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RESEARCH

Bridging the grand canopy! How does plant canopy width affect the cooling capacity of green walls?

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Abstract

Growing plants on buildings provides a range of ecosystem services. In addition to offering wildlife habitat, green walls insulate buildings and reduce their thermal load in summer. But how does plant choice/design affect building cooling? While some research indicates the importance of foliage width (foliar density), limited information is available on what density optimises cooling. This research aims to determine how plant canopy width impacts wall cooling. Cooling was estimated by comparing wall panel temperatures behind plant foliage against control panels exposed to direct solar irradiance; the plant canopy width varying by the addition of extra plants, i.e. altering Wall Leaf Area Index (WLAI). The value of wall cooling per unit leaf area for six contrasting taxa was estimated, and factors affecting these attributes were identified. The potential to cool a wall increased with additional canopy layers, but was not proportional to the greater leaf area. Greatest cooling was recorded with *Heuchera micrantha* cv. Palace Purple, with 21 °C of cooling provided by a single canopy layer when control wall temperatures were 45 °C. Adding two more canopy layers increased the cooling differential to 24 °C under these conditions. Shading accounted for much of the cooling, but variations in cooling capacities for taxa with similar leaf areas suggest variable evapotranspiration was also influencing cooling. This study concludes that for those taxa that cool primarily via shading additional canopy layers are beneficial, but for those that cool via evapotranspiration, then a single layer suffices.

Keywords Thermal regulation · Green vertical systems · Green infrastructure · Evapotranspiration · Shading · Relative humidity

Introduction

In recent years, the idea of attaching vegetation to building structures (green roofs, walls and podiums) has evolved as a form of remediation for lost ecosystem processes in the built environment. Green walls (also known as vertical green [or greenery/greening] systems [VGS]) provide vegetation where space is restricted, add three-dimensional plant structure that aids ecological complexity and promote opportunities for wider ecosystem service delivery (Guimarães-Steinicke et al. 2022; Patti et al. 2025). There are some disservices, however, most notably costs, on-going maintenance (e.g. frequent pruning of foliage), additional weight to a wall, access to the built part of the façade, fire risk and perceptions of nuisance/dangerous animals having greater access to human living spaces (Manso and Castro-Gomes 2015; Chow et al. 2018). Nevertheless, the services appear extensive. Green walls have been linked with better thermal comfort (Hoelscher et al. 2016; Vox et al. 2018; Cui et al. 2022; Oquendo-Di Cosola et al. 2023), energy conservation (Cameron et al. 2014, 2015; Wong and Baldwin 2016; Coma et al. 2017; Lee and Jim 2019; Karimi et al. 2022), air quality improvement (Redondo-Bermudez et al. 2021; Irga et al. 2023), carbon dioxide reduction (Torpy et al. 2016), flood control (Palermo et al. 2023), noise mitigation (Pérez et al. 2016; Shushunova et al. 2022), human psychological health and well-being (Yeom et al. 2021; Shao et al. 2024) as well as habitat for biodiversity (Madre et al. 2015; Salisbury et al. 2023). Increasing demand for green walls proves their importance in an urban environment and the necessity to explore their capacity to provide ecosystem services (Pérez-Urrestarazu et al. 2016a; Tan et al. 2022).

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Notably, there is a call for greater urban green spaces of all types to help cities deal with more aggressive heat wave events in future (Nazish et al. 2024).

Green walls are primarily classified into two types based on the construction technique, supporting structure, and type of plants and substrate (Priya and Senthil 2021). 1: Green façades- vines, climbers and wall shrubs planted in the ground or large containers, and where the shoots climb up or cascade down a wall; or where the shoots are attached to a frame against a building wall. The plants can attach themselves via morphological features such as twisting stems, aerial roots, leaf tendrils, and adhesion pads (Vox et al. 2018). 2: Living walls- perennial plants (herbaceous, shrubs, alpines, ferns etc.) root into substrate-embedded cells either in modular systems such as trays, planter tiles, and flexible bags or in continuous systems where plants are individually attached into lightweight and permeable growing medium (Manso and Castro-Gomes 2016; Pérez-Urrestarazu et al. 2016b).

Results from numerous studies conducted in various parts of the world confirmed the consistent cooling effect of green walls (Olivieri et al. 2014; Blanco et al. 2021; Wong et al. 2021), reducing wall surface temperature by 7 to 25 °C (Chen et al. 2013; Hoelscher et al. 2016; Kunasingam et al. 2024); and air temperatures by between 3 and 8.7 °C (Cameron et al. 2014; Shafiee et al. 2020). Several studies suggest living walls provide better insulation compared to green façades (Wong et al. 2010; Perini et al. 2011; Jaafar et al. 2013). For example, Coma et al. (2017) found that modular living wall systems reduced artificial air conditioning energy use by 59%, whereas double-skin green façades only achieved a 34% reduction. Living walls seem to have additional insulating properties due to the growing medium mounted on the wall and perhaps in some cases a more even distribution of wall plants (i.e. foliage) compared to façades (Pérez et al. 2021). Differences in cooling performance of green walls are highly influenced by climate (Vox et al. 2018), weather (Mazzali et al. 2013), orientation (Kontoleon and Eumorfopoulou 2010; Jim 2015a; Pérez et al. 2017), characteristics of the growth substrate (Fernández-Cañero et al. 2011; Bustami et al. 2022), water availability (Pan et al. 2020) and plant-related factors.

The plant related factors that affect wall cooling include their capacity to intercept irradiance and cast shade on a wall or building (Freewan et al. 2022; Zhao et al. 2022), reflect incoming radiation back to space (albedo affect, He et al. 2021) and by cooling the air around the wall through evapotranspiration of water via leaf stomata (Cameron et al. 2014; Bakhshoodeh et al. 2022a; Rahman et al. 2023). Small amounts of solar energy are utilised for photochemical activity too, e.g. photosynthesis and respiration. Plant taxonomic choice (Cameron et al. 2014; Perini et al. 2016; Kunasingam et al. 2024) affects these; and other secondary factors such as the speed of air moving through, or volume of water vapour released by, the plant canopy.

In terms of shade cooling, aspects such as leaf size, thickness, orientation and canopy density impact on the amount of irradiance penetrating through to a wall surface (Niinemets 2010; Susorova 2015; Li et al. 2019). Canopy density is expressed as the Leaf Area Index - in green walls this is explained as the total area of leaves (one-side only) expressed as a ratio of the wall area. In simpler terms, it expresses the number of fully covered layers that can be formed by leaves in a vertical plane (De Bock et al. 2023). Plants that increase the LAI either through their leaf/branch morphology or age (older plants tend to be thicker with more dense canopies) will provide more shading and more cooling due to shading. For example, research on *Hedera helix* showed a strong correlation between canopy width and wall cooling (Sternberg et al. 2011). In practice for green walls, the LAI can vary depending on several factors including type and age of wall system, taxa selection, season and climatic conditions (Ip et al. 2010; Sanusi et al. 2017; Pérez et al. 2022). Zhang et al. (2022) demonstrated that the LAI of the evergreen *Lonicera confusa* remains static at 2.56 throughout the year, whereas LAIs for the deciduous *Parthenocissus tricuspidata* and *Wisteria sinensis* - varied between 2 and 4 and 1.5–3.5, respectively, across the seasons. Leaf area index can be determined directly by a destructive leaf harvesting technique or indirectly by measuring the light transmission through the foliar canopy (De Bock et al. 2023; Pérez et al. 2022).

The number and density of leaves are not the only important criteria when foliage interacts with light. Incoming solar radiation can be reflected via leaf albedo. Albedo is itself affected by leaf colour, hairiness (hirsute character), surface texture and the presence of reflective waxes (Lundholm and Williams 2015).

Key biological and physical factors also influence the degree of evapotranspirational cooling that is provided (Lopatin 2025). Factors that include: plant size, canopy size, the position of leaves within the canopy, individual leaf size, albedo, hirsute character, water availability in the soil, non-hydraulic root signals, water-use efficiency and nutrient content (Daudet et al. 1999; Monteiro et al. 2016; Hoelscher et al. 2016; Rahman et al. 2020; Richter et al. 2021; Tang et al. 2021; Bakhshoodeh et al. 2022a; Niklas et al. 2023). The latter two aspects influence how efficiently plants intercept solar radiation, use water to perform photosynthesis and control stomatal behaviour (Díaz et al. 2016). Vegetation around walls does not only change temperature. Plant evapotranspiration increases local relative humidity (RH). The difference in RH between bare walls and the presence of vegetation in green walls ranges from 2 to

30% (Thomsit-Ireland et al. 2020; Abdo & Huynh, 2021). There is a feedback mechanism involved here however, and high RH often inhibits effective plant transpiration (Bakhshoodeh et al. 2022a) due to lower Vapour Pressure Deficits (VPD) and thicker boundary layers around the leaf; thus, in practice, high RH can reduce cooling potential.

Many studies suggest the shading from green walls is the most prominent factor contributing to cooling (Koyama et al. 2015; Hoelscher et al. 2016; Pan et al. 2020; Bakhshoodeh et al. 2022b). However, others argue that evaporative cooling is not insignificant in determining wall cooling (Cameron et al. 2014; Perini et al. 2016). In practice, both factors are probably strongly affected by plant choice. Previous studies on green walls have shown that taxonomic choice affects cooling significantly (Kunasingam et al. 2024). Wall cooling potential within or between taxa seems to be broadly dependent on canopy coverage; Kunasingam et al. (2024) for example, attributed maximum cooling found with *Hebe*, to the effective and even distribution of leaves in the canopy of this taxa. When leaf coverage is similar, however, then other leaf traits become defining factors, i.e. albedo, solar transmittance ratio and evapotranspiration rates (Armson et al. 2012; Koyama et al. 2013). Indeed, Perini et al. (2016) found that *Hedera helix* had higher evapotranspiration despite less foliar coverage (25%) than *Cistus* cv. Jessami Beauty (with 65% foliar coverage). The evenly distributed leaves of *Hedera helix* expose more leaf surface directly to radiation, resulting in overall more evapotranspiration. Background ecophysiology may be a key component too, when determining the cooling capacity of wall plants. Lin et al. (2017) studying 38 different taxa found that those from hot dry climates were more effective at keeping their leaves cool than those from hot wet climates. This corresponded to features such as smaller leaf: areas, perimeters, lengths and length-width ratios. The xerophytic plants also possessed greater stomatal and vein densities across a leaf, as well as higher maximum evapotranspiration rates.

In theory, increasing the canopy coverage and depth in green walls seems a plausible mechanism to increase cooling capacity. However, adding more canopy layers has implementation difficulties. For living wall systems, a denser canopy may mean the requirement for more plants to be purchased at planting time, with cost implications. In façade systems, it may take some time for a uniform canopy cover to develop across the building. Moreover, once a thick canopy develops there may be concerns that the plants become excessively vigorous requiring frequent pruning to avoid coverage of windows and interference with drainpipes and other infrastructure. Larger, thicker canopies may put more strain on the frame systems supporting the plants. Even when designers may not opt to optimise cooling performance of green walls by using higher initial planting densities, the concept is worthy of study, however, as it is important to know how thermal performance may vary as plants grow and develop naturally over time.

Although several studies have highlighted the link between LAI and plant cooling, very few have explored the influence of foliage width on the thermal performance of wall plants. Thus, this study aims to investigate the most efficient canopy coverage of wall plants to optimise the thermal benefits. For example, do thicker canopies always provide greater cooling than thinly covered ones? The research uses a systematic approach to compare different model taxa and different canopy widths using a system that facilitates randomised, replicated data collection over a relatively short period of time. We hypothesised that:

1. Species with numerous small leaves and dense canopies such as *Hebe* and *Hedera* will be the more effective at wall cooling.
2. Cooling would be greater with increased canopy width (number of plants directly in front of the wall).
3. The benefits of wider canopies would be greater at higher ambient temperatures.

Materials and Methodology

Plant material and husbandry

Taxa were selected from a range of common green wall plant types (e.g. woody climbers, small sub-shrubs, herbaceous perennials and grasses). Specific taxa were chosen with contrasting leaf characteristics and canopy arrangements to investigate the influence of these traits to cool a building wall, and hence more generally help to cool a building (Table 1). To maintain uniformity between taxa, 2–3-year-old juvenile plants were purchased three months before the experiment (Johnsons of Whixley Nursery, UK) and transplanted into 5 L black pots. Pots were filled with a growing substrate to a depth of 0.25 m with 20 mm of fine-chopped straw mulch covering the top of the substrate to help avoid excessive evaporation/cooling due to the substrate itself (Tan et al. 2017). The substrate used was Miracle-Gro Peat Free All-Purpose Compost (Evergreen Garden Care Ltd, Frimley, Surrey, UK), composed of composted green waste and coir (pH 6.6–7.0.6.0, 45–55% air porosity, 1.1–1.3 g cm^{-3} bulk density and >60% of water holding capacity). Controlled-release fertiliser provided 330 g of N, 104 g of P, and 339 g of K m^{-3} of substrate. Individual plants were trimmed to give approximately similar canopy dimensions within a taxon and across taxa (approx. 800 mm h x 400 mm w x 300 mm l), although leaf number, density and arrangement could vary per plant within this arrangement.

Table 1 Plant taxa used in the experiment

Plant name	Family	Description	Leaf length range smallest/largest (mm)	Photo
Hebe cv. Mrs Winder	Plantaginaceae	Compact, evergreen shrub. Sclerophyllous leaves	20-50	
Heuchera micrantha cv. Palace Purple	Saxifragaceae	Semi-evergreen perennial. Purple foliage with pubescent leaves	30-80	
Alchemilla mollis	Rosaceae	Herbaceous perennial. Light green foliage, with hirsute leaves	60-100	
Hydrangea macrophylla	Hydrangeaceae	Deciduous shrub. Dark green, soft, hydrated leaves	70-120	
Carex buchananii cv. Red Rooster	Cyperaceae	Sedge. Bronze narrow leaves	400-800	
Hedera hibernica	Araliaceae	Woody climber, Dark green glaucous leaves	30-70	

The planting substrate and moisture content were evenly maintained throughout the experiment. Plants were irrigated heavily in the evening prior to data recording, thus avoiding the presence of water droplets on the surface of the substrate/leaves during the experiment per se, which can additionally influence local cooling. All the pots were watered initially to container capacity; and checked for moisture status during the experiments with a ML3 ThetaProbe Soil Moisture sensor (Delta-T Devices Ltd, Cambridge, UK) to ensure water content stayed within a $0.35-0.25\ m^3m^{-3}$ spectrum, i.e. the growing medium stayed wet enough to avoid stomatal closure and potential loss of evapotranspirative cooling (Blanusa et al. 2013).

Experimental setup

The experiment was carried out in the summer of 2023 at the University of Sheffield, Sheffield, UK. Four, single black panels (10 mm black polypropylene board) with the dimension of 1 m X 1 m, were positioned on a south-facing single brick wall and insulated using 5 mm polystyrene insulation board at the back and a 30 mm plywood layer in the middle. This ensured the panels acted as independent units, being partially insulated from heat migrating laterally along the brick wall, i.e. from warmer, unshaded zones (see Kunasingam et al. 2024 for further rationale). Panels were placed 1m apart and 0.3 m above the ground. Data loggers were used to monitor temperature and relative humidity (Tiny-tag -TGP-4505; range = −25 °C to 85 °C and 0 to 100% relative humidity; with a temperature accuracy of 0.35 °C, Gemini Data Loggers, Chichester, UK) with the external thermocouple probes attached to the centre of each black panel.

The objective of the experiment was to determine how a single 'layer' of plants cooled the wall panel, and whether there was an additional advantage by adding a second layer of plants to help block spaces in the first row.

For completeness, a third layer composing a single plant specimen was placed in front of the gap in the second row. For each taxon, treatments were set up based on plant canopy width – namely 1 Layer (LAI1) = a single layer of 3 specimen plants arranged in a row (Fig. 1A); 2 Layers – (LAI2) = two layers of plants (3 specimens in one row and 2 in a row in front – Fig. 1B) and 3 Layer (LAI3) = three layers of plants (3 specimens in one row, 2 in a row in front, and single plant in front of this row – Fig. 1C). The first layer of plants was positioned approximately 100 +/−10 mm in front of each panel, with the second layer approximately 400 +/- 20 mm and the third layer 800 +/- 30 mm in front of the panel, respectively. Plants were aligned in this way to both represent the realistic vertical planting approach of adding more layers in some wall systems (Honeycomb planting – Briscoe and Bright 2019), but also to investigate the general principle of how wall thermal properties change as the plant canopy thickens over time – e.g. is a 3 year old wall with large established plants a better thermal insulator than a newly established wall, with perhaps incomplete and thinner cover? The aim was to add more foliar leaf area while covering the wall as homogeneously as possible, i.e. to fill gaps where the original canopy was thinnest. The temperature and humidity of the panel behind these treatments were compared to that of an uncovered panel (Control – C1 – Fig. 1).

Temperature and humidity at the panel were recorded when incidental sunlight was at approximately right angles to the wall, i.e. between 10.30 h and 13.30 h daily. To avoid excessive irradiation being absorbed by the black pots and re-emitted as local heat, the pots were screened with a white vinyl cloth. Data was compared to an uncovered control black panel at each time. The location of the layer treatments and control (bare wall) was randomised between consecutive days of recording, i.e. the control treatment was not always on the left side of the wall (as shown in Fig. 1).

For each scenario, the amount of leaf area in front of the panels was calculated as the Wall Leaf Area Index (WLAI). The total number of leaves was manually counted for each canopy layer. Randomly harvested leaves (fifteen per plant) were scanned using an HP scanner (MFP77940), and the leaf area was estimated using ImageJ (Pérez, et al., 2017). The leaf area of the grass-like *Carex* was calculated by measuring the width and length of leaf strands manually (Busch 2000). Recordings of wall panel temperature and humidity in the presence of six different taxa with various canopy characteristics were documented from the 23rd of May −6th of September 2023 on randomly selected days (both sunny and cloudy).

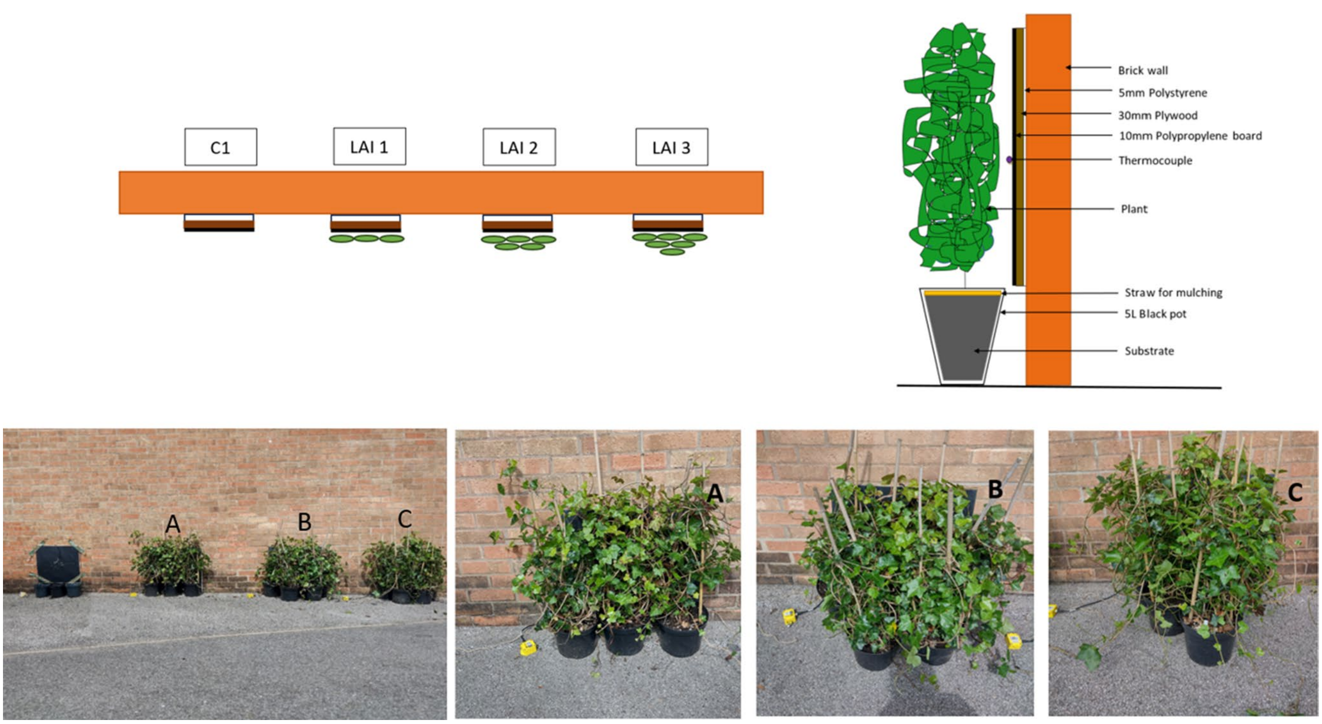

Fig. 1 Top view diagram (Top left) shows plant positioning in front of wall panels (Plants are green with different canopy coverage in front of the wall panels i.e. LAI1, LAI2, and LAI3 and a non-planted control – C1). The wall is depicted in brown, and the insulated panels are black. Side view (Top right) of individual panel setup of LAI1 with plant spacing (Kunasingam et al. 2024). The bottom image shows the experimental setup (with *Hedera hibernica* in this case) in a wide range (left) and a close-up of planting arrangements of three different canopy width levels A- LAI1, B-LAI2, and C- LAI3 (right). Note a white vinyl cloth used to stop thermal gain in the black pots has been removed to show the position of the plants

Data handling and statistics

In each experimental setup, the wall panel surface temperature and humidity were recorded every 30 s for 3 h. Data for each taxon was collected over a minimum of 12 different days. To avoid the temporal variation in solar intensity, the differential temperature (control panel value - plant shaded panel value) was used instead of the absolute value (Tan et al. 2018; Kunasingam et al. 2024). A mean value of panel temperature and relative humidity was estimated every 5 min. The temperature difference between the control wall panel and plant-shaded wall panels was represented as wall cooling capacity per taxon for certain canopy layer treatments (1 Layer vs. 2 Layers vs. 3 Layers). To demonstrate the influence of canopy width on the cooling of taxa in warm and hot ambient temperatures, the mean cooling capacity of each taxon with various canopy widths was calculated for the control panel temperature of 25 +/−5 °C and 45 +/−5 °C and the wall cooling of different taxa affected by their WLAI was presented. Similarly, differences in relative humidity between the control wall panel and the presence of plants were analysed. A one-way analysis of variance (ANOVA) was used to determine the significant differences in the cooling potential of various canopy widths within taxon and between taxa, and post-hoc Bonferroni tests (SPSS statistical package) were used to differentiate the canopy width that cools significantly better than others; different letter in figures denoting statistical differences between means (Kunasingam et al. 2024).

Results

Canopy coverage percentage

The number of leaves corresponded to the different levels of canopy coverage within the taxon; meanwhile, the difference in average leaf area combined with the number of leaves (WLAI) determined the coverage percentage between taxa. Leaves of *Hebe* were relatively small (4.79×10^{-4} m^2) and thinly-dispersed through the stem, thus unable to cover the wall at least by 1 layer (WLAI < 1). In contrast, *Alchemilla* and *Heuchera* had larger fan-shaped leaves (116.83×10^{-4} m^2 and 86×10^{-4} m^2, respectively) that could cover the entirety of the wall panel in layers. The *Carex* with relaxed up-right, V-shaped foliage corresponded with WLAI (3.3–6.7) (Table 2). For the 1 st layer the WLAI was smallest for *Hebe* (0.9) and greatest for *Carex* (3.3). When 3 layers were compared, the smallest value was still with *Hebe* (2.2) and the greatest with *Carex* (6.7). The ratio of WLAI between 3 different layers of each taxon in *Hebe*, *Heuchera*, and *Hydrangea* was 1:1.5:2.5, whereas *Carex*, *Alchemilla*, and *Hedera* were approximately 1:1.6:2 (Table 2).

Table 2 Physical parameters of different plant species

	Canopy Layer	Mean No. leaves	Average leaf Area (x 10^{-4} m^2)	WLAI	Leaf coverage within taxon
Hebe cv. Mrs Winder	1st	1806	4.79	0.9	x
	2nd	2709	4.79	1.3	1.3x
	3rd	4515	4.79	2.2	2.4x
Carex buchananii cv. Red Rooster	1st	3327	10.00	3.3	y
	2nd	5545	10.00	5.5	1.7y
	3rd	6654	10.00	6.7	2y
Hedera hibernica	1st	614	33.51	2.0	z
	2nd	1023	33.51	3.4	1.6z
	3rd	1227	33.51	4.1	2z
Heuchera micrantha cv. Palace Purple	1st	128	86.00	1.1	q
	2nd	192	86.00	1.7	1.5q
	3rd	321	86.00	2.8	2.5q
Hydrangea macropylla	1st	296	65.00	1.9	r
	2nd	445	65.00	2.9	1.5r
	3rd	742	65.00	4.8	2.5r
Alchemilla mollis	1st	91	116.83	1.1	s
	2nd	152	116.83	1.8	1.6s
	3rd	243	116.83	2.8	1.9s

Relationship of wall cooling with LAI

Applying a wider canopy (three layers of vegetation) significantly increased the cooling capacity of the plants ($P < 0.05$, when comparing the three-layer canopy against the one-layer canopy). This was true of all taxa when the bare wall panel was ≈25 °C (Fig. 2) and ≈45 °C (Fig. 3). Cooling capacity was greater at the higher ambient temperatures (i.e. 45 °C, Fig. 3). Here the presence of the plants cooled the wall panel by between 12 and 24 °C (Fig. 3), whereas only 2 to 6 °C cooling was noted at 25 °C ambient conditions (Fig. 2). The most effective wall cooling was observed with *Heuchera* (three layers), *Alchemilla* (three layers), *Heuchera* (one layer), and *Carex* (three layers) (Fig. 3).

Differences in cooling capacity due to canopy width were often noticed when the temperature of the bare wall panel was approximately 24 °C (Fig. 4). As the bare wall panel temperatures increased (i.e. ambient conditions became warmer) the cooling advantages of a wider canopy became more evident (Fig. 4). The relative benefits though could vary with taxa; e.g. 6–7 °C additional cooling in *Hedera* (Fig. 4C), 5 °C in *Carex* (Fig. 4B), and 4 °C in *Alchemilla* (Fig. 4F), compared to only 2 °C in *Hydrangea* (Fig. 4E). *Alchemilla* and *Heuchera* were particularly effective taxa for wall cooling, with even a single layer of plant canopy

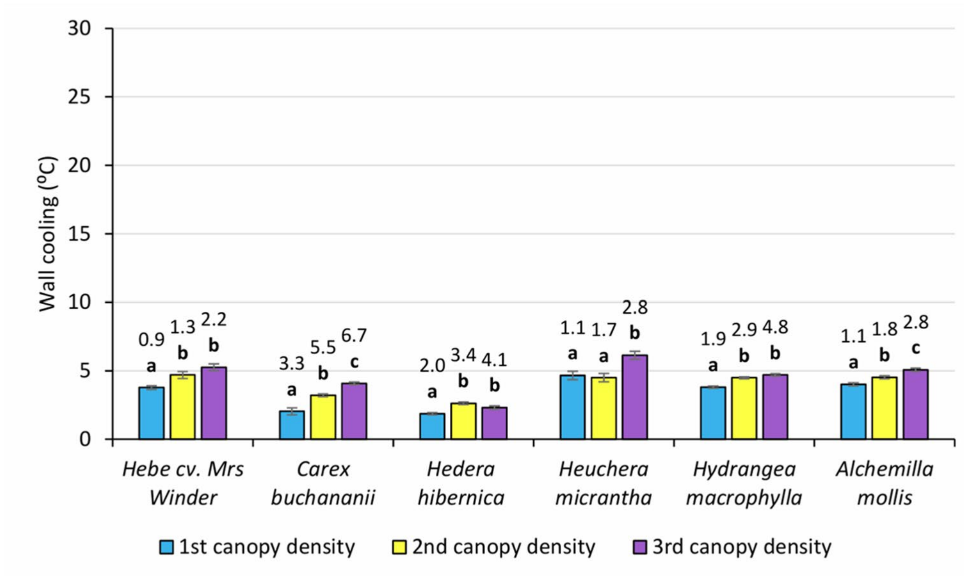

Fig. 2 Mean wall panel cooling (ºC) by different taxa when the control wall panel temperature is 25 °C. Numbers above the bars are WLAI and lines on the bars denote +/- standard errors. Different letters note the significant difference between the mean values of a taxon

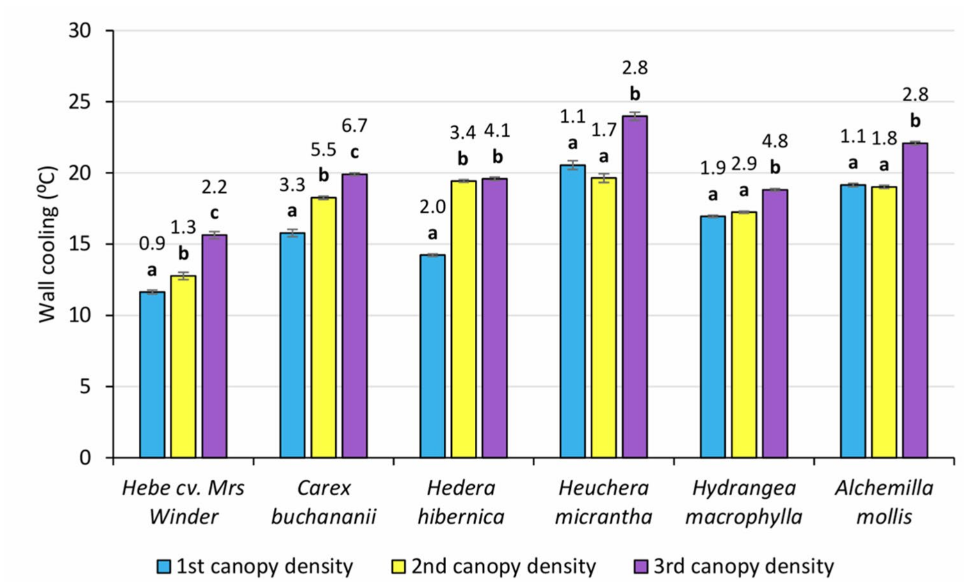

Fig. 3 Mean wall panel cooling (ºC) by different taxa when the control wall panel temperature is 45 °C. Numbers above the bars are WLAI and lines on the bars denote +/- standard errors. Different letters note the significant difference between the mean values of a taxon

keeping the wall at about 25 °C when the bare wall panel had a comparable temperature of 48 °C (Fig. 4F and D).

Although cooling potential increased with the width of the canopy – the change of cooling was not proportional to the number of leaves present. A doubling of the leaf number in front of the wall did not increase the wall cooling by twice as much (e.g. See *Alchemilla* data in Fig. 3, a LAI of 2.8 due to three layers only cooled the wall panel by 22.5 °C compared to 19 °C cooling with a LAI of 1.1 – single canopy layer). When the LAI value is approximately 2, the wall cooling of *Alchemilla*, *Hydrangea*, *Hebe*, and *Hedera* varied significantly, with respective cooling values of 22.5 °C, 16.9 °C, 15.6 °C, and 14.2 °C. However, when the LAI was doubled to 4, additional cooling effects differed between taxa, with *Hedera* and *Hydrangea* showing increases of 5.3 °C and 1.8 °C, respectively. Interestingly, a single layer of dark purple-leaved *Heuchera* (WLAI 1.1) was more effective at cooling the wall compared to the three canopy layers of *Hedera* (WLAI 4.1), *Hydrangea* (WLAI 4.8) or *Hebe* (WLAI 2.2) (Fig. 3). Overall, correlating wall panel cooling to WLAI across all taxa at the higher temperature (45 °C) showed little relationship (only 10.2% of the variance was accounted for by the WLAI – Fig. 5).

The fact that a single layer of canopy was effective in *Heuchera* and to some extent *Alchemilla* is supported by cooling data for a set unit of leaf area (Figs. 6 and 7). Cooling per unit of leaf area was very effective in the single canopies of *Heuchera* and *Alchemilla* (> 18 °C, when the bare wall panel was experiencing 45 °C). Significantly more so

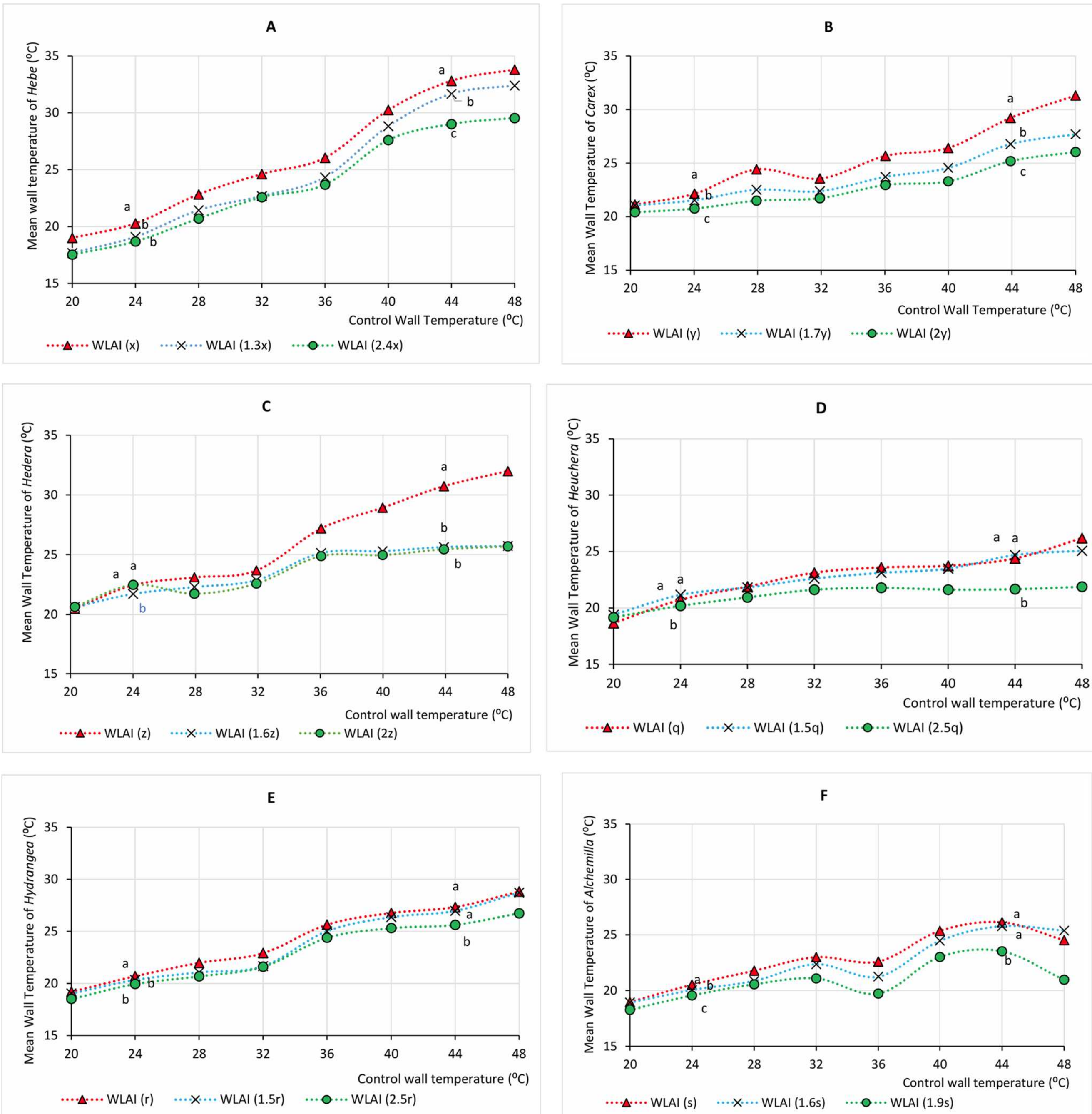

Fig. 4 Comparison of wall panel temperature (ºC) between levels of canopy coverage in various taxon – *Hebe* (**A**), *Carex* (**B**), *Hedera* (**C**), *Heuchera* (**D**), *Hydrangea* (**E**), and *Alchemilla* (**F**). Different letters denote significant differences in the trend line at control temperatures of 24 and 44 °C

than in the two-layer and three-layer conditions (between 8 and 12 °C) (Fig. 5).

Changes of relative humidity with canopy width

Mean relative humidity on the control panel is comparatively greater on moderately warmer days (≈48%) than on hot days (≈26%). Despite this difference, relative humidity increased with the presence of plants; 5–20% when the control wall panel temperature is 25 °C (Fig. 8) and 18–52% when the control wall panel temperature is 45 °C (Fig. 9). Even though adding more layers often shows a significant rise in relative humidity (especially on hot days), the additional accomplishment is 2–8% only. Relative humidity reached by *Heuchera* and *Alchemilla* (first layer) is on par with the third layer of other taxa indication that more vapour

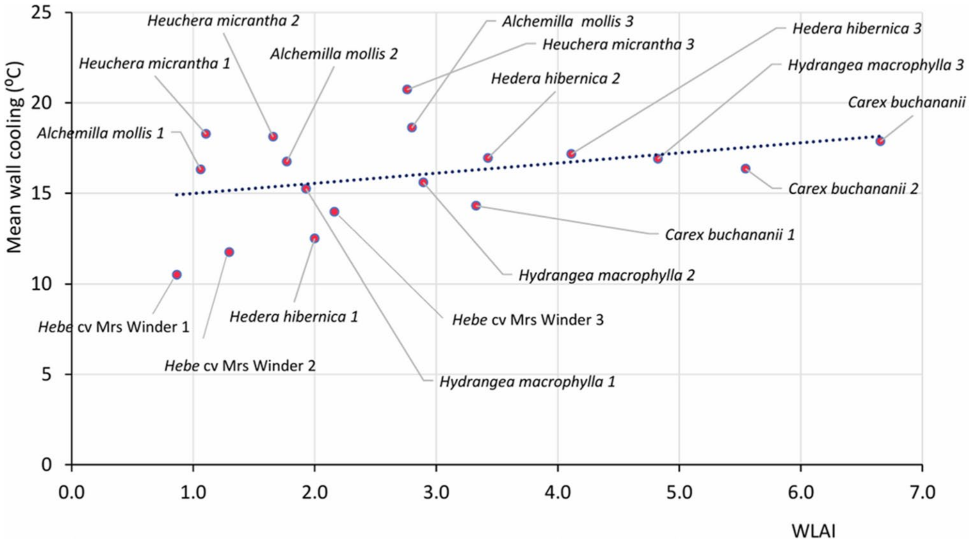

Fig. 5 The relationship between WLAI and wall panel cooling (mean of all temperatures (ºC)). Correlations explained 10% ($r^2=0.10$) of the variance

may be coming off a single layer of these plants than multiple layers of other taxa.

Discussion

The value of additional canopy layers

Increasing the width of the foliage in front of a wall increases the cooling capacity, but not always to a significant extent for each taxon. For taxa with good cooling capacity associated with a single layer (*Heuchera*, *Alchemilla* and *Hydrangea*), providing a second additional layer did not significantly increase wall panel cooling at the higher temperature scenarios (Fig. 3). Adding a third layer, however, did enhance cooling significantly in these taxa, giving an extra 2–3 °C of cooling. In contrast, taxa with the lower cooling capacity when provided as a single layer, did enhance their cooling when additional layers were provided, by as much as 6 °C in the case of *Hedera*. Thus, the value of adding additional layers to a green wall or façade may strongly depend on the plant taxa that are being used. In this study, increasing canopy width is justified for *Hebe*, *Carex* and *Hedera*, but perhaps less so for *Heuchera*, *Alchemilla* and *Hydrangea.*

When the amount of leaf in front of the panel is considered, i.e. the WLAI, there was a poor correlation with cooling, at least when data is pooled across all taxa. Thus, leaf mass per se is not necessarily always determining the cooling. A single layer of *Heuchera* leaves (WLAI = 1.1) was more effective at cooling a wall panel (by 20 °C under the warm scenario) than three layers in *Carex* (WLAI = 6.7), *Hydrangea* (WLAI = 4.8), *Hedera* (WLAI = 4.1) or *Hebe* (WLAI = 2.2). Evidently, *Heuchera*, and to a lesser extent, *Alchemilla* provide useful cooling, without the need to maximise leaf biomass in front of the wall. These two taxa were associated with high cooling per unit of leaf area (Fig. 7) and higher relative humidity values (Fig. 9), suggesting a proportion of the cooling may be attributable to evapotranspiration. Thus, for these taxa, thin layers of high transpiring leaves (with good air circulation around each) are effective at providing much of the cooling, and although additional layers may help provide further cooling via shading, they may not enhance evapotranspiration further due to interference with the irradiance and air movement that the first layer of leaves experience. (In essence, more shade on the first layer of leaves and higher humidity around them, may reduce the evapotranspiration rate e.g. Niklas et al. 2023). Such plants could be termed "evapotranspirational coolers".

For the three other taxa, it is less clear as to whether additional cooling associated with more layers is simply due to more shading (Cameron et al. 2014; Freewan et al. 2022), or potentially more evapotranspiration as well (Cameron et al. 2014; Rahman et al. 2023). The steady increase in relative humidity as more layers are added could relate to more evapotranspiration, but also less air movement as more layers result in trapping more moisture in and around the canopies. When data is analysed for a single layer canopy alone, *Hebe*, *Carex* and *Hedera* have lower RH than the other taxa (Fig. 9), tending to suggest they are nominally "shade coolers".

Overall, the data does not fully support our first two hypotheses. There was no strong evidence that when the wall was shielded with a single layer of plants that the smaller-leaved *Hebe* and *Hedera* outperformed larger-leaved taxa. Although, increasing the width of the canopy, generally did improve cooling, it was not always proportionate and when a second layer was applied under the 45 °C scenario,

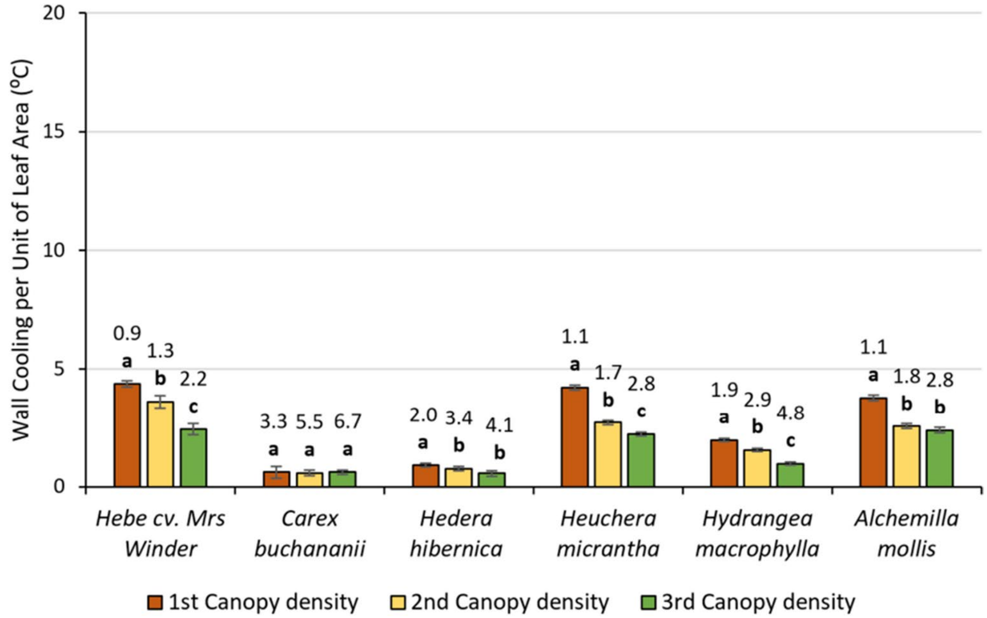

Fig. 6 Mean wall panel cooling per WLAI (ºC) when the control wall panel temperature is 25 °C. Numbers above the bars are WLAI and lines on the bars denote +/- standard errors. Different letters note the significant difference between the mean values of a taxon

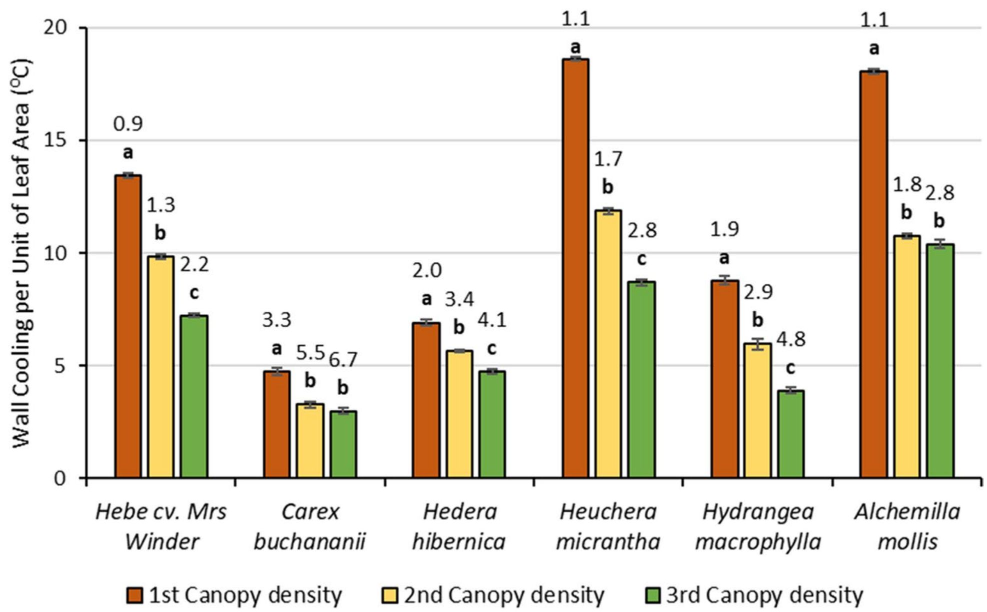

Fig. 7 Mean wall panel cooling potential per WLAI (ºC) when the control temperature is 45 °C. Numbers above the bars are WLAI and lines on the bars denote +/- standard errors. Different letters note the significant difference between the mean values of a taxon

it was only significantly notable for some taxa (i.e. *Hebe*, *Carex and Hedera* – Fig. 3). For the third hypothesis – 'the benefits of wider canopies would be greater at higher ambient temperatures' this was only true in absolute terms (the temperature differences between the different widths were greater at 44–45 °C compared to 24–25 °C; Figs. 2–4), as it was also clearly evident that increasing canopy width provided significant additional cooling at the lower ambient temperatures (e.g. 24–25 °C). Defining cooling capacity by leaf morphology may be an over- simplification (Díaz, et al., 2016), but it was notable that the two taxa that cooled most effectively as a single layer (*Heuchera* and *Alchemilla*) possessed round/ovate relatively thin leaves.

Consistency with previous results

The most effective taxon for keeping walls cool was the dark purple-leaved *Heuchera.* Three layers of this taxon kept the wall 24 °C cooler than the bare control panel when ambient temperatures were highest. Even a single canopy layer of this genotype cooled the wall by a margin of 20 °C on the warmest days. This result is supported by previous research suggesting *Heuchera* has good localised cooling properties (Gräf, et al., 2021; Monteiro et al. 2017; Cascone et al. 2019). The data for both *Heuchera* and *Alchemilla* were very similar to previous studies conducted using this experimental system (Kunasingam

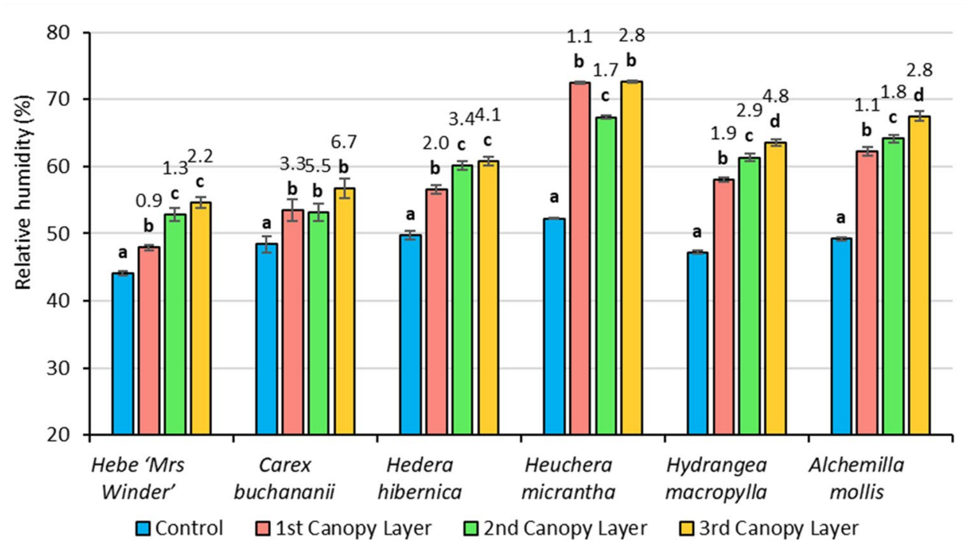

Fig. 8 Mean relative humidity (%) by different taxa when the control panel temperature is 25 °C. Different letters note the significant difference between the mean values of a taxon. Numbers are related to LAI. Note the statistical comparisons are conducted between the differences of LAI within the taxon

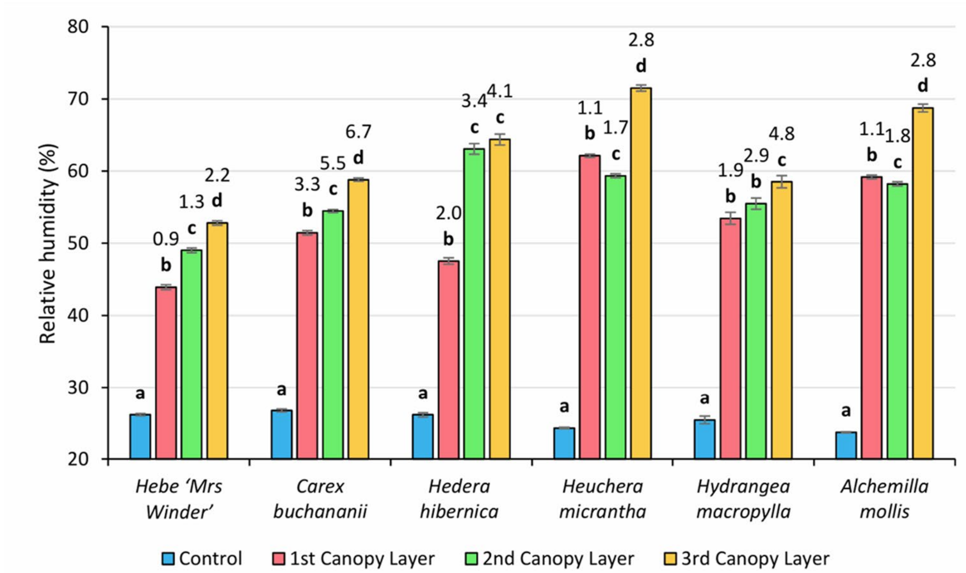

Fig. 9 Mean relative humidity (%) by different taxa when control panel temperature is 45 °C. Different letters note the significant difference between the mean values of a taxon. Numbers are related to LAI. Note the statistical comparisons are conducted between differences of LAI within the taxon

et al. 2024). At a 45 °C mean bare wall panel temperature, a single canopy layer of *Heuchera* foliage cooled the wall panel to 20.2 °C in this study, and by 18.5 °C in the previous year (Kunasingam et al. 2024). Similarly, a single canopy layer of *Alchemilla* provided 19.0 °C cooling here and 19.0 °C previously. Results for *Hedera* were relatively consistent too between the two years. In contrast, though, there was a marked reduction in the cooling potential of *Hebe* (11 °C cooling compared to 20 °C cooling in our previous study). This, however, may relate to not being able to compare 'like for like' plants for this taxon. The plants in this study were smaller than in the previous one and had only a 0.9 WLAI compared to the previous 3.99 WLAI. The genotypes of *Hydrangea* were different between the two years, but interestingly, the cooling profiles were similar.

The reliance on evapotranspiration (e.g. especially in taxa such as *Heuchera* and *Alchemilla*) somewhat contrasts to our previous result with the same system (Kunasingam et al. 2024), where most cooling seemed to be attributed to shade effects. In this earlier study, the area of leaves in front of the wall could account for up to 50–66% of the variance encountered at warmer ambient temperatures (when bare wall panels were approximately 45–55 °C). In the data presented here though, the overall relationship seems less dependent on the leaf mass present and its shading effect (Fig. 5).

The contrast in the two years' data may relate to different weather patterns on key recording days. Evapotranspiration tends to be promoted in plants when there is high solar irradiance, but also light winds (sometimes referred to colloquially by farmers and growers as "ideal growing" conditions), and root systems have a consistent supply of water. It is possible that in

Table 3 Differences in humidity were recorded on bare (control) walls and that recorded behind a single canopy of plants. Data comparison between a previous study (2022 – Kunasingam et al. 2024) and this data (2023)

	Overall mean difference in humidity (%)		Mean difference in humidity when control wall T≈40 °C (%)	
	2022	2023	2022	2023
Heuchera	13.7	21.8	16.7	26.9
Carex	13.5	15.9	11.1	16.5
Alchemilla	14.8	21.0	18.1	30.7
Hedera	14.0	18.6	14.0	23.8

this study, more of the warm days coincided with light winds and ideal evapotranspirational conditions (Schymanski and Or 2015); in contrast to the previous year (Kunasingam et al. 2024), where an absence of 'light wind days' resulted in most cooling being attributable to shading. The greater differentials in humidity in the later study (Table 3) lends support to theory that plants were releasing more water and using evapotranspirative cooling more effectively in the second year/later study. Such year-on-year variations again indicate that landscape managers need to use a *range* of plant taxa (covering a spectrum of different ratios of shade and evapotranspirational cooling) to ensure that some cooling is induced irrespective of the prevalent warm weather conditions encountered.

Plants as effective cooling agents

Overall, the results here re-confirm that wall shrubs, climbers, and plants within a modular green wall system provide remarkable cooling to a building façade. This cooling potential increases as ambient temperatures (and the temperature of building walls) increase. The reasons could be high evapotranspiration rates due to the temperature gradient between the plant surface and the surrounding environment (Tan et al. 2015; Pan et al. 2020) and the low solar transmissivity of the canopy promoting very effective shading (Jim 2015b; Coma et al. 2017). Data here confirms our previous study, in that when bare wall façades reach 45–55 °C in the UK, a screening of vegetation brings these temperatures down to approximately 20–30 °C – a radical reduction in the thermal load on a building. Our data again suggests that plant taxonomic choice matters when optimising the cooling potential, agreeing with our (Cameron et al. 2014) and others (Perini et al. 2016) previous work.

Limitations of the study

The data was collected over a brief period (summer and early autumn) of a single year, therefore, the changes of LAI in different taxa throughout the year were not documented. Further studies may be warranted to cover warm spells in spring, perhaps before a full canopy has developed on deciduous plants. We also only measuring cooling capacity around the middle of the day, but plant evapotranspiration characteristics can vary with time of day (and indeed with solar irradiance levels e.g. Tang et al. 2024) and more information is required on how evapotranspirational behaviour influences the cooling capacity at other times of day; a point that may be especially important as human thermal comfort tends to decrease during the evening (Beckmann et al. 2021). Wall panel temperature was recorded at the centre of the panel, assuming leaves of all taxa were homogeneously distributed. Even though an attempt was made to cover the wall panel uniformly, certain traits of some taxa (e.g. larger leaves at the base of the plant and smaller leaves near the apex) may have some influence on the panel thermocouple. Thus, recording the wall panel temperature at several parts of the panel in future may reduce any potential errors here.

As in Kunasingam et al. (2024) we also acknowledge that black walls are not particularly typical on buildings, and that care is needed when comparing the empirical thermal data here to that in other studies (where lighter coloured walls have a greater albedo). Our surface temperature may have been proportionally higher than other studies. Despite this our strong focus on temperature *differences* between our treatments (not absolute temperatures) is effective at helping understand taxonomic and design differences. We also acknowledge that three layers of pot plants placed in front of wall, represents what we feel is an excellent, simple, elegant experimental systems it is not a traditional, nor a typical commercial green wall system. Our (small) system may have been influenced to a greater extend by edge effects (e.g. greater movement or influence from the wind) and the thermal properties of surrounding features than would occur on a commercial green wall. We may have experienced more extremes of temperature with our wall panels being influenced by the warm microclimate of the brick wall/nearby tarmac, but also more air movement/cooling than that found with a larger, more uniformly vegetated green wall. Further research is required to verify how the principles studied here, play out in real green walls *in situ*.

Stomatal conductance can widely vary even within one plant, depending on the leaf's solar exposure, internal characteristics, and placement. Due to the practical difficulties of testing the stomatal conductance and solar transmittance in several places simultaneously, evapotranspirative cooling in this study was indicated by the RH value recorded between the canopy and the wall panel, rather than direct measurements of transpiration. Despite strong correlations between evapotranspiration and relative humidity in previous studies (Mohan and Arumugam 1996; Chatzithomas & Alexandris, 2015), further research on specific taxa in this context may warrant more focus on stomatal behaviour.

Conclusion

The data presented highlights the importance of plant taxonomic choice in green wall systems and the need for understanding the relative cooling mechanisms. It challenges the notion that simply increasing the leaf mass of the wall plant is always appropriate to maximise cooling, especially when this corresponds to the need for more plants and more financial outlays. Although statistically-significant cooling and humidity can be achieved by providing wider/denser foliage, increments are not linear with greater leaf area; and cooling capacity is still largely determined by taxa. However, additional layers of foliage are helpful for those taxa that cool primarily by shading. Intensifying the canopy layer is likely to block more radiation and increase shade (Convertino et al. 2022; Pérez 2022; Kunasingam et al. 2024), but it has minimal impact on evapotranspirative cooling. More research is required to identify which taxa are primarily 'shade coolers' and which are 'evapotranspirational (ET) coolers', and how ancillary factors such as location, latitude, temporal effects and weather alter their cooling capacities. Early data suggests those taxa with numerous thick leaves may help with shade and medium-sized, thin leaves may be linked to greater evapotranspiration, but linking these traits in general terms to cooling needs verification over a greater range of taxa. Nevertheless, the data presented here is important, as it starts to identify which taxa fall into the 'super-coolers' category, and why. Such taxa can be prioritised by landscape architects to optimise urban environmental cooling, an important consideration as the climate continues to warm. This builds on our cataloguing of landscape plants for the sector that are identified as 'Functional Ornamental Plants' (FOPS) (Cameron & Blanuša, 2016; Nur Hannah Ismail et al. 2023) or the Royal Horticultural Society's 'Plants for Purpose' (PFPs) (Griffiths & Blanusa pers. comm.).

Overall, the data shows again the huge impact plant canopies can have in cooling walls and buildings (24 °C of cooling), even in temperate zones. In light of this, policy makers and designers should, arguably, be using green infrastructure much more effectively to provide passive cooling mechanisms to buildings.

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Data availability Data Availability Statement: A summary of the results will be placed within the University of Sheffield PhD data repository.

Declarations

Competing interests The authors declare no competing interests.

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