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High water use plants influence green roof substrate temperatures and their insulative benefits

Andrea Pianella [a,*], Zheng Zhang [b], Claire Farrell [b], Lu Aye [c], Zhengdong Chen [d], Nicholas S.G. Williams [b]

[a] *Faculty of Architecture, Building and Planning, The University of Melbourne, Victoria 3010, Australia*
[b] *School of Ecosystem and Forest Sciences, Faculty of Science, The University of Melbourne, Burnley 3121, Australia*
[c] *Renewable Energy and Energy Efficiency Group, Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Parkville 3010, Australia*
[d] *CSIRO Land and Water, Clayton South 3169, Australia*

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ABSTRACT

Green roofs are amongst the solutions employed to deliver sustainable buildings in cities. Their vegetation and substrate layers can reduce the heat transfer through the roof, thus potentially reducing energy used for building cooling and heating. However, little research has investigated the insulative properties of drought-tolerant plants which also have high water use. These plants have been found to improve runoff retention by removing larger volumes of water from the substrate through higher transpiration rates than succulents. This planting strategy may also enhance green roof cooling performance due to their greater evapotranspiration rates.

In this study, the thermal performance of three drought-tolerant species with high water use — *Lomandra longifolia, Dianella admixta*, and *Stypandra glauca* — was evaluated and compared with a commonly used succulent species (*Sedum pachyphyllum*) and a bare unplanted module.

L. *longifolia* had the best insulative performance during the entire investigated period, reducing green roof substrate surface temperature up to 1.86 °C compared to succulent *S. pachyphyllum*. In summer, the mixture reduced heat gain to a greater extent than monoculture plantings of all species except L. *longifolia*. Summer measurements also suggest that plants with high leaf area index (LAI) and higher albedo should be selected to reduce surface temperatures. High evapotranspiration rates of high water use L. *longifolia* led to greatest reduction of bottom surface temperatures during a heatwave when decreasing its water content from 18.5% to 2.9%. Results obtained using an analytical hierarchical partitioning technique indicated air temperature had the most significant impact on temperatures at both the surface of the planting substrate and the bottom of each green roof unit, accounting for 48% to 58% of the variation.

Introduction

Green roofs have been extensively used as a passive strategy to reduce building energy consumption for heating and cooling. Green roofs are a type of roof system that incorporate vegetation, substrate, and drainage layers on top of a traditional roof structure. The vegetation layer of a green roof reduces the solar energy transmitted into the building through several mechanisms. Leaves have higher solar reflection than the substrate, thus increasing the heat loss by higher emissivity rates. They also reduce the substrate's temperature by foliage shading and can provide additional cooling through plant transpiration [1–9]. As such, plants can significantly contribute to the net solar balance between a green roof and the building [10,11]. Research has extensively demonstrated that vegetated green roofs are more effective than conventional roofs in reducing the heat transferred indoors [12–14], sometimes even more than building insulation [15].

A large body of research has investigated what type of plants best enhance the hydrology [16–23], social [24–26], and ecological [27–29] benefits that green roofs provide. Despite this, the greatest driver of green roof plant selection is to select plants that will survive the harsh conditions often found on extensive green roofs [30–36], i.e. shallow substrate, exposure to strong winds and high solar radiation levels,

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* Corresponding author.
E-mail address: andrea.pianella@unimelb.edu.au (A. Pianella).

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Fig. 1. Experimental set-up of 18 green roof modules under a polytunnel structure equipped with an overhead rainfall simulator.

drought episodes, etc. [37–40]. Therefore, succulent species are the usual plant choice for green roofs because they have high survival rates during drought conditions and have low maintenance and irrigation requirements. A side effect of this is that succulents may not enhance the green roof thermal performance due to low evapotranspiration rates and likely lower associated cooling benefits. A few studies [41–44] have had the aim of selecting species different from *Sedum* to investigate their green roof thermal benefits, but none have evaluated plants with high water use. Farrell et al. [45] suggested that plants with high water use that are also drought tolerant may be best options to enhance green roof stormwater runoff reduction. These species are also referred to as having plastic water use strategies as they modify their rates of water use depending on its availability (i.e., high transpiration when water is available, low transpiration during drought). Potentially, species with plastic water use strategies may also enhance cooling benefits of green roofs due to greater evaporative cooling due to higher transpiration, while also emptying the substrate pores of water and lowering the substrate thermal conductivity [46]. Also, as succulent plants with crassulacean acid metabolism (CAM) plants, tend to decrease air temperatures at night instead of during the day like C3 and C4 plants likely do, because CAM plants close stomata during the day to preserve water as a survival strategy and open stomata at night to absorb CO_2 necessary for the photosynthesis. This infers that *Sedum* may not be the best option for mitigating ambient air temperature [33].

The contribution plants make in reducing solar energy transmission into the building is strongly influenced by their characteristics, or traits such as vegetation density, leaf colour, plant architecture and growth form, life cycle (perennial or deciduous), transpiration strategy (low or high rates). For example, Onmura et al. [6] and Jim [47] found that dense and vigorous vegetation better reduces cooling energy demand than sparse vegetation. Olivieri et al. [31] and Niachou et al. [5] had similar findings with the latter suggesting that leaf colour (i.e. dark green) is the plant trait able to enhance the green roof thermal performance by reducing indoor net heat gain. Schweitzer and Erell [43] agree on the importance of vegetation shading, however they acknowledge the need to either abundantly irrigate the roofs to maintain consistently high water availability for the plants, or select plants able to both survive long drought periods and maintain plant coverage. Jim [47] looked at the cooling benefits from plants with other traits, such as height and biomass quantity, and found short plants, tolerant to drought and with low maintenance requirements better enhance the cooling thermal performance of green roofs in Hong Kong. Consequently, the selection of plants with traits likely to reduce substrate temperature [48] could therefore improve green roof thermal benefits, particularly for cooling [38,41]. Therefore, while species with higher water use will likely improve green roof thermal performance, it is likely that species with greater coverage and higher albedo will have greater cooling potential. Planting mixtures may also influence the cooling benefits of green roofs as Lundholm et al. [49] suggested that a combination of plant species with varying functionality and life forms, may enhance the ecosystem services provided by green roofs, including cooling. However, few studies have investigated and compared the thermal performance of plants when planted as monoculture or amongst other plant species in mixtures. Therefore, the testing of plants planted as monocultures and mixtures will help to determine which planting option will contribute towards better thermal performance [11,50].

In this study, we tested whether drought tolerant plants with high water use planted in monocultures or in mixtures can reduce the heat load of green roofs under varying substrate moisture conditions and across seasons. We compared the performance of the high water using species as mixtures or monocultures with a monoculture planting of a succulent species and bare unplanted substrate. We hypothesised that, a) plants with thick coverage and higher albedo would help reduce the surface temperature of the modules regardless of the species and water use strategy, b) species with high-water use would decrease the temperature underneath the module to a greater extent than a succulent species due to higher evapotranspiration, c) modules planted with a mixture of high water using species would perform more efficiently than monocultures due to the variety of traits.

Novelty and significance of this research are based on the investigation of the cooling potential of plants with high water use, and the exploration of different plant arrangements. The findings from this study will contribute to the field of green roof design and urban sustainability.

Materials and methods

An open ended polytunnel (28 m long x 2.6 m high), was built to cover 18 1.15 × 1.15 m^2 green roof modules each comprising 0.6 mm filter layer (ZinCo filter sheet SF), 40 mm drainage layer (ZinCo Floradrain® FD 40-E) and 100 mm deep scoria mix substrate [19] (Fig. 1). The modules were planted in 2012 with five species treatments and an additional unplanted substrate control treatment. Each module had 18 plants. Planted treatments included monocultures of *Lomandra longifolia, Dianella admixta, Stypandra glauca, Sedum pachyphyllum*, and one mixture consisting of all species except *Sedum pachyphyllum*. L. *longifolia, D. admixta* and *S. glauca* are grass-like monocots (Table 1 [45]). These plants have demonstrated the ability to enhance runoff retention by extracting larger quantities of water from the substrate through heightened transpiration rates in comparison to succulents. This approach to planting could further amplify the cooling efficacy of green roofs, owing to their increased rates of evapotranspiration. Leaf size and plant architecture differ for each species (Figs. 2 and 3), and specific traits influencing the thermal performance of green roof, including Leaf Area Index (LAI), coverage and height, are detailed in Table 1.

Treatments were designed to compare the thermal performance of the *Sedum*, which is a conservative water user commonly planted on green roofs, with the other species which have higher water use [45]. Each treatment had three replicates. A parallel study examined the hydrological performance of the same green roof modules, investigating the different rainfall retention between highwater use plants and conservative use plants [21].

The temperature of each green roof module was monitored with two Emerson 501–1126 thermistors sensors (± 2% uncertainty): one placed under the plant canopy, slightly covered by the substrate, and the other attached under the module with 48 mm Scotch® heavy duty tape and insulated by a 60 mm layer of EXPOL™ polystyrene (Fig. 2) for accurate measurements without disturbance or influence from ambient air temperature. The purpose of recording temperatures at the surface is to gauge the impact of solar radiation and air temperature on this specific reading, as well as to assess the effectiveness of vegetation in providing shade and facilitating evapotranspiration. On the other hand, measurements at the bottom level serve to appraise the substrate's insulating characteristics and its moisture content. The 36 thermistors were extended with Electra F2875 cable; the joints were united with blue butt connectors PT4628, and then connected in parallel with resistors

Table 1
LAI, foliage coverage, plant height and reflectance for planted and non-planted green roof modules.

Module	LAI [-]	Coverage [%]	Height [m]	Reflectance of solar radiation at varying wavelengths [%]					
				530	570	650	855	1240	1640
No plants	–	–	–	6.7 ± 1.6	7.3 ± 1.7	9.0 ± 1.9	12.8 ± 2.4	19.6 ± 2.3	20.2 ± 2.2
S. pachyphyllum	1.9 ± 0.1	87.4 ± 1.9	0.15–0.18	10.0 ± 1.4	11.0 ± 1.5	10.1 ± 0.7	38.6 ± 5.67	23.6 ± 1.8	13.3 ± 2.6
D. admixta	0.8 ± 0.1	73.6 ± 1.5	0.15–0.18	8.6 ± 0.4	9.5 ± 0.5	8.7 ± 0.8	42.3 ± 4.1	45.7 ± 2.5	28.3 ± 2.7
L. *longifolia*	3.3 ± 1.1	94.1 ± 0.9	0.35–0.45	11.8 ± 1.3	13.9 ± 1.6	12.5 ± 2.4	53.5 ± 3.8	44.5 ± 3.2	25.4 ± 2.6
S. glauca	1.0 ± 0.1	49.3 ± 0.6	0.65–0.75	6.1 ± 0.8	7.2 ± 1.2	7.9 ± 1.1	33.1 ± 3.1	40.6 ± 3.7	27.9 ± 3.1
Mixture	1.3 ± 0.1	66.4 ± 1.8	0.07–0.80	7.2 ± 0.3	8.7 ± 0.5	9.8 ± 0.6	40.4 ± 3.7	46.1 ± 2.7	30.8 ± 2.4

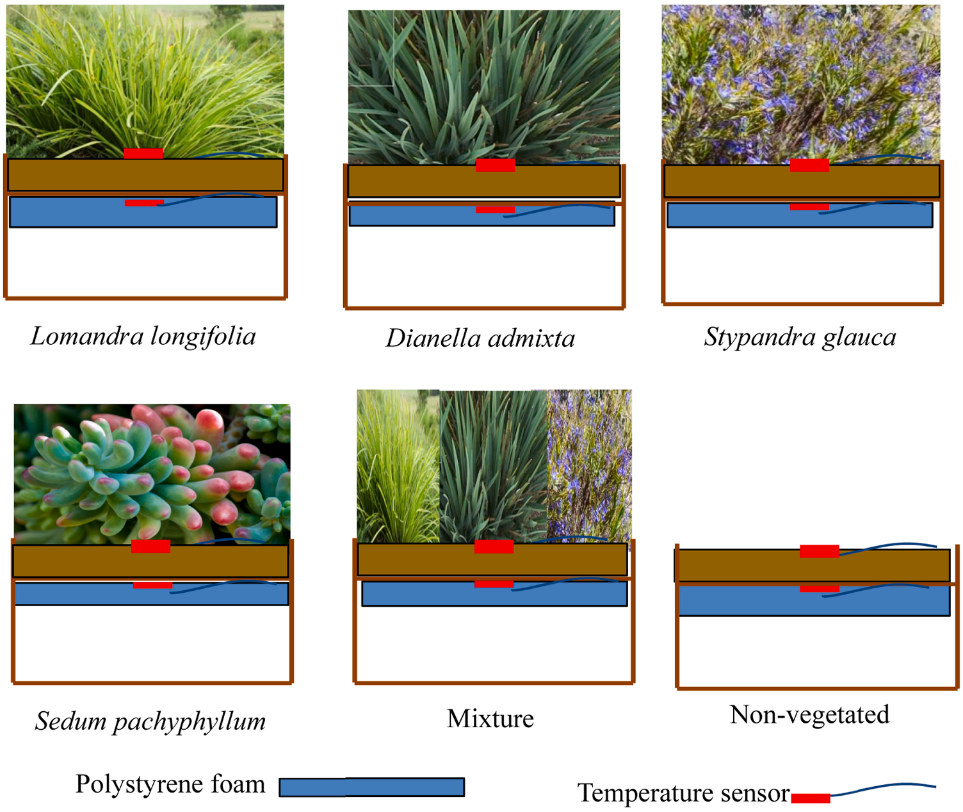


Fig. 2. Temperature sensor (thermistors) position at the surface and bottom level of six green roof module typologies.

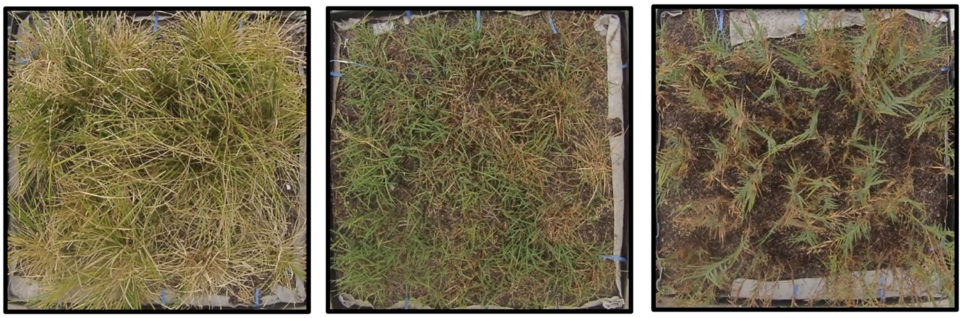
SOANAR RR0598 to a DataTaker DT 85 data logger. Extended thermistors were calibrated following the temperature sensor calibration protocol in Appendix A. The data logger was expanded with two CEM20 expansion modules to accommodate all the temperature sensors.

A HOBO U30 weather station was positioned midway along the polytunnel to measure air temperature, relative humidity, total solar radiation, wind speed and wind direction. Weather data, together with the green roof module temperatures, were collected every five minutes and, except for a few breaks due to equipment failure, continuously from August 2015 to September 2016. Data were averaged to hourly periods and data for summer and winter are presented in this study.

The polytunnel was also equipped with an overhead rainfall simulator to simulate rainfall events over the modules, a gantry crane, able to lift and weigh each module through a load cell (HBM RSCC s-type), and water collectors equipped with a 0.5 m Odyssey capacitance water level sensor (Datafow Systems Ltd) to collect and measure water runoff. Rainfall was simulated for the entire duration of this study from July 2015 to September 2016, encompassing a total of 67 rainfall events [21]. Modules were weighed before watering and 24 h after each rainfall simulation to calculate the substrate water content. Substrate moisture content and plant evapotranspiration rates were calculated using Szota et al's. [51] model, which considers water added, the amount of runoff from each module and plant stomatal resistance.

Plant foliage coverage was quantified through photo pixel counts using Adobe Photoshop CC 2015 from photos taken with a GoPro Hero4 Camera placed 1.3 m above the central point of each module (Fig. 3). Photos were taken in summer months; November and December in both 2015 and 2016. All modules were also scanned twice with five replicates each time in November 2016 by a CROPSCAN Multispectral Radiometer (MSR) sensor to measure the modules' calibrated surface reflectance at six wavelengths: 530, 570 and 650 nm (visible radiation), 855 nm (near infrared), 1240 nm (medium infrared) and 1640 nm (shortwave infrared) [52].

Statistical analyses, including analytical hierarchical partitioning, correlation and relation analyses between green roof temperatures and weather variables, were performed using R and R Studio v. 3.4.2, including packages 'hier.part', 'gtools', 'MASS', 'ggplotgui' and 'ggplot2' and Microsoft Excel 2016. Linear regression was conducted using data from 100 summer days (from November 15th to December 29th, 2015, and January 16th to March 10th, 2016) and 130 winter days (from July 31st to September 9th, 2015; May 20th to June 19th; and July 13th to September 9th, 2016). We are unable to present the data in the breaks between the selected period because the logger failed to collect the data. Table 2 shows the coefficients of the linear regression.



Lomandra longifolia *Dianella admixta* *Stypandra glauca*

Sedum pachyphyllum Mixture Non-vegetated

Fig. 3. Overhead view of five planted green roof modules and one non-vegetated control module. Planted coverage (%) is L. *longifolia* 94.1 ± 0.9, *D. admixta* 73.6 ± 1.5, *S. glauca* 49.3 ± 0.6, *S. pachyphyllum* 87.4 ± 1.9 and mixture 66.4 ± 1.6.

Table 2

The relationship between air temperature and green roof substrate temperature measured at surface and bottom in winter and summer.

Season	Treatment	Temperature	R^2	Slope	Intercept
Winter	No plants	Surface	0.86	1.03	0
		Bottom	0.52	0.65	4.43
	S. Pachyphyllum	Surface	0.86	0.97	0
		Bottom	0.52	0.49	6.01
	D. Admixta	Surface	0.63	0.98	0
		Bottom	0.44	0.47	6.67
	L. *Longifolia*	Surface	0.61	0.94	0
		Bottom	0.53	0.50	6.04
	S. Glauca	Surface	0.84	1.02	0
		Bottom	0.55	0.57	5.90
	Mixture	Surface	0.80	0.99	0
		Bottom	0.44	0.47	6.58
Summer	No plants	Surface	0.83	1.11	0
		Bottom	0.72	0.81	6.33
	S. Pachyphyllum	Surface	0.74	1.03	0
		Bottom	0.69	0.54	10.45
	D. Admixta	Surface	0.75	1.08	0
		Bottom	0.64	0.59	11.08
	L. *Longifolia*	Surface	0.74	1.00	0
		Bottom	0.74	0.60	9.70
	S. Glauca	Surface	0.73	1.08	0
		Bottom	0.67	0.63	9.75
	Mixture	Surface	0.73	1.06	0
		Bottom	0.62	0.57	10.95

Coefficients for slope and intercepts were averaged per treatment. Figs. 4 and 5 display the hourly average for each treatment.

Results and discussion

Due to the large amount of data collected only selected periods during the course of this study are presented. They illustrate the thermal performance of the modules, across seasons and during extreme events (i.e., heatwave or prolonged droughts) and single rainfall events. The substrate temperature profiles of the green roof modules are presented for summer (from December 11th to 25th, 2015; Fig. 4) and winter (from July 16th to 30th, 2016; Fig. 5). The summer period includes the modules' thermal performance during a heatwave (Fig. 4, hours 145–240), a long period of drought (Fig. 4, hours 121–288), with high (Fig. 4, hours 73–120) and low moisture content (Fig. 4, hours 241–288), and associated high and low evapotranspiration. This period has been chosen to better represent the thermal performance of the green roof modules during this extreme weather scenario.

Coverage, LAI and albedo

The overhead photos (Fig. 3) illustrate the variety of plant canopy architecture and cover in the modules. The amount of shade they provided depends on the percentage of substrate covered (coverage ratio), the thickness of the plant canopy (LAI), and solar reflectance. Table 1 shows the reflectance (or albedo) of solar radiation measured for six wavelengths. L. *longifolia* had the highest reflectance of visible (530, 570 and 650 nm) and near infrared (855 nm) radiations. The mixture planted had the highest reflectance of medium (1240 nm) and shortwave (1640 nm) infrared radiation. Non-vegetated modules had the lowest reflectance for infrared radiation, while *S. glauca* had lower reflectance to visible solar radiation than non-vegetated modules.

Moisture content and evapotranspiration

Due to resource constraints and the experimental design, moisture content and plants transpiration were not continuously measured during the whole period investigated, but only on selected days depending on the schedule of simulated rainfall for the parallel hydrology experiment explained above. Moisture content was used to analyse the variance explained by substrate temperature by means of analytical hierarchical partitioning, while plants transpiration is only considered in the discussion. This is because, in contrast with the other variables, we do not have enough measured data of plants transpiration to accurately analyse and assess its contribution to the thermal performance of the green roof modules. This is not a major concern because we are not investigating

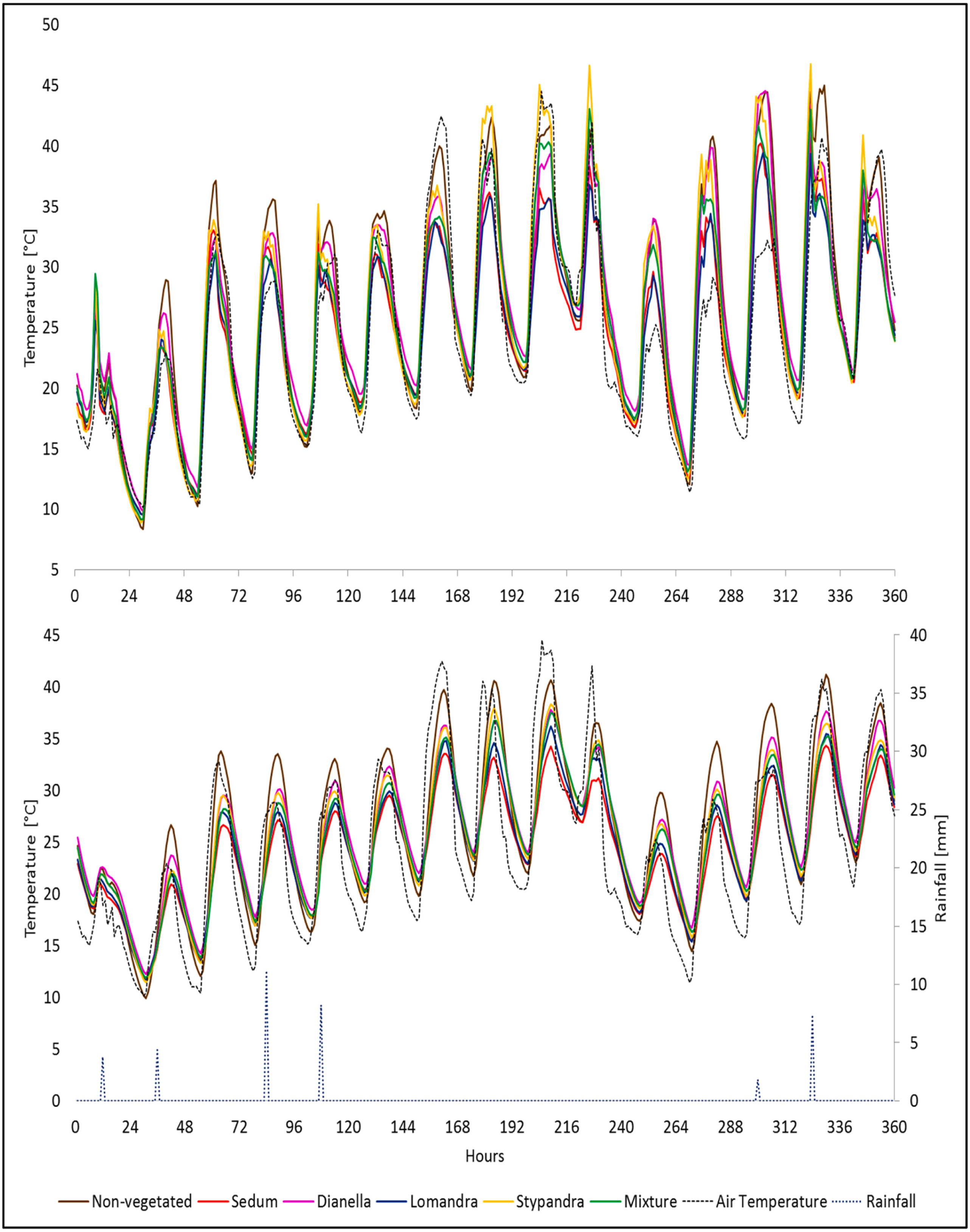


Fig. 4. Temperature swings of green roof substrate measured at surface (A) and bottom (B) levels for six different modules from 11th to 25th December 2015.

the cooling of ambient air temperature due to plant transpiration, but instead the effect of plants on the green roof substrate temperatures.

Surface temperature of green roof substrate in summer: the importance of dense coverage and high albedo

Surface temperature is variable in summer (Fig. 4) and can be

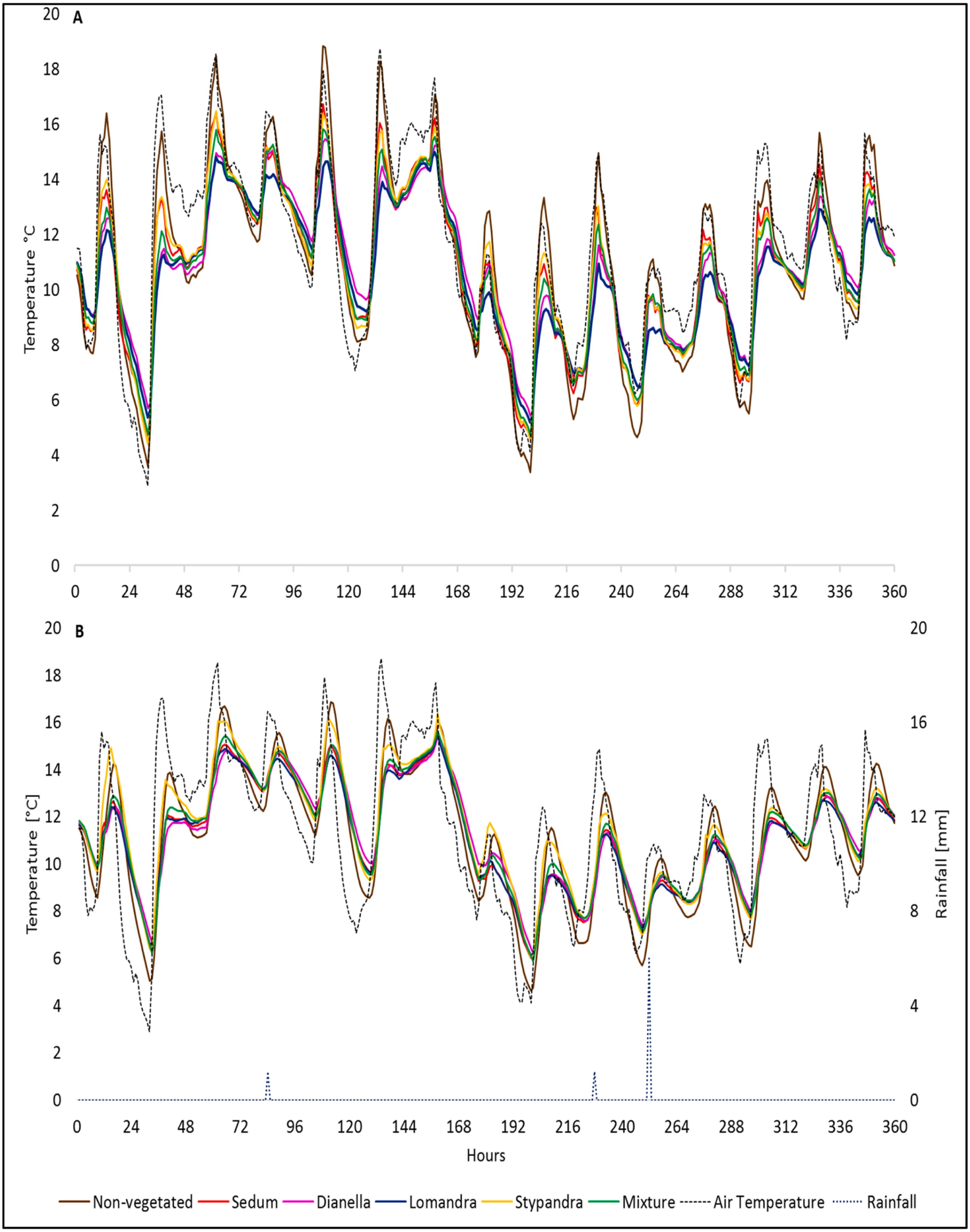


Fig. 5. Temperature swings of green roof substrate measured at surface (A) and bottom (B) levels for six different modules from 16th to 30th July 2016.

subdivided and analysed into three main periods: i) warm and rainy days (hours 0–144), ii) hot and dry days with air temperature over 40 °C (hours 145–240), iii) warm and dry days following the heatwave and followed by two low to medium rainfall events (hours 241–360). All the modules show a daily typical bell-shaped temperature profile [47] which is strongly related to air temperature, with the temperature increasing until the daily peak in early afternoon. The non-vegetated control modules had the largest temperature swings (8.34 °C to 45 °C)

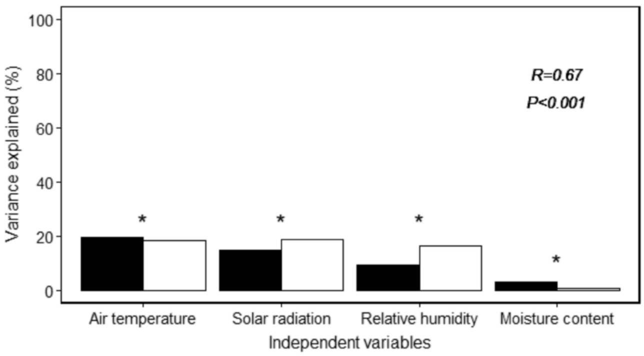


Fig. 6. Analytical hierarchical partitioning of four independent variables against averaged surface substrate temperatures of fifteen planted green roof modules and three non-vegetated control modules. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

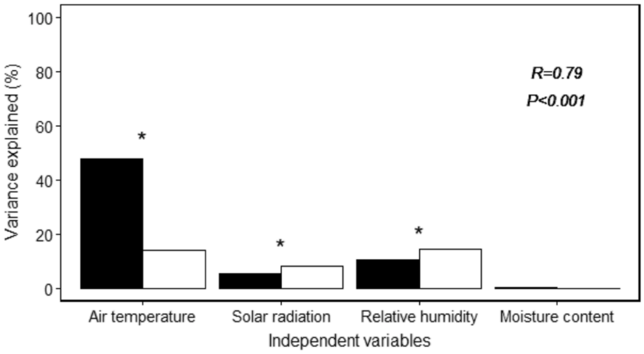


Fig. 7. Analytical hierarchical partitioning of four independent variables against averaged temperatures collected at the bottom of fifteen planted green roof modules and three non-vegetated control modules. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

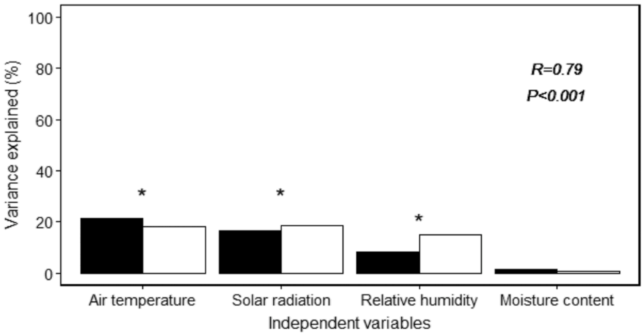


Fig. 1B. Analytical hierarchical partitioning of four independent variables against averaged surface substrate temperatures of three non-vegetated green roof modules. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

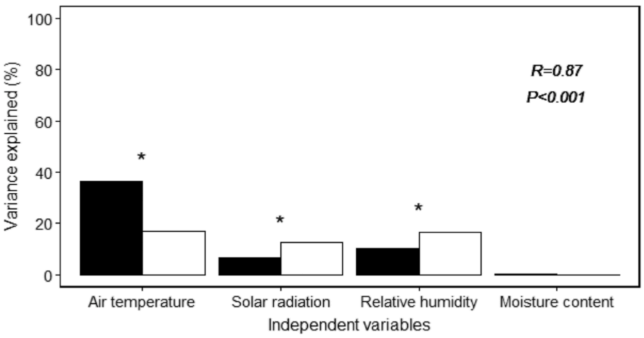


Fig. 2B. Analytical hierarchical partitioning of four independent variables against averaged temperatures collected at the bottom of three non-vegetate green roof modules. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

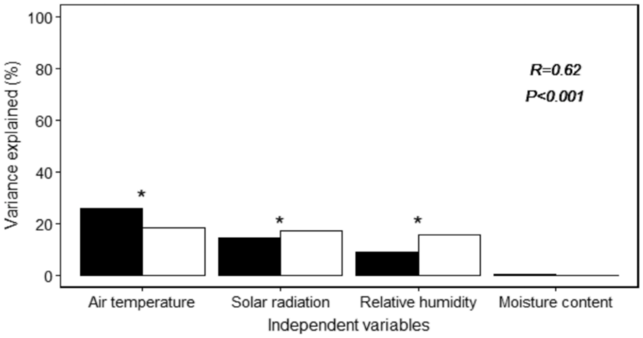


Fig. 3B. Analytical hierarchical partitioning of four independent variables against averaged surface substrate temperatures of three green roof modules planted with *Sedum pachyphyllum*. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

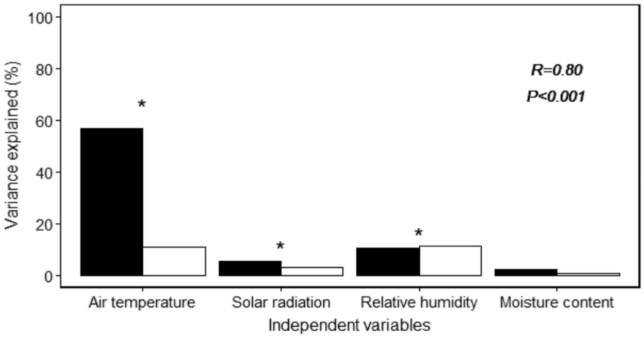


Fig. 4B. Analytical hierarchical partitioning of four independent variables against averaged temperatures collected at the bottom of three green roof modules planted with *Sedum pachyphyllum*. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

across the analysed period due to the absence of vegetation shade, which resulted in increased day time heat gain and allowed radiative heat loss during the night [53]. Because of lower vegetation cover [54], *S. glauca* recorded the second largest temperature swing, even exceeding the non-vegetated modules during the period ii) (e.g., 1.67 °C higher, hour 207) and partially in iii) before the rainfall event on hour 324. This is likely due to drier substrate moisture content in the *S. glauca* modules compared to the non-vegetated module during or just after the heatwave event (13.6% volumetric moisture content vs 15.8%). Low moisture content in the substrate likely reduces evapotranspiration and its associated evaporative cooling effect, but it also reduces the total thermal mass of the substrate and causes larger temperature swings. Our results are similar to Wong et al. [53], who found that sparse vegetation and low moisture content may not reduce green roof substrate temperature. In some cases, they found that substrate temperatures even exceeded

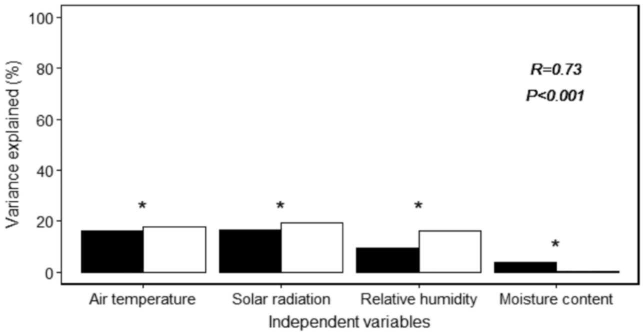


Fig. 5B. Analytical hierarchical partitioning of four independent variables against averaged surface substrate temperatures of three green roof modules planted with *Stypandra glauca*. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

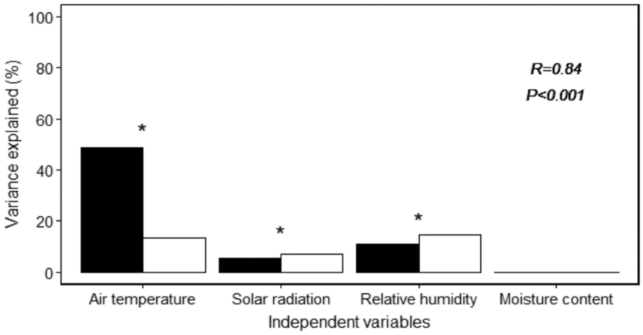


Fig. 6B. Analytical hierarchical partitioning of four independent variables against averaged temperatures collected at the bottom of three green roof modules planted with *Stypandra glauca*. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

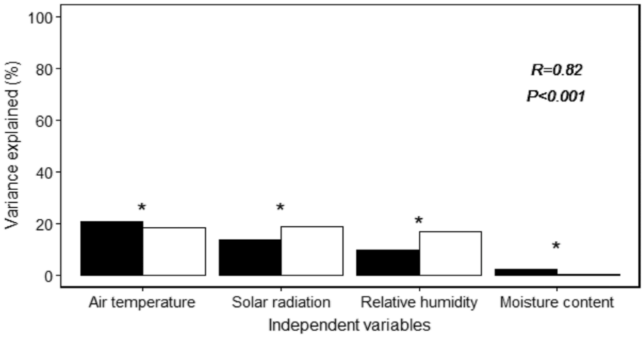


Fig. 7B. Analytical hierarchical partitioning of four independent variables against averaged surface substrate temperatures of three green roof modules planted with *Dianella admixta*. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

roof surface temperatures. The reason these modules are drier than the control is because the roots of *S. glauca* cause water to preferentially flow out of the substrate and reduce the amount of water that can be retained in the substrate [21]. Because of this phenomenon, *S. glauca* also strongly influences the thermal behaviour of the mixture modules. While shade from *S. glauca's* foliage reduces surface temperature during period i), this is not sufficient during the heatwave when higher temperatures and heat demand for thicker shade.

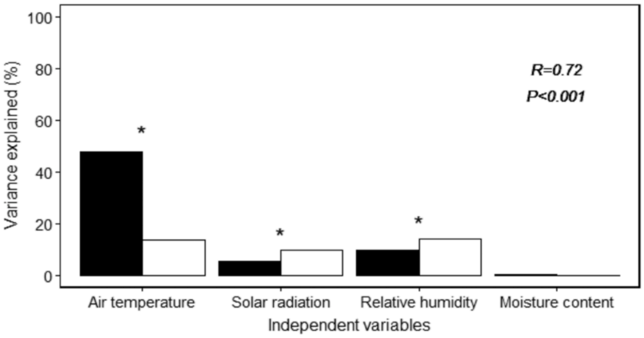


Fig. 8B. Analytical hierarchical partitioning of four independent variables against averaged temperatures collected at the bottom of three green roof modules planted with *Dianella admixta*. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

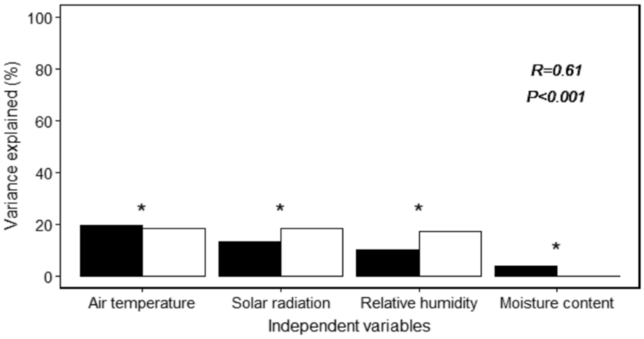


Fig. 9B. Analytical hierarchical partitioning of four independent variables against averaged surface substrate temperatures of three green roof modules planted with *Lomandra longifolia*. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

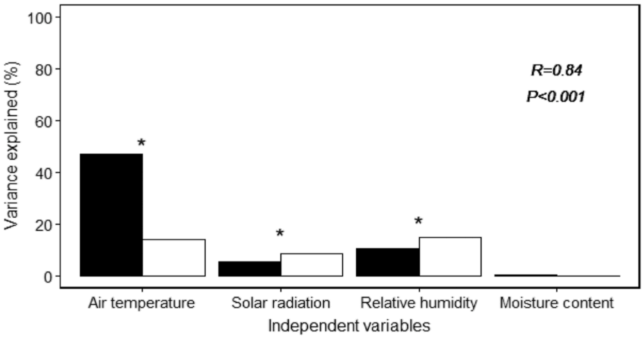


Fig. 10B. Analytical hierarchical partitioning of four independent variables against averaged temperatures collected at the bottom of three green roof modules planted with *Lomandra longifolia*. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

During the first day of the heat wave (hours 145–168) there was very little effect of the mixed planting on the surface temperature, compared with modules planted with *S. glauca* as a monoculture. However, by the fourth day of the heatwave, the consistently high air temperature and drier substrate moisture content, led to increased temperatures in the mixture which were very similar to the *S. glauca* monoculture modules. Although *S. glauca* contributes strongly to the low moisture content in the mixture modules due to preferential flow, the surface temperature

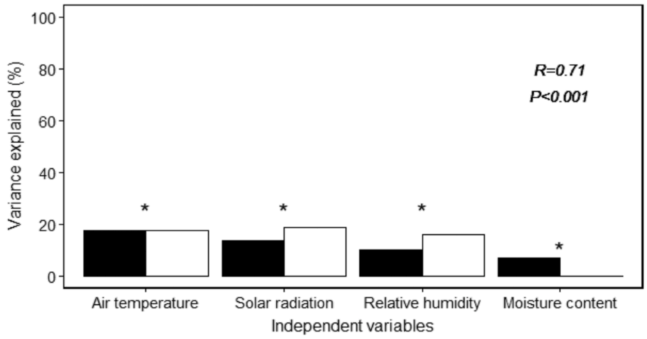


Fig. 11B. Analytical hierarchical partitioning of four independent variables against averaged surface substrate temperatures of three green roof modules planted with a mixture of *Stypandra glauca, Dianella admixta* and *Lomandra longifolia*. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

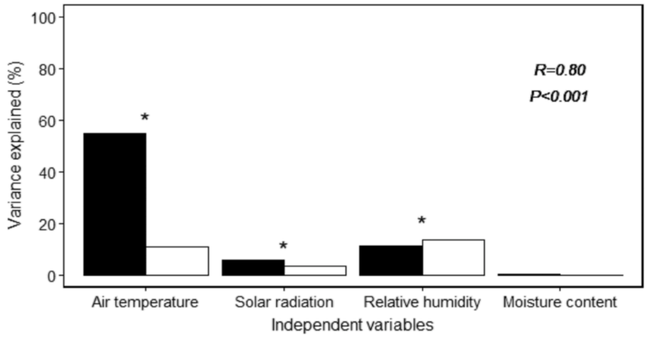


Fig. 12B. Analytical hierarchical partitioning of four independent variables against averaged temperatures collected at the bottom of three green roof modules planted with planted with a mixture of *Stypandra glauca, Dianella admixta* and *Lomandra longifolia*. Black bars show individual contribution to the variance explained, while white bars show joint contribution. Significant contributions are marked with '*'.

did not exceed the S. *glauca* monoculture module because of the higher vegetation coverage and the associated deep shade and high albedo of the mixture [55].

In contrast with *S. glauca,* the *D. admixta* treatment had higher foliage cover, greater substrate moisture content and also had a slightly higher reflectance to visible light than *S. glauca*. The combination of these factors helped to reduce surface temperature fluctuations during the heatwave period. However, in period i) and iii) *D. admixta* modules had a peak daily surface temperature (hours 25–49, or 337–360) similar to, or exceeding *S. glauca*. This is likely due to the lower LAI of *D. admixta,* meaning it has less leaf surface area and therefore potential for transpiration. Plant structure is less important than coverage for cooling potentials during hot and dry period [32,55], such as the heatwave in period ii) when *D. admixta* with higher shade reduces substrate surface temperature more than *S. glauca*. However, during periods i) and iii), with lower solar radiation than during the heatwave, thermal performances are alike, likely because *S. glauca* probably compensates for lower shade with higher evapotranspiration. At night, *D. admixta* consistently had the highest surface temperatures, likely due to lower substrate night sky radiation and less effective convective heat transfer due to lower and denser plant structure.

Lomandra longifolia (temperature variation from 9.55° to 39.40 °C) and *Sedum pachyphyllum* (from 9.56° to 41.26 °C) have different water use strategies and plant structure, however they offer similar thermal performances in the summer period we investigated. Both species have very high and dense vegetation coverage and provide a deep shade to the substrate which translates into the lowest surface temperature across all their treatments in this period. Moreover, *Lomandra longifolia* and *Sedum pachyphyllum* have the highest visible radiation reflectance, so they reflect greater amount of solar radiation than all the other species and limit the heat intake into the module itself [10]. These factors explain the smaller diurnal temperature swings across the period, and why high surface temperatures, similar to the non-vegetated and *S. glauca* modules, were not recorded during the heatwave. A cooler substrate temperature at surface level during the heatwave is likely helped by the relatively high water content before the heatwave (hour 150) of *S. pachyphyllum* (20%) and L. *longifolia* (18.5%) modules compared to the moisture content of the other treatments (mixture 13.1%; *S. glauca* 13.6%; non-vegetated 15.8%; *D. admixta* 16.6%). The higher water content not only reduces substrate temperature and allow plants to resist drought, but also enables evaporative cooling and increases the overall thermal mass [42].

Bottom temperature of green roof substrate in summer: the importance of moisture content and evapotranspiration

The temperatures at the bottom of the modules had smaller swings across all the treatments than the surface temperatures, and they appear to be less directly influenced by weather variables, such as solar radiation and ambient air temperature. This is because all treatments benefit from the substrate layer, which acts as insulator and heat sink reducing temperature fluctuations [56].

As described in Section 3.3., control modules had the greatest temperature amplitude fluctuations across the period we investigated due to absence of plant shade and lower solar reflectance. All planted modules have peaks and lows at similar times, but with different amplitude. *D. admixta* and *S. glauca* show similar thermal behaviours and daily peak temperatures. Similar to substrate surface temperature (Section 3.3), *D. admixta* consistently had the highest nightly temperature at the bottom of the green roof module and it is suggested that the heat trapped under the plant canopy increased the air temperature [35,56] and reduced night radiation, while the low plant structure reduced convective heat transfer. Although L. *longifolia* and *S. pachyphyllum* treatments have greater foliage cover, they reflect a larger portion of solar radiation (Table 1) and have different plant structure.

The thermal behaviour of mixture modules was comparable to L. *longifolia* in period i), however L. *longifolia* generally reduced bottom temperatures more than the mixture in the summer period considered due to higher foliage cover, higher water use and likely associated higher evapotranspiration. For example between rainfall events on December 15th and 23rd (Fig. 4B: hours 108 to 300), the average water content of L. *longifolia* reduced from 18.5% to 2.9% which is greater than the average reduction of the mixture modules water content from 13.1% to 1.9% This suggests greater use of water for evaporative cooling [13, 57] and greater thermal mass of L. *longifolia* modules due to higher water content than mixture modules [58]. This result agrees with Ouldboukhitine et al. [42], and Jim and Peng [59], who reported the how substrate moisture increased substrate thermal capacitance in summer. Jim and Peng did not measure a linear increase of evapotranspiration rates with increasing moisture content as we inferred here. However, this was likely due to a thinner substrate (70 mm vs 100 mm) with less water retention ability, and use of succulent species with conservative water use.

After the heatwave and following the last rainfall event in the selected period (hour 300), which increased the average moisture content of L. *longifolia* and mixture modules to comparable values (6.4% and 5.0% respectively), their two temperature profiles overlap. Franzaring et al. [55] and Lundholm et al. [49] report that mixtures do not necessary improve cooling and water retention benefits. However, in our research, the mixture modules had better thermal performance than all monoculture modules except L. *longifolia*.

Similar to the surface temperature results, *S. pachyphyllum* had the lowest bottom temperature in the summer period analysed. *S. pachyphyllum* treatments had high coverage ratio, together with the second highest (hours 289–312) or highest (hours 337–360) evapotranspiration rates. It also had the highest moisture content (20%) available for evaporative cooling, particularly during period ii). Large water availability retained by the substrate and great leaf surface area enabled high evapotranspiration rates of *S. pachyphyllum* despite its conservative water use strategy. Notable evaporative cooling is further suggested by *S. pachyphyllum* modules having the second greatest moisture content reduction (20% to 13.3%).

High thermal performance of succulent species during a summer heat wave was also found by Eksi et al. [60], who compared *Sedum* spp with perennials and shrubs, and by Lin and Lin [61], who investigated the thermal performance of *Sansevieria trifasciata* and *Rhoeo spathacea*. In these studies succulents were able to significantly reduce heat transfer through the green roof because of good coverage and drought tolerance. Finally, Dvorak and Volder [62] also reported the insulative contribution of succulent species during hot and dry summer in irrigated and unirrigated conditions.

The analysis we carried out for summer concludes that large canopy volume, high LAI and reflectance are important to reduce the heat transfer through green roofs. However, significant cooling benefit is provided by plants able to retain water and make it available for evaporative cooling.

Green roof substrate temperature in winter: plants offer additional minimal benefit

In the winter period selected, vegetation coverage reduced temperature swings regardless of the LAI (Fig. 5). Non-vegetated and *S. glauca* modules showed the amplest temperature swings due to no or low plant shade respectively. *S. pachyphyllum* had higher surface temperatures than all the other planted modules, including *S. glauca* (hours 97–168), suggesting that in winter the surface temperature reduction is not due to LAI or plant height absorbing solar radiation, which is less intense in winter, but is likely due to higher evapotranspiration rates of high water use plants which reduce surface temperature. In fact, rapid changes of surface temperature in winter are strongly correlated to rainfall and the associated increase in substrate moisture content [35].

Our study confirmed that in winter succulents experienced greater temperature extremes because less heat has been dissipated by evaporative cooling [60] and the air trapped under the canopy increased its surface temperature [35,56] and reduced convective heat transfer. During the day, L. *longifolia* consistently had the lowest surface temperature, followed by *D. admixta* and the mixture. During the night, *D. admixta* had the highest temperature, which is desirable to reduce building heating load.

Average temperature measured at the bottom of all green roof treatments in winter had smaller differences between daylight peaks and nighttime lows than the summer peaks and lows. In summer, planted modules had up to 4 °C difference in daily peak bottom temperature, and non-vegetated modules up to 7.5 °C (Fig. 4, box B, hour 184). In winter, the difference was reduced to 1.4 °C for the planted modules, and 2.3 °C in the non-vegetated modules (Fig. 5, box B, hour 112). If we exclude *S. glauca*, which on some occasions had higher temperature peaks than non-vegetated modules at bottom level due to lower moisture content and less cooling effect (Fig. 5, box B, hours 0–24, 169–192), the difference amongst the other planted modules was minimal and between 0.3–0.5 °C, with L. *longifolia* having the lowest peaks. During the night, differences were even less, suggesting that in winter plant canopy contributed equally to the reduction of bottom temperature, regardless of the plant architecture or canopy shade, and that the insulative influence of substrate is much greater. However, non-vegetated modules had the amplest temperature swings due to higher radiative loss at night and no shade during the day [35].

In winter, there were not significant changes in temperature performance between mixture and monoculture modules, although occasionally mixtures had the highest night bottom temperatures (i.e., hours 145–150, 265–270, 313–318). This suggests that on this occasion, mixing plants with different life forms [49,55] did not improve green roof thermal performance for heating purposes.

In summer, intense long periods of solar radiation and hot air temperatures drive the substrate temperature. To minimise the influence of the weather variables, plants need to be selected to reduce heat transfer through the green roof. High foliage coverage, LAI, and solar albedo can help this. In winter, because of cooler air temperatures and shorter periods of less intense radiation, plant contribution in enhancing thermal performance for heating is minimal. LAI and albedo do not offer additional benefits, while high coverage does thanks to the ability to trap air and reduce convective heat loss. Greater retention of water enables evaporative cooling and reduces substrate temperature, which is not desirable in winter. However, the insulative contribution of the substrate layer is dominant and minimised the substrate temperature reduction at surface level.

Analytical hierarchical partitioning

The variance explained by air temperature, solar radiation, relative humidity and substrate moisture content (independent variables) to green roof substrate temperatures measured at the surface and bottom level, have been analysed and assessed by analytical hierarchical partitioning. This statistical technique is used to assess the relative importance of the independent predictor variables in explaining the variation of the substrate temperature response variables (Figs. 6 and 7). Because moisture content was not measured continuously but only on the days corresponding to simulated rainfall events, we selected discrete values of the other independent variables at the time when the modules were weighed, and moisture content was assessed. In total, 34 discrete values for each independent variable were identified between November 15th, 2015, and March 9th, 2016.

As we expected, air temperature and solar radiation explained the greatest variance of surface temperature, followed by relative humidity and moisture content. In Appendix B, graphs for each treatment are presented. The individual contribution (black bars) of air temperature to the surface temperature is consistently greater than the joint contribution (white bars) for all treatments, except for *S. glauca* and the mixture modules. In contrast, joint contribution of solar radiation and relative humidity is always greater than the individual contribution. The contribution explained by moisture content is uninfluential for *S. pachyphyllum* and non-vegetated modules, while it provides a significant contribution (marked with '*') to all other modules.

Individual contribution of air temperature to the variance of bottom temperature was significantly higher, between 48% (L. *longifolia*) and 58% (*S. pachyphyllum*), than all the other independent variables. Moisture content was always uninfluential, between 0 for *S. glauca* and 5% for *S. pachyphyllum*, which were the driest and wettest modules respectively during all the rainfall events. As we found that air temperature is the main driver of substrate temperature at bottom level, and one of the top two at surface level, in the next section, we present the exact correlation for summer and winter.

Correlation of air temperature with substrate temperature at surface level

Air temperature had a strong influence and a close relationship with the green roof substrate temperature. All the regression lines showed strong R^2 correlations, larger in winter than summer, except for *D. admixta* and L. *longifolia* modules. The 100 days in summer and 130 days in winter we used for the linear regression clearly show that the control modules had the steepest gradients of the treatments, more pronounced in summer than in winter (Table 2) due to the lack of vegetation cover able to shade the substrate. Excepting *S. glauca,* the planted treatments all had fewer steep slopes than the control modules, all greater than 1 in summer, but below 1 in winter. While *S. pachyphyllum* and L. *longifolia* occupied the two lowest positions in the order of gradient steepness in both seasons, the other planted modules interchanged. In summer, LAI, drove the order as the greater leaf area implied more energy absorbed by the plants (Bare greater than *D. admixta* greater than *S. glauca* greater than Mixture greater than *S. pachyphyllum* greater than L. *longifolia*). In contrast, in winter the intensity of solar radiation is far smaller, and the coverage ratio drove the order of the slope (Bare greater than *S. glauca* greater than Mixture greater than *D. admixta* greater than *S. pachyphyllum* greater than L. *longifolia*).

Correlation of air temperature with substrate temperature at bottom level

Regression analysis for the bottom temperature showed a greater dispersion of the data clouds than the surface analysis. This is likely due to the dynamic thermal behaviour of green roofs, which is strongly affected by changes in moisture content, air porosity and associated convective and radiative fluxes. However, gradients were all lower than 1, meaning that the insulative effect of the substrate reduced the influence of the air temperature. As expected, the control module was the treatment with the highest gradient, followed by *S. glauca*, the treatment with the lowest vegetation cover. As explained in Section 3.4, *S. pachyphyllum* appeared to be the most insulative treatment in summer, while it was not in winter, stressing again that high moisture content, together with canopy cover, helps maintain the substrate at low temperature in summer, while in winter the most affective mechanism is plant cover, regardless of the LAI and associated leaf area. However, it should be noted that mixture module performed very well, reducing the bottom temperature in summer, and having amongst the highest night bottom temperatures in winter, although differences were minimal. Only *D. admixta* in winter and *S. pachyphyllum* in summer did better. Looking at the intercepts, high water use plants both as monocultures and mixtures, except for *S. glauca*, had the greatest intercept values. This suggests that in the long term (i.e., 230 days are investigated in this study) and across seasons, *D. admixta*, L. *longifolia* and mixture treatments had the largest effect in mitigating substrate temperature, although they may not be the best option during heatwaves because they retained less water than *S. pachyphyllum*, which is essential to increase thermal mass and evaporative cooling.

Conclusions

In this study, we investigated the effect of five different plant treatments and an additional non-vegetated control treatment on green roof temperatures during winter and summer. Results from analytical hierarchical partitioning technique showed that amongst four independent weather variables (air temperature, solar radiation, relative humidity and substrate moisture content), temperatures at both the substrate surface and the bottom of each green roof module were best explained by air temperature, accounting for 48% to 58% of the variation.

Linear regression between air temperature and green roof module temperatures throughout the study and in selected summer and winter periods showed that temperature reductions at the substrate surface in summer were due to greater LAI and high albedo, as offered by high water use L. *longifolia* which reduced substrate temperature of 1.86 °C compared to succulent *S. pachyphyllum*.

L. *longifolia* green roof modules, with their elevated substrate moisture content and efficient evapotranspiration, led to the lowest reduction in bottom temperatures compared to the other modules, achieving a remarkable decrease in water content from 18.5% to 2.9%. While mixture modules came in second after L. *longifolia* in terms of performance, they still outperformed monoculture modules, suggesting a positive impact of planting mixtures. However, this positive effect of the mixtures modules was not observed in winter, as all planted modules exhibited minimal temperature differences regardless of plant composition and LAI.

Green roofs planted with L. *longifolia* had the best insulative performs in the long term and across seasons due to a combination of cooling mechanisms in summer and insulation effects of the substrate. These findings imply that incorporating high water use L. *longifolia* should be considered when designing green roofs to mitigate heat buildup. Focusing on high water use plants to enhance the potential for cooling microclimates and to mitigate the urban heat island effect would be a valuable direction to pursue in future studies.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A

1. Fill the temperature bath machine with distilled water. Be careful to avoid water spillage. Minimum water level is just above the pump intake and water heater. Maximum water level after putting all sensors in water is just below the cover.
2. Set a temperature according to the expected measured temperature - i.e. if you expect to record an average temperature of 25 °C, set the machine to 25 °C, and turn the device on. Temperature set point must be higher than the initial temperature of water and sensor in the bath. If a lower temperature is required, put ice tubes made from distilled water and wait until all ice tubes are melted. Maximum allowable set point temperature is 70 °C (check manual).
3. Turn on and place in the fluke stik thermometer model 1551A making sure it is set in Celsius with three significant digits. Make sure the valve to the drain is closed before switching on the water bath circulation. If the valve is open, the plastic drain pipe will be spraying water. Never switch on the bath without correct water level. The heater must be immersed in water while in operation.
4. Connect the sensor(s) to the logger and connect the logger to the computer.
5. Place the sensor(s) in the temperature bath making sure the sensors do not touch the interior walls of the machine.
6. Wait until the bath reaches the set point. Time varies according to the temperature point. The higher, the longer.
7. When the temperature equilibrates, start recording data every 5 min for at least 2 h.
8. In an Excel spreadsheet, create a column for date and time, one for the reference temperature from the fluke stik thermometer and one for the temperature from the sensor (see Excel example

file). The temperature recorded from the machine is usually slighter higher than the thermometer.

9 The fluke stik thermometer cannot log data, so it is needed to record temperature values manually. As per its manual, the fluke stik thermometer has a response time of 20 s. This means you need to wait about 20 s from the sensor temperature recording before recording the temperature from the thermometer.

10 After at least 2 h (25 data), turn off the machine and take out the sensor(s) and the thermometer.

11 Empty the machine and get sure to wipe away all the water drops.

Appendix B

NBS Impacts and Implications

- Environmental: our study evaluates new planting options for green roofs with higher transpiration rates than succulent species. This would increase biodiversity and help mitigate the urban heat island effect thanks to a stronger cooling effect.
- Economic: green roofs have been shown to have positive economic impacts, such as reducing energy costs. Our study examines which plants can reduce cooling and heating loads in a building, thus reducing energy costs for space conditioning.
- Social: our study uses plants that are native in Victoria to create a functional and thriving green roof. Such result would enhance the visual appeal of a building, and would improve the overall quality of life for residents and visitors when the green roof is accessible as a social space.

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