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Title: Relationships between plant drought response, traits and climate of origin for green roof plant selection

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Abstract

The ideal species for green or vegetated roofs should have high water use after rainfall to maximise stormwater retention but also survive periods with low water availability in dry substrates. Shrubs have great potential for green roofs because they have higher rates of water use, and many species are also drought tolerant. However, not all shrub species will be suitable and there may be a trade-off between water use and drought tolerance. We conducted a glasshouse experiment to determine the possible trade-offs between shrub water use for stormwater management and their response to drought conditions. We selected 20 shrubs from a wide range of climate of origins, represented by heat moisture index (HMI) and mean annual precipitation (MAP). Under well-watered (WW) and water deficit (WD) conditions, we assessed morphological responses to water availability; evapotranspiration rate (ET) and midday water potential (Ψ_{MD}) were used to evaluate species water use and drought response. In response to WD, all 20 shrubs adjusted their morphology and physiology. However, there were no species that simultaneously achieved high rates of water use (high ET) under WW and high drought tolerance (low Ψ_{MD}) under WD. Although some species which had high water use under WW conditions could avoid drought stress (high Ψ_{MD}) used. Water use was strongly related to plant biomass, total leaf area and leaf traits (SLA and LAR). Conversely, drought response (Ψ_{MD}) was not related to morphological traits. Species' climate of origin was not related to drought response or water use. Drought avoiding shrubs (high Ψ_{MD}) could optimize rainfall reduction on green roofs. Water use was related to biomass, leaf area and leaf traits, thus these traits could be used to assist the selection of shrubs for stormwater mitigation on green roofs. The natural distribution of species was not related to their water use or drought response, which suggests that shrubs from less arid climates may be suitable for use on green roofs. Selecting species based on traits and not climate of origin could both improve green roof performance and biodiversity outcomes by expanding the current plant palette.

Keywords: Drought response strategies; ET; green roof; habitat template; heat moisture index (HMI); plant selection; shrub; trait; water use

Introduction

Green or vegetated roofs are increasingly being built in cities because of the range of ecosystem services they provide, including cooling, stormwater runoff reduction, habitat provision for biodiversity and improved air quality (Oberndorfer et al. 2007, Berndtsson

2010, Williams et al. 2014). A prominent benefit of green roofs in cities is the reduction of stormwater runoff (Teemusk and Mander 2007, MacIvor et al. 2016), which otherwise causes degradation to aquatic ecosystems (Walsh et al. 2005). In some cases, green roofs can retain up to 100% of rainfall (Berndtsson 2010). The reduction in runoff from green roofs is largely result of substrate water holding capacity and depth, yet vegetation water use can increase the ability of a roof to retain rainfall by drying out the substrate after rain events (Villarreal and Bengtsson 2005). Maximizing transpiration by plants on the roof may thus increase the total amount of water prevented from flowing off into waterways or sewer system. However, plants with high transpiration rates may not be able to survive on green roofs due to the low water holding capacity and shallow depth of many green roof substrates (Szota et al. 2017).

The extensive green roof environment can be highly stressful for plants, as they are exposed to wind and high irradiance, large temperature fluctuations, low substrate water availability and shallow substrate depths (<20 cm) (Nagase and Dunnett 2010, Walker and Lundholm 2017). Consequently, green roofs are often planted with succulent species such as *Sedum* species, which are shallow-rooted and very drought tolerant due to water storage in their fleshy leaves and/or stems (Sayed 2001, Durhman et al. 2006). However, in terms of stormwater retention, succulent plants are not the best choice due to their reduced transpiration (Wolf and Lundholm 2008, Farrell et al. 2012), which means they do not dry out substrates sufficiently between rainfall events.

There has been an interest to expand the list of plant species used on green roofs (Lundholm 2015). A variety of different growth forms, including grasses, shrubs and herbs, have been tested as they potentially provide greater stormwater retention than traditional *Sedum* monocultures (Wolf and Lundholm 2008, Nagase and Dunnett 2012, Farrell et al. 2013). There are several approaches that have been applied to select plants which will be suitable for the green roof environment. Plant trait methods (Farrell et al. 2012, Nagase and Dunnett 2012, Lundholm et al. 2015) and habitat template approaches (Lundholm 2006, Farrell et al. 2013, Lundholm and Walker 2018) have been successful in selecting native species across a range of life-forms for green roofs. More recently physiological approaches tested the ability of plants to tolerate drought and use water as the main factors determining plant selection for green roofs where stormwater management is important (Farrell et al. 2013). Another potential method is the climate of origin approach, which has yet not been tested for green roofs.

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96 Climate is the ultimate driver of broad-scale ecosystem composition and structure, and
97 temperature and precipitation have large influences on the distribution of species (Birks et al.
98 2000, Birks and Birks 2014). Aridity indices, such as the mean heat moisture index (HMI),
99 can be useful measure as they represent the aridity of the environment and consider the
100 interaction between temperature and precipitation (Dobbs et al. 2014). Species from climates
101 with greater HMI endure drier and hotter conditions and this may indicate greater potential
102 for tolerance of water deficit conditions (Aspinwall et al. 2013). Although plants for green
103 roofs in hot and dry climates have often been selected from dry environments as part of the
104 habitat template approach (MacIvor et al. 2011, Farrell et al. 2013, Papafotiou et al. 2013),
105 the influence of a species climate of origin on plant performance on green roofs has not been
106 investigated.

107
108 In terms of diversifying the range of life-forms used on green roofs, shrubs are potentially of
109 interest because they can have higher rates of water use than commonly used succulent plants
110 and therefore improve stormwater retention (Wolf and Lundholm 2008). Shrubs can also be
111 very drought tolerant, for example, shrubs from dry rocky habitats were able to survive water
112 deficit conditions when growing in shallow green roof substrate (Farrell et al. 2013). While
113 several studies have evaluated the drought tolerance of shrubs from dry and semi-dry habitats
114 (Farrell et al. 2013, Papafotiou et al. 2013, Raimondo et al. 2015, Savi et al. 2016) there are
115 no studies which have assessed shrubs based on physiological and climate of origin
116 approaches. For stormwater retention, the ideal shrub species for green roofs would have high
117 evapotranspiration under well-watered conditions, but will also tolerate water deficit as
118 demonstrated by a more negative midday water potential (Farrell et al. 2013) (Fig 1). This
119 strategy has been demonstrated for monocot and herb species from rocky outcrops, which
120 showed high water use under well-watered conditions but also drought tolerance by reducing
121 water potentials under drought. However, it is unclear whether this ideal combination of high
122 water use and high drought tolerance also exists in shrubs as drought tolerance is often
123 negatively correlated with transpiration rate (Orians and Solbrig 1977, Tardieu 2005).

124
125 Drought avoidance, which is another drought response strategy differing from drought
126 tolerance (decrease ψ_{MD} under WD). Drought avoiding plants maintain water potentials (high
127 ψ_{MD}) during drought stress through deep root systems (water spenders) or stomatal closure,
128 leaf rolling or below-ground organs (water savers) (Levitt 1980, Price et al. 2002, Bodner et

al. 2015, Delzon 2015). As extensive green roof systems are designed with shallow substrates, plants which avoid drought through deep roots will not be able to persist on green roofs due to limited access to deep stored water (Raimondo et al. 2015, Szota et al. 2017), but plants which avoid drought through stomatal closure have great potential to be used on green roofs.

The first objective of this study was to determine whether shrubs on green roofs can provide stormwater management benefits by a high-water use when water is available and avoidance of drought stress when water is limiting. A second objective was to evaluate whether the physiological response to water availability; water use (ET under WW conditions) and drought response (ψ_{MD} under WD) is related to climate of origin (HMI) and morphological traits.

Methods

Plant material

In this experiment, 20 shrubs were selected from different climates of origin based on their Heat Moisture Index (HMI), across southern Australia (Table 1). We used species occurrence records in the Atlas of Living Australia (ALA, www.ala.org.au) to determine the climate envelope of each species. For each species, mean annual temperature (MAT) and mean annual precipitation (MAP) were determined for each location that the species had been recorded and these were used to calculate HMI for each location. HMI was calculated as, $(MAT+10)/MAP \times 1000$. The mean HMI ranged from 20 to 98, and MAP from 280 mm to 1100 mm. Species with higher HMI were distributed in drier and hotter sites, while species with lower HMI were from wetter and cooler regions.

Six-month old seedlings in tube-stock, 20 plants per species, were obtained from an indigenous commercial nursery (Goldfields Revegetation). All plants were individually potted into 6 l plastic pots (200 mm diameter and 190 mm height) containing green roof substrate (3.8 kg per pot) consisting of 60% scoria 7 mm minus block mix, 20% 7 mm scoria aggregate and 20% composted coir (Farrell et al. 2012). Low phosphorous slow release fertiliser (12 g per pot; Osmocote plus, Scotts Australia Pty Ltd.) containing 61% nitrogen, 34% potassium and 5% phosphorus was added to the surface of each pot at planting. For the establishment period, three months before the start of the experiment, plants were grown outside and were watered automatically for 30 minutes twice a day (0600 h and 1800 h) to

ensure sufficient water availability. The experiment was conducted in the nursery at the Burnley Campus, University of Melbourne, Australia (37°47'S; 144°58'E)

Experimental design

In March 2016, plants were moved into a glasshouse and watered by hand for another week before the experiment started. Five replicates of each of the 20 species with uniform size were allocated randomly to two different watering treatments: well-watered (WW) and water deficit (WD) and arranged in a complete randomised block design. The remaining 100 pots (5 replicates per species) were used for the initial harvest to determine plant biomass. WW plants were watered to pot capacity at 1700 h three times per week (Monday, Wednesday and Friday). The plants in the WD treatment were also watered at the same time with the quantity of water added determined from the water use of each individual species under WW. That is, 50% of the water used by WW plants (calculated by the difference in pot weights of WW plants after the last watering and before the current watering event) was added to WD plants using a measuring cylinder. All pots were weighed before being watered and again after watering to determine plant water use and soil water content (SWC). Watering treatments continued until each plant in the WD treatment had experienced 30 days of SWC below 20% to enable them to adjust physiologically to water stress conditions. Consequently, different species were harvested on different days based on their dry-down rates.

Morphological traits

Five replicates of 20 species were initially harvested prior to the watering treatments to obtain total plant dry mass, total leaf dry mass and total leaf area. Leaf area was measured using a LI3100 area meter (Li-Cor, Lincoln, NE, USA). Total leaf and stem dry mass was recorded separately after drying in 70 °C oven for at least 48 hrs or until constant weight was reached. Specific leaf area (SLA $\text{m}^2 \text{kg}^{-1}$ leaf) and leaf area ratio (LAR, $\text{m}^2 \text{leaf kg}^{-1}$ plant) were calculated from leaf area and dry leaf/whole plant mass. These measurements were repeated at the conclusion of the experiment on all WW and WD plants. The difference in mass between the final and initial harvests was also used to calculate relative growth rate (RGR) of WW and WD treatments and was determined as: (final dry mass- initial dry mass)/ (initial dry mass/days).

Whole plant water use and plant water status

Cumulative evapotranspiration per pot was determined as the sum of evapotranspiration (mentioned above) over the 42-81 days of the experiment, depending on each species dry-down rate. Daily evapotranspiration rate ($\text{g H}_2\text{O pot}^{-1} \text{ day}^{-1}$) was then determined from cumulative evapotranspiration.

At the conclusion of the dry-down for each species, leaf water potentials at pre-dawn (ψ_{PD} ; 0500-0530 h) and midday (ψ_{MD} ; 1230-1300 h) were measured using a Scholander-type pressure chamber (Soilmoisture Equipment Corp., Santa Barbara, CA, USA) on individual leaves or terminal shoots for both WW and WD treatments.

Statistical analyses

Differences in species morphological and physiological response between WW and WD treatments were analysed using one-way ANOVA. Pearson correlation analyses were used to explore the relationships between morphological traits, HMI and physiological response. Significant differences between species and treatment means were determined by Tukey's post-hoc tests ($P < 0.05$). All analyses were performed using SPSS Statistics 22 (IBM SPSS Statistics 22, Inc).

Results

Whole plant water use and plant water status

The rates of water use (ET) differed greatly among 20 shrubs under both WW and WD treatments (both $P < 0.001$) (Table 2). Under WW conditions, ET ranged from 199.7 (*I. australis*) to 59.1 (*C. linearis*) $\text{g H}_2\text{O pot}^{-1} \text{ day}^{-1}$, and under WD from 113.1 (*P. incisa*) to 31 (*C. linearis*) $\text{g H}_2\text{O pot}^{-1} \text{ day}^{-1}$. All species, except *D. stenozyga* significantly decreased ET under WD and the change in ΔET ranged from 28.1 (*C. linearis*) to 84.6 (*P. aspalathoides*) $\text{g H}_2\text{O pot}^{-1} \text{ day}^{-1}$.

There were significant differences in the water potential of species at the end of the experiment under both WW and WD conditions (Table 3). Under WW, predawn water potential (ψ_{PD}) ranged from -0.24 to -0.98 MPa, while midday water potential (ψ_{MD}) ranged from -0.64 to -2.02 MPa. All species had a significantly lower ψ_{PD} and ψ_{MD} in response to WD compared with the WW treatment, with the exception of *C. linearis*. Under WD, the largest decrease in ψ_{PD} was observed in *D. ulicifolia*, while *E. polyclada* did not significantly

lower its ψ_{PD} . For ψ_{MD} , *C. linearis* maintained leaf water potential, while *E. microphylla* lowered its ψ_{MD} by 3.01 MPa under WD.

While the ideal shrub for green roofs was considered to have greater water use under WW conditions and have greater drought tolerance, evapotranspiration rate (ET) under WW was not significantly related to ψ_{MD} under WD ($R^2=-0.224$, $P=0.343$; Fig 2). However, by using the relative position of the 20 shrubs on these axes, we could categorise the species according to their drought response (ψ_{MD} under WD; x axis) and their water use (ET under WW; y axis) (Fig 2). Using this categorisation, species in the top left corner were classified as having high water use (high ET values) and high drought avoidance (high ψ_{MD} values), while species in the bottom left corner were species with low water use and high drought avoidance. Species in the bottom right corner were low water users with high drought tolerance. Hence, there was a general trend that high water using plants tended to have higher water potentials with lower drought tolerance. Therefore, high water users which were also drought tolerant were not observed in our study.

Relationships between water use and drought tolerance with morphological traits and climate of origin

Water use (ET) under WW conditions was significantly correlated with all morphological traits (measured under WW conditions), including: total shoot dry mass ($R^2=0.84$, $P<0.001$), total leaf area ($R^2=0.66$, $P=0.001$), SLA ($R^2=-0.57$, $P=0.009$), LAR ($R^2=0.49$, $P=0.013$) and RGR ($R^2=0.459$, $P=0.042$) (Fig 3). However, there were no statistically significant relationships between drought response (ψ_{MD}) and any of the morphological traits measured under WD conditions, including: total dry mass ($R^2=0.29$, $P=0.218$), total leaf area ($R^2=0.29$, $P=0.209$), SLA ($R^2=0.34$, $P=0.144$), LAR ($R^2=0.35$, $P=0.129$) and RGR ($R^2=0.39$, $P=0.088$) (Fig 3). In addition, there were no significant relationships between root mass fraction (RMF) and ψ_{MD} under WD or ET under WW (data not shown).

Heat moisture index (HMI) was not related to water use (ET under WW; $R^2=-0.11$, $P=0.653$) or drought response (ψ_{MD} under WD; $R^2=-0.03$, $P=0.898$) (Fig 4). There were also no significant relationships between mean annual precipitation (MAP) or mean annual temperature (MAT) and ET or ψ_{MD} (data not shown).

Discussion

The 20 shrubs showed considerable variation in their morphological and physiological responses to the experimental water deficit, indicating a range of diverse behaviours and adaptations in response to water deficit. This likely reflects the fact that species originate from a range of different climates, which likely contributed to the evolution of a series of different adaptive strategies (Valladares and Sánchez-Gómez 2006). For instance, in this experiment some species reduced their above ground biomass, total leaf area, SLA or growth in response to water limitations, while others also reduced transpiration or were able to lower their water potentials as soil water deficit increased. Hence, there was no uniform response of the shrubs to drought and as a consequence we did not observe relationships between climate of origin and water use or drought tolerance.

Trade-off between high water use and drought tolerance

We observed a trade-off between water use and drought tolerance in the 20 shrubs selected from across a broad precipitation gradient. Shrubs that had high water use generally were not very drought tolerant and we did not observe any shrubs which had high water use and high drought tolerance. This result is in contrast with a previous study which evaluated the physiological response of a range of life-forms for green roofs and showed that high water users could also be drought tolerant (Farrell et al. 2013). However, in that study, it was the grass-like monocots and one herb species which achieved this and not any of the four shrubs species. The trade-off between drought tolerance and water use in shrubs may be related to their woody nature. In woody plants, xylem vessel dimensions influence both the amount of water that can be transported and the risk of cavitation under drought stress (Sperry and Tyree 1988, Bartlett et al. 2016). Hence, woody plants with large vessels have more efficient water transport at higher transpiration rates but are more likely to have lower cavitation resistance under low water potentials (Dong and Zhang 2001, Christman et al. 2012). Conversely, woody plants with narrow xylem vessels are not be able to transport water at high rates but are likely more resistant to cavitation (Brodribb et al. 2003). As a consequence, we mainly observed shrubs which had low water use (water savers) and high drought tolerance or shrubs which had higher water use (water spenders) and low drought tolerance. Shrubs which had low drought tolerance maintained relatively high midday water potentials under water deficit, and avoided drought stress by minimizing water loss (decreasing ET) during drought. These drought avoiding shrubs may be able to survive dry conditions on green roofs through leaf area reduction and stomatal closure to postpone dehydration (Farrell

et al. 2013, Raimondo et al. 2015, Szota et al. 2017) and still achieve optimal water use for stormwater management. In line with Szota et al. (2017), we suggest the drought avoiding shrubs which can achieve high rainfall retention should be considered on future green roof designs, especially in temperate climates, which have plentiful precipitation during summer (Kottek et al. 2006).

Relationships between morphological traits, water use and drought tolerance

We observed a number of significant correlations between water use and morphological traits. Plants with higher water use generally had greater above-ground biomass, greater leaf areas, and higher SLA in line with previous studies (Wolf and Lundholm 2008, Farrell et al. 2013). For example, Nagase and Dunnett (2012) showed that taller species with higher dry shoot mass had greater runoff retention compared with shorter species with lower dry shoot mass in a simulated green roof study. In addition, Farrell et al. (2013) proposed that plant size or leaf area is a key determinant of water use and should be an important consideration for green roof design to mitigate stormwater. It is likely that positive correlations between above-ground biomass and water use are observed because larger plants have greater surface area and more stomata to transpire water back to the atmosphere (Vertessy et al. 1995, Nagase and Dunnett 2012). Thus, to some extent, morphological traits could be used to determine water use of plants for green roofs.

Although plant water use was coupled with leaf area, it is important to note that the reduction in evapotranspiration rate (ΔET %) was not accompanied by a significant change in the leaf area (ΔLA %) (Appendix S1: Figure S1), suggesting that leaf area adjustment was not the main determinant of changes in plant water use in our study. Variation in wood anatomy, especially xylem vessel diameters in leaves, stem or roots, may also influence shrub water use and hydraulic conductance in response to extreme drought (Vasellati et al. 2001, Hacke et al. 2009). In addition, conservative stomatal control can minimize plant water loss and maintain water balance for efficient survival of the plant under extreme situations (Farquhar and Sharkey 1982, Dong and Zhang 2001). Hence, the stomatal regulation can be a protective mechanism to avoid plant complete hydraulic failure and xylem cavitation (Sperry 2000). Therefore, it is likely to be another significant driver of vegetation water use for stormwater reduction and should be taken into account in future green roof studies.

However, there were no relationships between drought response (midday water potential under WD) and any of the measured morphological traits, suggesting that drought response does not depend on plant size, shoot biomass, leaf structure, root mass or growth rate. This is in contrast with Mitchell et al. (2008) which showed that there were significantly positive relationships between ψ_{MD} and SLA and RMF, with species with lower ψ_{MD} having lower SLA (smaller but thicker leaves) and smaller RMF. Furthermore, Farrell et al. (2013) demonstrated that species with higher RMF maintained higher water status (ψ_{PD} , not ψ_{MD}) under water deficit conditions. The reason for the lack of relationships between morphological traits and drought response in our study is still unclear. It may be due to differences in rooting volume and access to stored water or due to differences in plant phenology between glasshouse pot and field-based conditions (Kaspar et al. 1984).

Relationships between climate of origin, water use and drought tolerance

Species from drier habitats are generally thought to be less susceptible to water limitation due to greater physiological plasticity (Lázaro-Nogal et al. 2015). Strong relationships between drought tolerance and the distribution of species have been reported (Mitchell and O'Grady 2015). In arid climates, species with greater drought tolerance often have a greater survival, lower water potentials and lower turgor loss points (Baltzer et al. 2008, Kursar et al. 2009, Mitchell and O'Grady 2015). However, we observed no relationships between climate of origin and either drought tolerance or water use. Under water deficit, not all species from hotter and drier climates (higher HMI) showed greater drought tolerance (more negative ψ_{MD}) and not all species from wetter and cooler sites were high water users under WW. This is in contrast to previous studies, which have suggested that drought tolerance measures such as turgor loss point, can predict species distribution and mortality (Engelbrecht et al. 2007, Bartlett et al. 2012). For example, Mitchell and O'Grady (2015) compiled a database for 174 woody species across a range of temperature and precipitation in Australia, and showed that natural habitat water availability (precipitation and temperature) was significantly related to plant drought tolerance, with species from drier and hotter regions having more negative turgor loss points than species from cooler and wetter regions.

In our experiment the lack of a relationship between climate of origin and plant water use or drought tolerance may be because under new studied environments, like the glasshouse, plants may adjust their physiology according to water availability to a greater extent than measured in their natural ecosystems. It is also possible that within shrubs, there may be more

drought tolerance and water use (water-spending and water-saving) strategies than previously reported for trees (Dong and Zhang 2001). That is, species with different rooting depths may respond differently to drought and have distinct water use patterns (Oberbauer and Billings 1981, West et al. 2012). Deep-rooted species often avoid drought (high Ψ_{MD}) and use large amounts of water, like *Prosopis* sp. (Delzon 2015), or alternatively, are conservative water-users (Wright et al. 1983, Hund et al. 2009). Some desert shrubs with shallower roots like *Artemisia scopulorum* and *Hymenoxys grandiflora* have also been shown to be drought tolerant (Hinckley et al. 1983) and use very little water because of their small plant size, due to restricted growth or due to leaf adaptations like finely divided hairy leaves (Oberbauer and Billings 1981, West et al. 2012). Alternatively, they may use a lot of water and have a low drought tolerance (high Ψ_{MD}) because they have developed extreme phenotypic plasticity by dropping all their leaves under WD and resprouting when conditions improve (drought escape strategy) (Delzon 2015). Therefore, there are likely multiple drought resistance strategies for plants growing in hot and dry climates and determining the drought tolerance of shrubs by minimum water potential or turgor loss point is not the only criterion to assess species real survival capabilities. On the other hand, stomata of mature field-grown trees or shrubs may not respond to water deficit as dramatically and readily as those of the young shrubs in pots or on green roofs with limited root systems and shallow substrates. This indicates that unlike for tree studies in field conditions, climate of origin may not be a suitable approach to select drought tolerant shrubs with high water use for stormwater management on green roofs. However, future studies of plant cavitation resistance, safety margin and anatomical measurements on shrub species with different climatic distributions are still required to be certain that climate of origin has no influence on plant tolerance of green roof conditions.

Conclusion

The results of this study demonstrate that mainly drought avoiding shrubs (high Ψ_{MD}), like *Correa glabra*, *Derwentia perfoliata* and *Olearia axillaris*, can optimize stormwater mitigation on green roofs. Unlike previous studies with monocots and geophytes, it was not possible to identify drought tolerant shrubs (low Ψ_{MD}) that had high water use under well-watered conditions. However, there were several drought avoiding shrubs which also had high water use. These shrubs probably have greater potential for stormwater mitigation on green roofs in temperate climates, which in summer have relatively high temperature but also high precipitation (high water availability), rather than Mediterranean-type climates with

frequent extreme droughts. In addition, as the water use of shrubs under well-watered conditions was related to their aboveground biomass and leaf traits like SLA, these are likely to be useful traits to predict the ability of shrubs to mitigate stormwater on green roofs. Finally, drought tolerance and water use of shrubs was not related to their climate of origin (MAT, MAP and HMI). Therefore, climate of origin is not a useful approach for selecting young woody shrubs for green roofs to reduce stormwater runoff from green roofs and survive periods of water limitations.

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DATA AVAILABILITY

Data are available on Figshare: <https://doi.org/10.4225/49/5b0de625052f9>

570 **Table 1.** Climate of origin (Köppen Classification) for the selected 20 shrubs: mean annual heat-moisture index (HMI), mean annual
571 precipitation (MAP) and mean annual temperature (MAT). Rows are ordered by increasing HMI at the climate of origin.

Species	Family	HMI	MAP (mm)	MAT (°C)	Climate classifications	Habitat
<i>Derwentia derwentiana</i>	Plantaginaceae	20.31	1126.36	10.64	Csb, Cfa, Cfb	Moist forest ¹
<i>Prostanthera incisa</i>	Lamiaceae	23.69	1126.11	15.45	Cfa, Cfb	Moist forest ¹
<i>Derwentia perfoliata</i>	Plantaginaceae	25.53	923.59	11.21	Cfa, Cfb	Mosit forest ¹
<i>Daviesia ulicifolia</i>	Fabaceae	29.06	900.52	13.98	BWh, Csa, Csb, Cfa, Cfb	Hilly country ¹
<i>Hardenbergia violacea</i>	Fabaceae	29.17	922.08	15.42	Am, BWh, BSk, Csa, Csb, Cfa, Cfb	Dry forest ¹
<i>Indigofera australis</i>	Fabaceae	32.09	851.22	14.62	Am, Aw, BWh, BSh, BSk, Csa, Csb, Cfa, Cfb	Inland woodland ²
<i>Dillwynia sericea</i>	Fabaceae	35.75	719.97	14.18	BSk, Csb, Cfa, Cfb	Heathy woodland ¹
<i>Cheiranthra linearis</i>	Pittosporaceae	36.48	688.22	14.11	Cfa, Cfb	Dry forest ¹
<i>Grevillea alpina</i>	Proteaceae	36.86	695.10	13.53	Cfb	Dry sclerophyll forest ¹
<i>Grevillea rosmarinifolia</i>	Proteaceae	37.64	704.43	13.93	Csb, Cfb	Coastal dune ¹
<i>Calytrix tetragona</i>	Myrtaceae	44.29	816.54	14.43	Bsh, BSk, Csb, Cfa, Cfb	Dry sclerophyll forest ²
<i>Correa glabra</i>	Rutaceae	52.73	532.10	15.62	BSk, Csb, Cfa, Cfb	Rock outcrop ³
<i>Olearia axillaris</i>	Asteraceae	55.34	555.19	16.14	Bwh, Bsh, Csa, Csb, BSk, Cfb	Coastal dune ³
<i>Eremophila gibbifolia</i>	Myoporaceae	61.33	436.74	15.52	Csa, Csb, Cfb, Bwh	Inland woodland ¹
<i>Goodenia benthamiana</i>	Goodeniaceae	61.45	420.24	15.29	BSk, Cfb	Inland woodland ¹
<i>Eutaxia microphylla</i>	Fabaceae	63.79	438.96	15.84	Csa, Csb, Cfb, Bwh	Rocky grassland ³
<i>Prostanthera aspalathoides</i>	Lamiaceae	70.97	388.06	16.07	BSk, Csa, Cfa	Inland woodland ¹
<i>Dodonaea stenozyga</i>	Sapindaceae	90.87	306.62	17.11	Csa, BSk, Csb	Inland woodland ¹
<i>Eremophila polyclada</i>	Myoporaceae	96.57	348.38	21.20	BSh, BSk	Inland woodland ¹

Eremophila divaricata Myoporaceae 98.34 283.44 17.56 BSk, BSh Floodplain¹

572 Climate classifications are based on species occurrence records in the Atlas of Living Australia (ALA, www.ala.org.au). Plant habitat based on
573 the information from ¹Flora of Victoria (<https://vicflora.rbg.vic.gov.au>), ²PlantNET (<http://plantnet.rbg.syd.nsw.gov.au>) and ³Farrell et al. (2017).

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574 **Table 2.** Mean daily evapotranspiration rate (ET) under well-watered (WW) and water deficit
575 (WD) conditions and the change in ET (Δ ET) from WW to WD.

Species	ET (g H ₂ O pot ⁻¹ d ⁻¹)		<i>P</i> -Value	Δ ET
	WW	WD		
<i>Derwentia derwentiana</i>	173.65(17.54)ab	102.96(1.98)b	0.004	70.69
<i>Prostanthera incisa</i>	196.06(11.92)a	113.09(1.51)a	0.012	82.97
<i>Derwentia perfoliata</i>	154.48(8.54)abc	91.70(1.04)c	< 0.001	62.78
<i>Daviesia ulicifolia</i>	107.93(11.02)cde	55.98(0.94)h	< 0.001	51.95
<i>Hardenbergia violacea</i>	120.90(7.27)cde	75.68(0.57)e	< 0.001	45.22
<i>Indigofera australis</i>	199.65(49.52)a	99.86(2.00)b	0.038	99.79
<i>Dillwynia sericea</i>	88.37(11.20)def	46.28(1.18)jk	0.006	42.09
<i>Cheiranthra linearis</i>	59.09(3.53)f	31.04(2.52)m	< 0.001	28.05
<i>Grevillea alpina</i>	123.35(14.55)cd	58.81(0.72)gh	< 0.001	64.54
<i>Grevillea rosmarinifolia</i>	114.94(15.80)cde	58.81(1.43)gh	< 0.001	56.13
<i>Calytrix tetragona</i>	95.69(13.37)def	62.37(1.25)g	0.038	33.32
<i>Correa glabra</i>	195.55(8.25)a	111.81(0.66)a	< 0.001	83.74
<i>Olearia axillaris</i>	135.49(10.46)bcd	85.20(0.78)d	0.002	50.29
<i>Eremophila gibbifolia</i>	101.87(7.08)def	50.77(2.21)i	< 0.001	51.10
<i>Goodenia benthamiana</i>	90.35(10.97)def	47.75(1.36)ij	< 0.001	42.60
<i>Eutaxia microphylla</i>	73.99(8.94)ef	39.89(0.33)l	< 0.001	34.10
<i>Prostanthera aspalathoides</i>	195.61(9.31)a	111.04(1.54)a	0.010	84.57
<i>Dodonaea stenozyga</i>	94.10(25.54)def	42.88(1.15)kl	0.092	51.22
<i>Eremophila polyclada</i>	180.11(7.23)a	100.07(0.81)b	0.004	80.04
<i>Eremophila divaricata</i>	110.81(7.05)cde	70.42(0.67)f	< 0.001	40.39
<i>P</i> -Value	< 0.001	< 0.001	< 0.001	

576

577 Values in parentheses show mean standard error. Difference letters indicate significant
578 differences between species within treatment and variable (one-way ANOVA; Tukey post

579 hoc test). *P*-values in table show significant differences among species and between WW and
580 WD treatments within each species (Tukey post hoc test).

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582 **Table 3.** Mean leaf water potential at pre-dawn (ψ_{PD}) and midday (ψ_{MD}) under well-watered (WW) and water deficit (WD).

Species	$\Psi_{PD}(-\text{Mpa})$			$\Psi_{MD}(-\text{Mpa})$		
	WW	WD	<i>P</i> -Value	WW	WD	<i>P</i> -Value
<i>Derwentia derwentiana</i>	0.50(0.04)bcde	2.17(0.33)bcd	0.001	0.86(0.08)defg	2.89(0.46)abcdef	0.002
<i>Prostanthera incisa</i>	0.47(0.05)cdef	1.68(0.13)bcde	< 0.001	0.94(0.08)cdefg	2.63(0.19)bcdef	< 0.001
<i>Derwentia perfoliata</i>	0.51(0.06)bcde	2.06(0.17)bcde	< 0.001	0.92(0.10)cdefg	3.13(0.22)abcd	< 0.001
<i>Daviesia ulicifolia</i>	0.33(0.03)def	3.42(0.44)a	< 0.001	0.98(0.10)cdefg	3.92(0.36)ab	< 0.001
<i>Hardenbergia violacea</i>	0.24(0.03)f	0.93(0.12)de	0.001	0.67(0.09)fg	1.67(0.23)ef	0.004
<i>Indigofera australis</i>	0.42(0.15)cdef	1.47(0.38)cde	0.032	1.13(0.20)bcde	2.62(0.43)bcdef	0.013
<i>Dillwynia sericea</i>	0.38(0.06)cdef	2.54(0.34)abc	< 0.001	0.77(0.10)efg	3.26(0.62)abcd	0.001
<i>Cheiranthra linearis</i>	0.37(0.05)cdef	1.18(0.31)de	0.033	1.18(0.19)bcd	1.58(0.31)f	0.307
<i>Grevillea alpina</i>	0.36(0.08)cdef	1.95(0.62)bcde	0.014	1.24(0.15)bc	2.90(0.55)abcdef	0.010
<i>Grevillea rosmarinifolia</i>	0.31(0.06)ef	2.90(0.70)ab	0.003	0.88(0.08)cdefg	3.82(0.78)abc	0.003
<i>Calytrix tetragona</i>	0.46(0.07)cdef	1.29(0.30)de	0.016	0.84(0.12)defg	2.51(0.39)cdef	0.002
<i>Correa glabra</i>	0.48(0.09)bcdef	1.54(0.14)cde	< 0.001	1.38(0.09)b	2.50(0.13)cdef	< 0.001
<i>Olearia axillaris</i>	0.51(0.05)bcde	1.69(0.19)bcde	< 0.001	1.03(0.05)bcdef	2.24(0.16)def	< 0.001
<i>Eremophila gibbifolia</i>	0.72(0.05)b	2.60(0.66)abc	0.022	1.09(0.09)bcde	3.30(0.81)abcd	0.027
<i>Goodenia benthamiana</i>	0.59(0.08)bc	2.17(0.40)bcd	0.002	1.19(0.10)bcd	3.03(0.31)abcde	< 0.001
<i>Eutaxia microphylla</i>	0.45(0.09)cdef	1.96(0.48)bcde	0.003	1.11(0.10)bcde	4.12(0.35)a	< 0.001

<i>Prostanthera aspalathoides</i>	0.58(0.10)bcd	1.86(0.07)bcde	< 0.001	1.07(0.12)bcde	2.88(0.14)abcdef	< 0.001
<i>Dodonaea stenozyga</i>	0.98(0.13)a	1.92(0.36)bcde	0.021	2.02(0.10)a	3.40(0.43)abcd	0.005
<i>Eremophila polyclada</i>	0.47(0.03)cdef	0.88(0.07)e	< 0.001	0.79(0.09)efg	2.04(0.09)def	< 0.001
<i>Eremophila divaricata</i>	0.40(0.04)cdef	1.65(0.21)cde	< 0.001	0.64(0.04)g	2.43(0.32)cdef	0.001
<i>P-Value</i>	< 0.001	< 0.001		< 0.001	< 0.001	

Values in parentheses show mean standard error. Difference letters indicate significant differences between species within treatment and variable (one-way ANOVA; Tukey post hoc test). P-values in table show significant differences among species and between WW and WD treatments within each species (Tukey post hoc test).

Figure legends

Fig1. The category of species based on the function of stormwater mitigation after rainfall and survival under water deficit on harsh roof. Four categories were included, the green block represents the ideal species for green roof, high water use when available and high drought tolerance under stress; the yellow and orange ones represent species with high water use, high drought avoidance and low water use and high drought tolerance. While the red block represents species with low water use and high drought avoidance.

Fig2. Correlations between midday water potential (Ψ_{MD}) under WD and evapotranspiration rate (ET) under WW, WD, and the change in ET from WW to WD. No high water users which are drought tolerant were found among 20 shrubs.

Fig3. Correlations between ET/d under WW, Ψ_{MD} under WD and different morphological traits for 20 shrub species. Solid line is the relationship that is significant across all species. Bars represent standard error of the mean (n=5). ET/d was significantly correlated with all the morphological traits under WW, but no correlations between Ψ_{MD} and morphological traits under WD.

Fig4. Correlations between HMI and evapotranspiration rate (ET) under WW and midday water potential (Ψ_{MD}) under WD for 20 shrub species. Bars represent standard error of the mean (n=5). Both traits were not significantly correlated with HMI.

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