structural attributes significantly influence water use dynamics. The substantially lower water use exhibited by the *C. maculata* and *M. styphelioides* growing in groups compared to single trees grown at the same site is predominantly attributable to increased competitive interactions for limited resources (Sun et al. 2022). In these tree groups, vertical stratification could result in the tallest one intercepting a greater proportion of solar radiation with its upper canopy. Through this asymmetric competition for light, the dominant trees experience greater radiative loading of their canopies, facilitating higher transpiration rates relative to the shorter ones. Additionally, the variations in water use of trees among three different species are likely due to discrepancies in soil profiles and soil water dynamics between study sites (Fig. 4). Notably, the two individual *M. styphelioides* exhibiting the highest water demand grew on soils classified as high plasticity silty clay, with average water content ranging from 26 to 31% at depths of 1–4 m. Comparatively, the study sites for *C. maculata* and *L. confertus* exhibited 18% and 74% lower mean soil moisture contents, respectively. These discrepancies in soil water availability between the study sites may induce significant differences in access to soil moisture available for transpiration.

The observed timing of peak sap flow suggests inherent differences in photosynthetic activity over the diurnal cycle among the three tree species. The peak sap flow for *C. maculata* indicates this species is more active photosynthetically in the early afternoon. On the other hand, the delayed peak photosynthetic

period of *M. styphelioides* could contribute to enhanced carbon gain and higher growth rates by taking greater advantage of late afternoon light conditions (Zhao et al. 2022).

While peak sap flow thresholds under high temperature and VPD provide insight into species' capacity to sustain transpiration under stress, they represent only one facet of drought and heat tolerance. Species may employ contrasting strategies. In this study, *C. maculata*'s lower temperature and VPD optima suggest earlier stomatal closure, a conservative approach that limits water loss and reduces the risk of xylem dysfunction, whereas *M. styphelioides* maintains flow at higher stress levels, potentially risking greater hydraulic strain. Other traits, including stomatal sensitivity, xylem vulnerability to cavitation, and stem-water storage capacity, also shape a species' overall resilience (Oren et al. 1999; Brodribb and Cochard 2009; James et al. 2003). Future work should integrate these complementary trait measurements to develop a multidimensional framework for selecting trees with appropriate water-use strategies for saline, heat-stressed urban environments.

It is essential to acknowledge several limitations of our study. First, the sample size of three trees per species, with one grouped specimen for two of the three species, limits the statistical power and generalisability of our findings. This constraint reflects the practical challenges of conducting year-long, continuous sap flow measurements in urban settings, including equipment costs, maintenance requirements, and the administrative complexities of obtaining permissions for public tree instrumentation. Future research should prioritise larger, balanced samples across both single and clustered plantings to validate the patterns reported here.

Second, our assessment of species' responses to heat and drought stresses relies primarily on sap flow dynamics, which capture only one aspect of plant stress responses. A more comprehensive evaluation would incorporate additional physiological metrics such as leaf water potential (Choat et al. 2018), stomatal conductance (Klein 2014), hydraulic vulnerability curves (Blackman et al. 2019), leaf osmotic adjustment capacity (Bartlett et al. 2014), and photosynthetic efficiency under stress (Flexas et al. 2002). These complementary measurements would provide a more comprehensive understanding of the species' adaptive mechanisms and tolerance thresholds.

Finally, while the high water use patterns and late-day sap low peaks observed in *M. styphelioides* suggest promising traits for phytoremediation of saline soils, we did not directly measure soil salinity changes associated with tree planting. To address this limitation, future research should include direct assessment of soil salinity profiles associated with different tree species using methodologies such as the Saturated Paste Extract (ECe) approach (Kargas et al. 2016), which represents an internationally recognised standard for determining soil salinity relevant to plant growth. Such measurements would establish a more direct link between tree water use patterns and actual salinity amelioration outcomes.

Conclusion

This study evaluated water use patterns and physiological responses of nine Australian native trees across three species in Melbourne, Australia, providing initial insights into their potential for phytoremediation in saline environments under climate change conditions. Through 12 months of continuous sap flow monitoring, *M. styphelioides* exhibited the highest water consumption, averaging 4.44 kL per month, which was 128% and 97% higher than *L. confer-tus* and *C. maculata*, respectively. Furthermore, *M. styphelioides* exhibited enhanced physiological resilience with a mean optimal temperature of 32.8 °C and a mean optimal VPD of 2.0 kPa, substantially exceeding the tolerance thresholds observed in the other studied species.

A key finding from this research is that *M. styphelioides* consistently maintained peak sap flow later in the day compared to other species, suggesting an adaptive advantage in maximising photosynthetic efficiency under extended daylight conditions. This characteristic, combined with its high water usage capacity and demonstrated ability to maintain transpiration under elevated temperature and VPD conditions, identifies *M. styphelioides* as a species of interest for further research into its potential applications in effective soil salinity reduction and groundwater regulation.

Based on these findings, we recommend further investigation through controlled field trials to directly measure changes in soil and groundwater salinity beneath *M. styphelioides* plantings. In addition, evaluating long-term water table drawdown in comparison

with other candidate species is essential. Such multi-trait investigations are critical to validate the effectiveness of *M. styphelioides* before its widespread implementation for practical phytoremediation in urban saline landscapes.

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Author contributions Conceptualization (XS and JL), methodology (XS), software (XS), investigation (XS and JL), validation (XS and JL), analysis (XS), resources (XS and JL), data curation (XS, JL and GR), visualization (XS, MS and YG), writing (XS, JL and XL), project administration (JL) and funding acquisition (JL). All authors approved the final version of the manuscript.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflicts of interest The authors have no conflict of interest to declare.

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References

- ABS (2010) Australian Bureau of Statistics. <https://www.abs.gov.au/>. Accessed 15 October 2022.
- AS 1289 (2009a) Methods for Testing Soils for Engineering Purposes, Method 3.1.2, Soil Classification Tests – Determination of the Liquid of a Soil– One Point Casagrande Method (Subsidiary method). Standards Australia International Ltd, Sydney, Australia

- AS 1289 (2009b) Methods for Testing Soils for Engineering Purposes, Method 3.2.1, Soil Classification Tests – Determination of the Plastic Limits of a Soil (Standard Method). Standards Australia International Ltd, Sydney, Australia
- AS1289 (1992) Methods for Testing Soils for Engineering Purposes, Method 2.1.1, Soil Moisture Content Tests – Determination of the Moisture Content of a Soil – Oven Drying Method (Standard Method). Standards Australia International Ltd, Sydney, Australia
- Barrett-Lennard EG (2002) Restoration of saline land through revegetation. *Agric Water Manag* 53:213–226
- Bartlett MK, Scoffoni C, Sack L (2014) The determinants of leaf turgor loss point and prediction of drought tolerance of species and biomes: a global meta-analysis. *Ecol Lett* 15(5):393–405
- Bell DT (1999) Australian trees for the rehabilitation of water-logged and salinity-damaged landscapes. *Aust J Bot* 47:697–716
- Berger C, Laurent F (2019) Trunk injection of plant protection products to protect trees from pests and diseases. *Crop Prot* 124. <https://doi.org/10.1016/j.cropro.2019.05.025>
- Blackman CJ, Creek D, Maier C, Aspinwall MJ, Drake JE, Pfautsch S, O'Grady A, Delzon S, Medlyn BE, Tissue DT, Choat B (2019) Drought response strategies and hydraulic traits contribute to mechanistic understanding of plant dry-down to hydraulic failure. *Tree Physiol* 39(6):910–924
- Bleby TM, Burgess SSO, Adams MA (2004) A validation, comparison and error analysis of two heat-pulse methods for measuring sap flow in *Eucalyptus marginata* saplings. *Funct Plant Biol* 31(6):645–658. <https://doi.org/10.1071/FP04013>
- BOM (2022) Climate data online. <http://www.bom.gov.au/climate/data/>. Accessed 22 July 2022.
- Boulton AJ, Brock MA, Robson BJ, Ryder DS, Chambers JM, Davis JA (2014) Australian freshwater ecology: processes and management, 2nd edn. John Wiley & Sons, Chichester, United Kingdom
- Brodrigg TJ, Cochard H (2009) Hydraulic failure defines the recovery and point of death in water-stressed conifers. *Plant Physiol* 149(1):575–584
- Burgess SSO, Adams MA, Turner NC, Beverly CR, Ong CK, Khan AAH, Bleby TM (2001) An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree Physiol* 21:589–598
- Choat B, Brodrigg TJ, Brodersen CR, Duursma RA, López R, Medlyn BE (2018) Triggers of tree mortality under drought. *Nature* 558(7711):531–539
- Clarke CJ, George RJ, Bell RW, Hatton TJ (2002) Dryland salinity in south-western Australia: its origins, remedies, and future research directions. *Soil Res* 40:93–113
- Edwards WRN, Warwick NWM (1984) Transpiration from a kiwifruit vine as estimated by the heat pulse technique and the Penman–Monteith equation. *N Z J Agric Res* 27:537–543. <https://doi.org/10.1080/00288233.1984.10418016>
- Espinosa Bancalari MA, Perry DA, Marshall JD (1987) Leaf area-sapwood area relationships in adjacent young Douglas-fir stands with different early growth rates. *Can J for Res* 17(2):174–180. <https://doi.org/10.1139/x87-030>
- Fensom DS (1963) The bioelectric potentials of plants and their functional significance: V. Some daily and seasonal changes in the electrical potential and resistance of living trees. *Can J Bot* 41:831–851. <https://doi.org/10.1139/b63-068>
- Flexas J, Escalon JM, Evain S, Gullás J, Moya I, Osmond CB, Medrano H (2002) Steady-state chlorophyll fluorescence (Fs) measurements as a tool to follow variations of net CO₂ assimilation and stomatal conductance during water-stress in C3 plants. *Physiol Plant* 114(2):231–240
- Francescantonio DD, Villagra M, Goldstein G, Campanello PI (2018) Leaf phenology and water-use patterns of canopy trees in Northern Argentinean subtropical forests. *Tree Physiol* 38(12):1841–1854. <https://doi.org/10.1093/treephys/tpy072>
- Gibert D, Mouel JL, Lamb L, Nicollin F, Perrier F (2006) Sap flow and daily electric potential variations in a tree trunk. *Plant Sci* 171:572–584. <https://doi.org/10.1016/j.plantsci.2006.06.012>
- Green SR, Clothier BE, McLeod DJ (1997) The response of sap flow in apple roots to localised irrigation. *Agric Water Manag* 33:63–78. [https://doi.org/10.1016/S0378-3774\(96\)01277-2](https://doi.org/10.1016/S0378-3774(96)01277-2)
- Hatton TJ, Wu HI (1995) Scaling theory to extrapolate individual tree water use to stand water use. *Hydrol Process* 9:527–540. <https://doi.org/10.1002/hyp.3360090505>
- Hogg EH, Black TA, den Hartog G, Neumann HH, Zimmermann R, Hurdle PA, Blanken PD, Nesic Z, Yang PC, Staeble RM, McDonald KC, Oren R (1997) A comparison of sap flow and eddy fluxes of water vapor from a boreal deciduous forest. *J Geophys Res* 102:28929–28937. <https://doi.org/10.1029/96JD03881>
- Hu Y, Schmidhalter U (2002) Limitation of salt stress to plant growth. In: Hock B, Elstner CF (eds) *Plant Toxicology*. Marcel Dekker Inc., New York, pp 91–224
- IPCC (2021) Regional Fact Sheet – Urban Areas. In: Masson-Delmotte V, Zhai P, Pirani A et al. (ed) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.
- Ismanov M, Francis P, Henry C, Espinoza L (2019) Relations among sap flow, soil moisture, weather, and soybean plant parameters in high water demand and final growth stages. *Agric Sci* 10:371–385. <https://doi.org/10.4236/as.2019.103030>
- James SA, Meinzer FC, Goldstein G, Woodruff D, Jones T, Restom T, Mejia M, Clearwater M, Campanello P (2003) Axial and radial water transport and internal water storage in tropical forest canopy trees. *Oecologia* 134:37–45
- Jonckheere I, Fleck S, Nackaerts K, Muys B, Coppin P, Weiss M, Baret F (2004) Review of methods for in situ leaf area index determination: Part I. Theories, sensors and hemispherical photography. *Agric for Meteorol* 121(1–2):19–35
- Jorenush MH, Sepaskhah AR (2003) Modelling capillary rise and soil salinity for shallow saline water table under irrigated and non-irrigated conditions. *Agric Water Manag* 61(2):125–141
- Kargas G, Popescou P, Kaliontzis N, Marougas D (2016) Estimation of the Electrical Conductivity of Saturated Paste

- Extract Using a Dielectric Sensor. *J Irrig Drain Eng* 143(5):04016086
- Kim HK, Park J, Hwang I (2014) Investigating water transport through the xylem network in vascular plants. *J Exp Bot* 65(7):1895–1904
- Klein T (2014) The variability of stomatal sensitivity to leaf water potential across tree species indicates a continuum between isohydric and anisohydric behaviours. *Funct Ecol* 28(6):1313–1320
- Kozłowski TT, Winget CH (1963) Patterns of Water Movement in Forest Trees. *Bot Gaz* 124:301–311
- Kumar R, Hosseinzadehtaher M, Hein N, Shadmand M, Jagadish SVK, Ghanbarian B (2022) Challenges and advances in measuring sap flow in agriculture and agroforestry: A review with focus on nuclear magnetic resonance. *Front Plant Sci* 13:1036078
- Li J, Guo L (2017) Field investigation and numerical analysis of residential building damaged by expansive soil movement caused by tree root drying. *J Perform Constr Facil* 31:1–10. [https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0000908](https://doi.org/10.1061/(ASCE)CF.1943-5509.0000908)
- Li J, Sun X (2015) Evaluation of changes of Thornthwaite Moisture Index in Victoria. *Aust Geomech J* 50:39–49
- Li J, Zhou Y, Guo L, Tokhi H (2014) The establishment of a field site for reactive soil and tree monitoring in Melbourne. *Aust Geomech J* 49:63–72
- Mayer XM, Ruprecht JK, Bari MA (2005) Stream salinity status and trends in south-west Western Australia. In: Salinity and land use impacts series, Report No. SLUI 38. Department of Environment, Government of Western Australia, Perth
- Mcferson EG, Rowntree RA (1988) Geometric solids for simulation of tree crowns. *Landsc Urban Plan* 15:79–83. [https://doi.org/10.1016/0169-2046\(88\)90017-5](https://doi.org/10.1016/0169-2046(88)90017-5)
- Meinzer FC, Goldstein G, Andrade JL (2001) Regulation of water flux through tropical forest canopy trees: Do universal rules apply? *Tree Physiol* 21(1):19–26. <https://doi.org/10.1093/treephys/21.1.19>
- Minhas PS, Dagar JC (2016) Use of tree plantations in water-table drawdown and combating soil salinity. In: Dagar JC, Minhas PS (eds) *Agroforestry for the management of waterlogged saline soils and poor-quality waters*. Advances in Agroforestry, vol 13. Springer, New Delhi. https://doi.org/10.1007/978-81-322-2659-8_3
- Muhammad M, Waheed A, Wahab A, Majeed M, Nazim M, Liu YH, Li L, Li WJ (2024) Soil salinity and drought tolerance: An evaluation of plant growth, productivity, microbial diversity, and amelioration strategies. *Plant Stress* 11:100319
- Niu Z, He H, Zhu G, Ren X, Zhang L, Zhang K, Yu G, Ge R, Li P, Zeng N, Zhu X (2019) An increasing trend in the ratio of transpiration to total terrestrial evapotranspiration in China from 1982 to 2015 caused by greening and warming. *Agric for Meteorol* 279:107701
- Oren R, Sperry JS, Katul GG, Pataki DE, Ewers BE, Phillips N, Schäfer KV (1999) Survey and synthesis of intra- and interspecific variation in stomatal sensitivity to vapour pressure deficit. *Plant Cell Environ* 22:1515–1526
- Qadir M, Tubeileh A, Akhtar J, Larbi A, Minhas PS, Khan MA (2008) Productivity enhancement of salt-affected environments through crop diversification. *Land Degrad Devel* 19:429–453. <https://doi.org/10.1002/ldr.853>
- Rahman AKMM, Ahmed KM, Butler AP, Hoque MA (2018) Influence of surface geology and micro-scale land use on the shallow subsurface salinity in deltaic coastal areas: a case from southwest Bangladesh. *Environ Earth Sci* 77:423. <https://doi.org/10.1007/s12665-018-7594-0>
- Richards RA (2000) Selectable traits to increase crop photosynthesis and yield of grain crops. *J Exp Bot* 51:447–458
- Sachs RM, Nyland G, Hackett WP, Coffelt J, Debie J, Giannini G (1977) Pressurized injection of aqueous solutions into tree trunks. *Sci Hortic* 6:297–310. [https://doi.org/10.1016/0304-4238\(77\)90087-5](https://doi.org/10.1016/0304-4238(77)90087-5)
- Shrivastava P, Kumar R (2015) Soil salinity: a serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. *Saudi J Biol Sci* 22:123–131. <https://doi.org/10.1016/j.sjbs.2014.12.001>
- Singh A (2021) Soil salinization management for sustainable development: A review. *J Environ Manage* 277:111383
- Stăncioiu PT, Șerbescu AA, Dutcă I (2021) Live Crown Ratio as an Indicator for Tree Vigor and Stability of Turkey Oak (*Quercus cerris* L.): A Case Study. *Forests* 12(12):1763
- Steppe K, Vandegehuchte MW, Tognetti R, Mencuccini M (2015) Sap flow as a key trait in the understanding of plant hydraulic functioning. *Tree Physiol* 35(4):341–345
- Sun X, Li J (2023a) A parametric study of the effect of trees on residential footing design on expansive soils. *Geotech Geol Eng* 41:2325–2341. <https://doi.org/10.1007/s10706-023-02400-0>
- Sun X, Li J (2023b) Tree root-soil interaction: field study of the effect of trees on soil moisture and ground movement in an urban environment. *Plant Soil*. <https://doi.org/10.1007/s11104-023-06307-w>
- Sun X, Li J (2023c) Case study of ground subsidence caused by the drying effect of a group of Australian native eucalypts. *J Perform Constr Facil* 37(5):1–11. <https://doi.org/10.1061/JPCFEV.CFENG-4254>
- Sun X, Li J (2024) Patterns of water use by the Australian native *Melaleuca styphelioides* in urban environments and comparison of transpiration prediction by three different micrometeorological models. *Trees* 38:493–506
- Sun X, Li J, Cameron DA, Zhou AN (2021) Field monitoring and assessment of the impact of a large eucalypt on soil desiccation. *Acta Geotech* 17(3):1971–1984. <https://doi.org/10.1007/s11440-021-01308-4>
- Sun X, Li J, Cameron DA, Moore G (2022) Sap flow monitoring of two Australian native tree species in a suburban setting: implications for tree selection and management. *Plant Sci*. <https://doi.org/10.1016/j.plantsci.2022.111194>
- Sun X, Li J, Cameron DA, Zhou AN, Bayetto P, Moore G (2023a) Assessment of the influence of an Australian native eucalypt, *Corymbia maculata*, on soil desiccation in a temperate climate. *Acta Geotech* 18:5901–5919
- Sun X, Li J, Ren G (2023b) Examining the impact of climate change on residential footing design in Australia: a case study analysis. *Geotech Geol Eng*. <https://doi.org/10.1007/s10706-023-02566-7>
- Sun X, Li J, Liu X, Wu S, Gao Y (2024) Mechanistic analysis of urban tree-soil interactions: species-specific water

- use and desiccation effects on expansive clays. *Plant Soil*. <https://doi.org/10.1007/s11104-024-07032-8>
- Sun X, Li J, Gao Y, Liu X, Zhou AN (2025) A quantitative framework for tree–soil interaction mechanisms in expansive clay: Field investigation and empirical modelling. *J Rock Mech Geotech Eng*. <https://doi.org/10.1016/j.jrmge.2025.03.015>
- Swanson RH (1983) Numerical and experimental analyses of implanted - probe heat pulse velocity theory, PhD Thesis. University of Alberta, Edmonton
- Tang H, Du L, Xia C, Luo J (2024) Bridging gaps and seeding futures: A synthesis of soil salinization and the role of plant-soil interactions under climate change. *iScience* 27(9):110804
- Tie Q, Hu H, Tian F, Guan H, Lin H (2017) Environmental and physiological controls on sap flow in a subhumid mountainous catchment in North China. *Agric for Meteorol* 240–241:46–57
- VVG (2023) Visualising Victoria's Groundwater. <https://www.vvg.org.au/>. Accessed 15 Oct 2023
- Wicke B, Smeets E, Dornburg V, Vashev B, Gaiser T, Turkenburg W, Faaij A (2011) The global technical and economic potential of bioenergy from salt-affected soils. *Energy Environ Sci* 4:2669–2681. <https://doi.org/10.1039/C1EE01029H>
- Zhao Q, Zhu Z, Zeng H, Myneni RB, Zhang Y, Peñuelas J, Piao S (2022) Seasonal peak photosynthesis is hindered by late canopy development in northern ecosystems. *Nat Plants* 8:1484–1492

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