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2R: Plant Performance Research 2

HOT, HIGH, DRY AND GREEN? – RESEARCH SUPPORTING GREEN ROOF PLANT SELECTION FOR ARID ENVIRONMENTS

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Abstract

The selection of plants for use on extensive green roofs is dominated by experiences and research from cooler, temperate climates; little is reported from drier and more arid climate zones. However, it is in these climates that the potential benefits of green roofs may be greatest. This paper summarizes a five year research program on plant selection for green roofs in dry Mediterranean-type climates. A total of 56 plant species have been evaluated, both on a green roof and in glasshouse drought experiments. The experimental green roof was used to screen 32 species, including plants commonly planted on green roofs internationally. The roof was a 125 mm deep unirrigated green roof and climatic conditions on the roof were often extreme, with surface temperatures up to 69 °C (156 °F) and very little rainfall. At the conclusion of the experiment only a few succulent plants remained alive, with many plants used successfully on cooler climate green roofs failing. To better understand how plant traits, such as succulence, influence survival when water is limited 31 plant species, including the surviving succulent species from the green roof, were evaluated in the glasshouse. These experiments identified key traits for predicting plant survival and performance. Our five year research program has highlighted the importance of plant trials in new and different climate zones and developed a successful template for extensive green roofs in dry Mediterranean climates. In these climates, plant selection should focus on species with low water use, high leaf succulence and the ability to resprout following desiccation to ensure survival.

Introduction

The selection of plants for use in extensive green roofs is dominated by experiences and research from cooler, temperate climates; little is reported from drier Mediterranean-type climate zones (for exceptions see Nektarious *et al.* (2004, 2011)). Relying on green roof technologies from the temperate northern hemisphere is problematic due to differences in climate, substrate and plant availability (Williams et al., 2010). The lack of research in these climates forms one of the major barriers to green roof uptake in countries such as Australia, where most southern cities are affected by extended drought during the warm summer months (Williams et al., 2010).

To help overcome these barriers and determine appropriate plants species for Australian green roofs in seasonally dry Mediterranean-type climates we have undertaken plant selection experiments over a five year research program. This paper reports the results of plant evaluation on an experimental green roof and in three glasshouse experiments which evaluated plant water use and survival under drought conditions. Plant selection has focused on plants from dryland Australian habitats, with an emphasis on plants from shallow soil environments such as rock outcrops and rocky grasslands. These habitats are analogous to conditions on green roofs and this approach has been widely used for plant selection globally (Lundholm et al., 2010, MacIvor and Lundholm, 2011, Nektarios et al., 2011, Simmons et al., 2008). We discuss the results from these experiments and identify the key plant traits affecting plant survival and performance on green roofs in Mediterranean environments.

Methods

The suitability of 56 plant species for use on green roofs has been assessed through a combination of experimental green roof and three controlled glasshouse experiments. Seven of the plant species planted on the green roof were also evaluated in the glasshouse experiments. These seven species included the three surviving succulent species and four of the native Australian species (one herb, one prostrate shrub and two geophytes). The species and life-forms of all of the species evaluated are listed in tables 1 and 2.

Burnley experimental green roof

An experimental green roof (20 m^3) was constructed on a flat roofed building at the University of Melbourne's Burnley campus in Melbourne, Australia. The green roof was used to screen 32 species including species from dryland habitats in Australia as well as succulents commonly planted on green roofs internationally (Table 1). Plant species represented four different life-forms (forb, grass/grass-like, upright succulents and spreading succulents), with eight species per life-form (Table 1).

The green roof was constructed (from bottom to top) using a plastic root barrier (Zinco Root Barrier WSF 40), a moisture retention and protection layer (Zinco SSM 45), a high-density polyethylene 40 mm drainage layer (Zinco Floradrain® FD40-E), a geotextile filter sheet layer (Zinco Filter Sheet SF), and a mineral-based substrate layer (125 mm deep). The substrate layer was scoria (lava rock) based and included (by volume): 50% 10 mm minus scoria, 20% 7 mm scoria aggregate, 20% 1-2 mm coarse washed sand and 10% horticultural grade coir. The substrate was developed according to FLL guidelines (FLL 2008).

The roof was planted with seedling plugs (tubestock) in July/August (winter). The roof was divided into four quadrats (each 4.2 m^2), with each randomly assigned to one of the four life-forms. Ten individuals per species were randomly established in each quadrat spaced at 20 cm apart, such that each quadrat contained 80 plants (19 plants m^2). Throughout the summer, climatic conditions on the roof were often extreme, with recorded air temperatures (thermocouples) above the roof reaching as high as 69 °C (156 °F; data not shown). Average maximum temperatures for the study period ranged from 24.0 to 36.5 ºC (72.5 – 97.7 ºF) and

<10 mm of rainfall was received from mid-December to early February (Figure 1; Australian Bureau of Meteorology). The green roof was not irrigated over the course of the experiment. Survival of each species was assessed at early (October; late spring), middle (January; mid-summer) and late (March; early autumn) stages of the drought cycle.

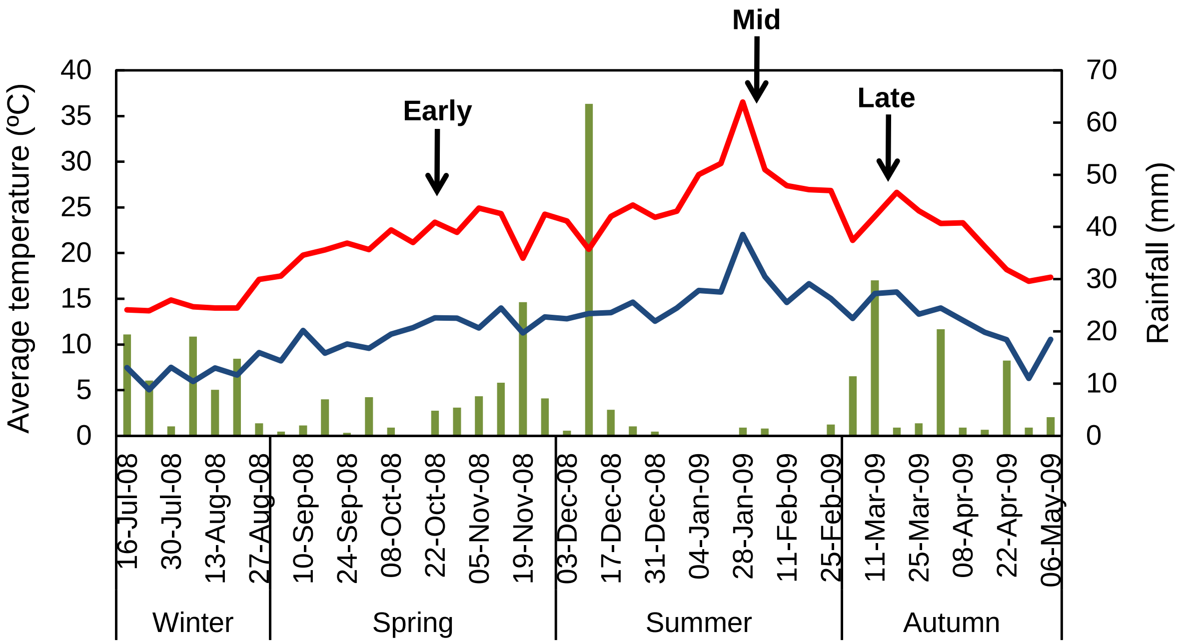

Figure 1. Average weekly maximum (red line) and minimum (blue line) temperature and total weekly rainfall (green bars) from time of planting to the end of the monitoring period.

<u>Glasshouse experiments</u>

Following the green roof plant selection field trial, we conducted three glasshouse experiments to determine plant water use and survival under controlled drought conditions. The first experiment determined how substrate properties influenced plant survival of five succulent species (including three species evaluated on the green roof) under drought conditions (Farrell et al., 2012). Only data for plants grown in scoria substrate (composition described below) is included here for comparison with the roof planting and the two other glasshouse experiments. The second and third experiments evaluated Australian species from dryland habitats. The second experiment evaluated 13 species from granite outcrops and the third experiment evaluated 18 species from four different dryland habitats including granite outcrops, coastal dunes, rocky grasslands and inland dry open-woodlands (habitat template experiment). For each habitat we selected 5 species, including one species from each life-form: geophytes, herb, prostrate shrub, small upright shrub (< 1m tall) and grass-like monocot. Two of the twenty species failed to establish and these were removed from the experiment (leaving 18 species).

The three drought experiments were conducted in temperature controlled glasshouses at The University of Melbourne's Burnley campus, Melbourne, Australia (-37.828472, 145.020883). All three experiments were complete randomized factorial designs with species and watering regime (drought and well-watered) as factors. There were five replicates of each treatment. For the first experiment three month old cuttings of *Disphyma crassifolium*, *Carpobrotus modestus*, *Sedum pachyphyllum* (the three species also on the Burnley green roof), *S. clavatum* and *S. spurium* were planted. For the plant trials with Australian native species, 6 month old plugs (tubestock) obtained from commercial nurseries were planted. All plants were planted into 200 mm diameter pots containing 160 mm deep scoria-based substrate. This pot size was chosen to approximate planting density on the green roof. Five pots of each watering regime were also left unplanted to determine evaporation rates from bare substrate. The scoria substrate was developed according to FLL guidelines (FLL, 2008) and contained 60% 8 mm minus scoria, 20% 8 mm scoria aggregate and 20% organic matter in the form of coir. The water holding capacity (WHC) of scoria was 46% and was related to high air-filled porosity (13.8%). Following a two month establishment period in which plants were well-watered, we commenced the drought treatment and droughted plants received no further watering. Well-watered plants were watered once a week in the succulent experiment and every three days for the two Australian plant experiments. Planted and bare pots were weighed before (all watering treatments) and after watering (well-watered pots only) to determine plant water use (planted pots) and evaporation (bare pots). When plants died or at the end of the drought experiments the surviving species were harvested to determine plant biomass. Transpiration was determined as the difference between water lost by weight from planted and bare pots. Transpiration per pot and transpiration per unit biomass are presented for well-watered plants only to show differences in inherent water use between species for all three experiments. For the habitat template experiment (18 species) the number of days it took for plants to dry down the soil water content to effectively zero (5% SWC; <-10MPa) was also determined from pot weights. When plants reached this critical SWC they were rewatered to determine potential recovery through resprouting. Regression analysis was used to analyse relationships between time to soil water dry down and transpiration. All data analyses were performed in GenStat 12.1 (2009, VSN International Ltd.).

Results

<u>Burnley green roof experiment</u>

No Australian native forbs or grasses/grass-like species survived the extreme conditions experienced over the summer drought period (Table 1). Only two native spreading succulents, *Disphyma clavellatum* and *Carpobrotus rossii* showed some survival (30 and 10%) at the end of the study. Three exotic species, all upright succulents, showed 100% survival at the end of the study: *Lampranthus deltoides*, *Sedum pachyphyllum* and *Sedum × rubrotinctum*. Not all exotic succulents performed well however, with *Sedum acre*, *Crassula multicava* and *Kleinia mandraliscae* showing low survival (20-40%).

<u>Glasshouse experiments</u>

Table 2 shows transpiration rates of 31 well-watered plants from three glasshouse studies. Daily rates of water use ranged from less than zero (*Sedum clavatum*; succulent) to more than 160 g H_2O d^{-1} (*Stypandra glauca*; monocot). There was no clear separation of life-forms with regard to rates of water use under well-watered conditions, with the exception of the succulents which all used <20 g H_2O per day (Table 2). When expressed per unit of final biomass at the end of the experiment, the non-native succulent species showed very low daily rates of water use (-0.02 – 0.21 g H_2O g DW^{-1} d^{-1}); while the 2nd and 3rd highest water users on a pot basis (*Prosthanthera nivea* and *Ficinia nodosa*) showed among the lowest rates of water use per unit final biomass (0.89 and 0.74 g H_2O g DW d^{-1}; Table 2).

Table 1. Survival (%) of species on the Burnley experimental green roof assessed at early (late spring), middle (mid-summer) and late (early autumn) stages of the 2008/2009 summer drought cycle. Recovery indicates whether species regenerated (re-seeded or re-sprouted) in autumn.

Life form	Species		Early	Mid	Late	Recovery
Forbs	*Chrysocephalum apiculatum*	Native	100	0	0	Re-seeded
	Rhodanthe anthemoides	Native	100	0	0	
	Wahlenbergia stricta	Native	80	0	0	Re-seeded
	Pelargonium rodneyanum	Native	70	0	0	
	Ptilotus exaltatus	Native	70	0	0	
	Leptorhynchos tenuifolius	Native	60	0	0	
	Dichondra repens	Native	40	0	0	
	Dampiera diversifolia	Native	30	0	0	
Monocots	*Austrodanthonia caespitosa*	Native	90	0	0	Re-seeded
	Lomandra micrantha	Native	90	0	0	
	Lomandra multiflora	Native	90	0	0	
	Austrostipa scabra	Native	90	0	0	
	Poa hiemata	Native	90	0	0	
	Themeda triandra	Native	80	0	0	
	Chloris truncata	Native	70	0	0	Re-seeded
	Austrodanthonia setacea	Native	40	0	0	Re-seeded
Upright succulents	*Lampranthus deltoids*	Exotic	100	100	100	
	Sedum x *rubrotinctum*	Exotic	100	100	100	
	Sedum pachyphyllum	Exotic	100	100	100	
	Sedum acre	Exotic	100	100	40	
	Crassula multicava	Exotic	100	80	30	
	Calandrinia polyandra	Native	90	80	0	Re-seeded
	Maireana georgei	Native	100	0	0	
	Bulbine bulbosa	Native	90	0	0	
Spreading succulents	*Disphyma crassifolium*	Native	100	100	30	
	Kleinia mandraliscae	Exotic	100	100	20	
	Carpobrotus rossii	Native	100	100	10	
	Carpobrotus modestus	Native	100	90	0	
	Zygophyllum billardierei	Native	100	0	0	
	Enchylaena tomentose	Native	90	0	0	

Tetragonia implexicoma	Native	90	0	0
Sellieria radicans	Native	30	0	0

Table 2. Transpiration (E) per pot and per unit final biomass for 31 species under controlled glasshouse conditions. Transpiration was determined from well-watered control plants from three consecutive experiments conducted under similar controlled climatic conditions. Species common to the green roof experiment and glasshouse experiments are marked with an asterisk. Recovery indicates whether species regenerated (re-sprouted or reseeded) after rewatering.

Life form	Species	E pot^{-1} (g H_2O pot d^{-1})	E Biomass^{-1} (g H_2O g DW^{-1})	Recovery
Monocot	*Stypandra glauca*	163.9	1.32	Re-sprouted
Shrub	*Prosthanthera nivea*	146.4	0.89	
Monocot	*Ficinia nodosa*	139.4	0.74	
Herb	*Chrysocephalum apiculatum*	138.3	1.69	Re-seeded
Geophyte	*Bulbine bulbosa*	137.9	2.79	Re-sprouted
Monocot	*Dianella revolute*	132.5	1.10	
Shrub	*Correa glabra*	110.8	1.18	
Shrub	*Olearia axillens*	101.9	1.91	
Shrub	*Enchylaena tomentosa*	93.7	1.09	Re-seeded
Herb	*Derwentia perfoliata*	92.7	2.82	
Monocot	*Dianella admixta*	71.0	2.20	Re-sprouted
Geophyte	*Arthropodium milleflorum*	69.2	1.86	Re-sprouted
Herb	*Isotoma axillaris*	67.9	1.27	Re-seeded
Shrub	*Calytrix tetragona*	58.5	4.18	
Shrub	*Senna nemophila*	55.2	2.14	
Shrub	*Platylobium obtusangulum*	54.2	1.88	
Herb	*Chrysocephalum semipapposum*	46.7	3.41	Re-seeded
Shrub	*Eutaxia microphylla*	45.5	1.36	
Monocot	*Lomandra filiformis*	44.6	1.17	Re-sprouted
Monocot	*Lomandra longifolia*	39.9	3.50	
Herb	*Brachyscome multifida*	36.3	3.66	
Shrub	*Correa reflexa*	34.0	3.53	
Monocot	*Stylidium graminifolia*	33.7	1.20	
Geophyte	*Pelargonium rodneyanum*	31.8	1.48	Re-sprouted
Shrub	*Hibbertia obtusifolia*	27.9	1.94	
Succulent	*Sedum spurium*	19.8	0.15	
Shrub	*Grevillea alpina*	14.4	2.64	
Succulent*	*Carpobrotus modestus*	13.7	1.19	
Succulent*	*Sedum pachyphyllum*	4.3	0.21	
Succulent	*Disphyma crassifolium*	2.0	0.37	
Succulent	*Sedum clavatum*	-9.0	-0.02	

There was no relationship between transpiration expressed on a pot basis compared with when it is expressed as a proportion of dry weight (R^2=0.0004; data not shown). There was, however, a strong non-linear (logarithmic) relationship between plant dry weight (DW; g^{-1}) and daily transpiration (E; g H_2O d^{-1}) on a pot basis (E = 42.3 ln DW - 75.5; R2 = 0.74; P<0.001; data not shown).

Ten of the 31 species recovered upon re-watering after drying down to an extremely low soil water status (<5% soil water content equivalent to a soil water potential of <-10 MPa; Table 2). Six species (all monocots and geophytes) re-sprouted from below-ground while the remaining four regenerated through seedling recruitment (Table 2). Only one shrub (*Enchylaena tomentosa)* regenerated through recruitment while all others did not recover.

Among the 18 species tested in our habitat template experiment, there was a negative relationship between the number of days taken for plants to dry down soil water content below 5% (droughted plants) and daily rates of water use under non-limiting conditions (well-watered plants). Of the 6 species which re-sprouted after re-watering (Table 2), three had inherently high rates of water use under non-limiting conditions (132.5 – 163.9 g H_2O pot^{-1} d^{-1}); and when exposed to terminal drought took between 13.6 – 21.8 days to deplete soil water content (SWC) below 5%. The remaining three species were among the low water users (31.8 – 44.6 g H_2O pot^{-1} d^{-1}) under well-watered conditions and took between 22.0 – 40.8 days to deplete SWC below 5% when exposed to terminal drought.

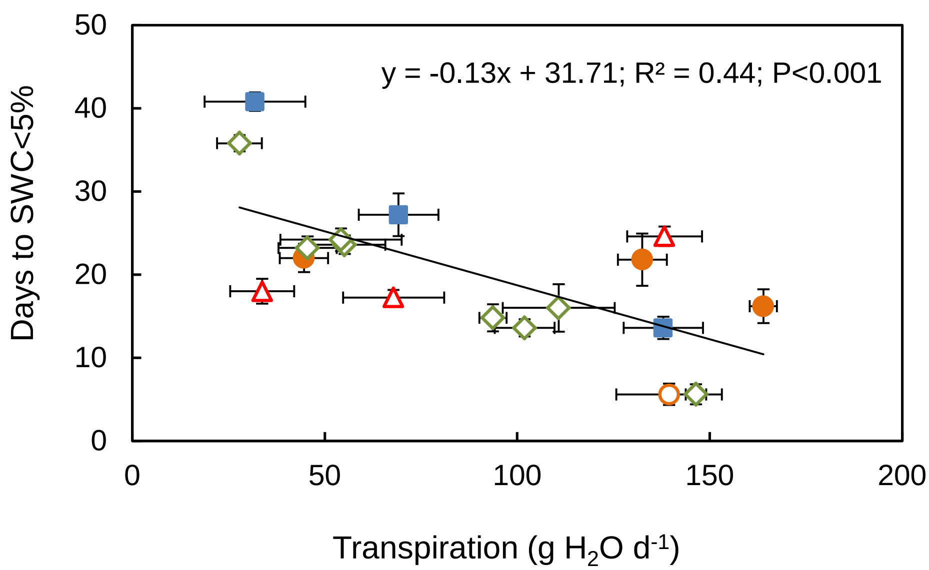

Figure 2. Relationship between maximum daily transpiration in well-watered control plants and number of days taken to deplete soil water content (SWC) below 5% in droughted plants in the Habitat Template experiment (18 species). Different symbols indicate different life-forms: geophytes (squares), herbs (triangles), monocots (circles) and shrubs (diamonds). Closed symbols indicate that species re-sprouted (recovered) upon re-watering while open symbols indicate no recovery or recovery through re-seeding.

Discussion

Our five year research program on plant selection has highlighted the importance of plant trials in new climate zones for successful green roof implementation. The combination of screening on an experimental green roof under extreme summer drought conditions and in glasshouse experiments has enabled us to evaluate plant suitability and to develop appropriate planting recommendations.

Our experimental green roof study at Burnley showed in high heat and drought stress conditions succulents survived better Australian native forbs and grasses/grass-like species. Although succulents were the only surviving species on the green roof after an extreme summer, not all succulents survived. The succulents with 100% survival at the end of the summer were all exotic succulents: *Lampranthus deltoides*, *Sedum pachyphyllum* and *Sedum* × *rubrotinctum*. Two Australian succulents survived, albeit at very low rates; however some exotic species planted widely on green roofs in the northern hemisphere died, highlighting importance of plant screening in new climates.

Differences in survival between succulent species may be due to water use or leaf succulence as this determines the amount of water available to plants once water is unavailable from the substrate (von Willert, 1992). All of the surviving succulent species on the green roof had large (greater than 1 cm leaf area) succulent leaves which may have been responsible for their high survival rates when compared with widely planted northern hemisphere green roof succulents such as *Sedum acre*. One of the surviving succulents, *S. rubrotinctum,* was found by Teeri *et al.* (1986) to survive two years without water due to leaf succulence. Identification of leaf succulence as an important trait for plant survival in dry climates could also lead to a re-evaluation of succulents previously found to have poor survival in other climates. For example, Durhman and Rowe (2007) reported 0% survival of *S. pachyphyllum* due to frost damage, so it is likely that leaf succulence is responsible for poor survival in temperate climates. Again this highlights the importance of climate based green roof plant selection.

Our glasshouse experiments showed that the evaluated Australian native forbs, grass-like monocots and shrubs all had much higher water use under well-watered conditions than the succulent species. This may explain their poor survival on the Burnley experimental green roof under severe drought conditions. Poor survival of grasses and forbs relative to succulents has also been found in other studies evaluating plants for green roofs (Nagase and Dunnett, 2010, Wolf and Lundholm, 2008). However, although poor survivors, their higher water use makes them a better option for stormwater mitigation and urban cooling (Oberndorfer et al., 2007).

Amongst the Australian native species there were no differences in water use between life-forms. However, there was a strong relationship between plant size and water use, where bigger plants showed greater water use. This has important implications for planting and maintenance of green roofs in dry environments. For example, selection of plants where size does not change dramatically over a plants' lifespan may ensure longevity of green roofs and reduce the need for maintenance to reduce plant biomass and water use. Further, spacing of plants relative to size, and therefore by water use requirements, could increase the diversity of plants suitable for green roofs.

An important consideration when evaluating native species for green roofs in Mediterranean-type climates is the ability to resprout after drought conditions. Resprouting occurred in plants with rhizomes and tubers, and is a common adaptation to drought in Mediterranean climates (Pate and Dixon, 1981). Resprouting from underground organs can be viewed as a form of succulence, in that water is stored in underground storage tissues for use when water becomes limiting (Eggli and Nyffeler, 2009). Amongst species which were able to recover after drought, there was also a range of water use strategies. Species with high water use which resprouted included *Stypandra glauca* and this species could be used to reduce stormwater runoff when water is available and survive drought periods. Species which are able to resprout reduce the risk of green roof failure, especially when planted in combination with species unable to recover. This will enable green roofs to achieve multiple benefits including aesthetics and habitat provision. Therefore, the ability to resprout after drought should be targeted for green roof plant selection in Mediterranean climates where both high survival and stormwater mitigation are desired.

Although many shrubs and herbs were unable to resprout when conditions were again favourable, a diversity of life-forms may improve the environmental benefits of green roofs. Dunnett *et al.* (2008) found that vegetation composition significantly influenced the amount of stormwater runoff from green roof platforms, with the highest runoff from roofs planted with succulent species and the lowest runoff from grasses or grass mixtures. Manipulation of substrate water availability or plant microclimates might improve the suitability of non-respouting species for green roofs in dry climates. Increasing substrate waterholding capacity by 4% improved the survivability of drought tolerant herbs (Thuring et al., 2010). Occasional irrigation, especially with non-potable water might also be an appropriate compromise between increased stormwater mitigation and diverse green roofs.

Our five year research program has highlighted the importance of plant trials in new and different climate zones and developed a successful planting template based on native dryland habitats for extensive green roofs in dry Mediterranean climates. Going forward, an important step in our research program will be to develop a framework for plant selection for Australian green roofs. As plant survival is dependent on water availability and duration of drought conditions this framework will be based on substrate properties and rainfall modeling to determine plant suitability and quantify stormwater benefits of green roofs in different Australian climates.

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