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How does plant taxonomic choice affect building wall panel cooling?

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A B S T R A C T

Vegetation is increasingly being valued for its contribution to urban cooling, with implications for mitigation of urban heat islands, building energy efficiency and human thermal comfort. Relatively little information exists, however, as to how plant taxonomic choice affects micro-climate cooling. This research used a building wall scenario to determine how plant type affected material cooling during summer in a temperate climate (UK). Thermocouples recorded wall panel temperatures behind 24 different plant taxa compared against a control panel unshielded by plants. When the control wall panel temperatures were 25 °C, 35 °C, 45 °C and 55 °C, the maximum cooling observed on panels screened by vegetation was 5.1 °C, 13.5 °C, 20.1 °C and 25.7 °C respectively. For each of these temperature scenarios, maximum cooling was attributed to *Hebe*, *Lonicera, Hebe* and *Hedera*, respectively, i.e. the optimum taxa choice could vary with the ambient conditions being experienced. Data was assessed, subsequently to determine if cooling potential could be associated to a certain plant attribute. Cooling was maximised by increasing the overall leaf surface area between the wall panels and the incoming solar irradiance, i.e. larger plants with dense canopies promoted cooling, but otherwise there was no overall consistent pattern linking cooling to key plant traits, such as leaf colour. The research confirms that plants are effective thermal regulators within the urban environment, but further wider evaluations of taxa are required before the landscape sector has a definitive list of optimum genotypes that it can recommend.

1. Introduction

Vegetation is a key component in mitigating the effects of urban heat islands [1–4] and can reduce the thermal load (heat gain) on an individual building [5–7]. Factors that are going to be exacerbated by a changing climate [8]. In warm climates, such as the southern/central USA, the value of the urban forest to provide protection against excessive heat, and reduce building energy costs have been acknowledged for a couple of decades [9,10]. Even in temperate regions, highly vegetated rural areas can be 1 to 6 °C cooler on average (air temperature) than their urban counterparts [11,12], with land surface temperatures as much as 12 °C cooler [13]. The capacity of plants to provide localised cooling can be exploited in urban design to reduce the heat loads on buildings, both through the action of plants to provide shade [14,15] and to keep air temperatures cooler through evapotranspiration of water through their foliage [16,17]. Trees, especially large canopy ones can cool entire buildings by as much as 9 °C [5]. There is not always space for large trees within densely-built urban spaces, however, and landscape architects have looked to smaller-scale plant interventions to provide localised cooling on- (green walls, green façades, green roofs) and around- (pocket parks, rain gardens, shrub plantings) buildings [16,18–22].

Such approaches can provide effective cooling, both to the surface materials of the building and the air that surrounds it. Green roofs, for example, can contribute to 30 °C reduction in median roof surface temperature in hot-humid cities and 28 °C in temperate climate cities [23]. Cooling via green roofs is promoted by high levels of moisture within the substrate and deeper substrates [24,25]. Green wall and green façade plants are considered to cool the exterior building walls by 8–15.5 °C [6,19,26,27] with shade often being cited as the main cooling factor [6,28–31]. Cameron et al. [16] however, suggested that evaporative cooling could be a significant cooling factor too for green façade plants. Combining different plant taxa can optimise the cooling effect. Walls covered by combination of 6 different plants in China exhibited a maximum of 20.8 °C surface temperature reduction [2]. The air layer trapped in between wall and vegetation was 3.1 °C cooler than the ambient air. Linked to wall cooling, plants can also affect other types of vertical façades. Windows shaded by climbing or hanging plants can

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benefit from a passive cooling effect [32–34]; with effects such as lowering the surface temperature of the glass (by up to 1.1 °C [35]) and reducing average indoor air temperature (by 2.6 °C when windows closed [36]) and (by 3.9 °C when left open; [15,37]). Cooling differences due to the contribution of shading and transpiration depends on aspects such as number of leaf layers present [38], water status [6,17] and weather conditions [39].

Climbing plants (vines) used to cool building walls include taxa such as *Hedera*, *Parthenocissus, Clematis, Jasminum, Rosa, Lonicera, Bougainvillea, Hydrangea, Solanum* and *Passiflora* [16,20]. Self-supporting 'wall' shrubs can also be used on single storey buildings or encorporated into green (living) walls systems; where they are grown in a containerised compartment (e.g. *Euonymous, Ceanothus, Fuchsia, Prunus, Cotoneaster, Hypericum* etc. [16]). Other smaller shrubs, hebaceous plants, grasses, ferns and epiphytes are often used in green wall systems too [40–42]. Plant taxa can affect the cooling potential [38,43], based on factors such as overall size, leaf area index, canopy density, evapotranspiration rates, foliage colour, and other leaf traits such as thickness or hairiness (hirsute character). In previous studies, plants with relative large leaf area indices (e.g. *Heuchera, Salvia* and *Stachys)* were more successful than those with smaller values [21,44,45]. Tall plants with dense foliage like *Codiaeum*, often prove effective compared to small or less dense plants [21,46]. Plants layered with dense foliage (high LAI) and with leaves parallel to the wall (leaf inclination angle) were deemed more successful than others in reducing façade surface temperatures and heat flux through façades [47]. Cameron et al. [16] found species such as *Fuchsia* cooled a wall primarily by evapotranspiration, whereas others - *Jasminum* spp. and *Lonicera* spp. contributed more via shade cooling. In such plants, the cooling performance can be significantly affected by the volume and frequency of irrigation [17,35,48].

Few studies, however, have systematically compared numerous taxa within one study to help determine if these traits that promote cooling are universal (i.e. work across species with similar leaf types or ecological background), or whether they are genotype specific. That is the purpose of this study where a range of contrasting plant types were selected for comparison under similar conditions. Moreover, we wished to determine how the capacity to cool a hard building surface, such as a wall panel, might change as the climatic conditions themselves change. For example, did some taxa lose their relative capacity to cool a building surface, as ambient temperatures increased. Thus, the objective of this study was to determine which species were most effective at keeping a building surface (in this case a wall panel) cool throughout a range of ambient temperatures. In effect was there a ranking between taxa and did that stay consistent across different temperature scenarios? Additionally, as alluded to above, data was assessed to determine if cooling was optimised by certain key plant traits (e.g. leaf type or colour). Finally, the research aimed to determine any links between panel surface cooling potential and the temperature of the leaves themselves across the different plant types.

2. Materials and methods

2.1. Experimental design

The experiment was implemented in one location – a single brick wall, with a South-South East aspect, at Goodwin Sports Centre, University of Sheffield, Sheffield, UK. Four, single black panels (10 mm black polypropylene board) with the dimension of 1 m × 1 m, were placed on the wall, but insulated from it via 5 mm polystyrene insulation board at the back, with a 30 mm plywood layer sandwiched between the panel and the polystyrene. This avoided heat being transferred from the wall to the panel itself, and thus reduced error from heat migration from one part of the wall to another. Thus, each black panel was in effect, an independent experimental unit, divorced from the influence of thermal gradients across the brickwork, whilst still experiencing the atmospheric microclimate typical of a real wall and building. The panels were set 300 mm above ground level.

The main reason for using insulated panels (rather than the brickwork *per se*) was to avoid 'contamination' of energy moving across the wall from one location to the other, but there were additional reasons too, why dark polypropylene panels were chosen. These were: the smooth panel surface interacted with solar irradiance more uniformly than a pitted brick surface (where light refraction and deflection can occur), smooth surfaces allowed the thermocouples to be in contact with the panel along the entire length of the thermocouple metal sheath, surface black panels retained their hue more effectively than white or light colours, where accumulated dirt and algae growth affect light interception and absorption to a greater extent over time. Whilst it is acknowledged that black panels absorb and retain more heat than other colours, this was intentional in the cool, maritime climate of the UK, where one of the research objectives was to determine a plant's capacity to cool at the higher end of the natural temperature spectrum, as well as at intermediate and lower temperatures.

During experimentation, at any one point, three of the panels were screened from direct sunlight with plant foliage, and the fourth panel was used as a control (bare panel). Surface temperature of each panel was recorded via a thermocouple probe attached to a data logger (Tinytag -TGP-4505; range = −25 °C to 85 °C and 0–100 % relative humidity; with a temperature accuracy of 0.35 °C, Gemini Data Loggers, Chichester, UK). The probe itself was secured to the black panel by adhering the adjacent wire to the panel with narrow transparent tape; leaving the probe open to the air, but consistently touching the panel on one side (following methods used by Ref. [49]). The system allowed 3 plant taxa to be placed in front of individual wall panels at any one time, and the temperature of the panels to be compared with a bare uncovered control panel. In this way the cooling capacity of plants on a nearby vertical surface could be assessed, using the control panel as a reference point. Plant taxa were compared for their capacity to cool the panels, by placing 3 individual potted specimens of one taxa in front of the wall (the middle plant was 110 mm directly in front of the black panel, (Fig. 1). Different plant taxa were placed randomly in front of one of three panels, and left there for 3 h each day, during which time, panel surface temperatures and humidities were recorded every 30 s. Three taxa could be evaluated at any one time, and taxa were rotated by repeated placement and removal of plants between each recording period; thus, allowing the cooling effect of individual taxa to be assessed across different time periods and weather conditions. The fourth 'control' panel, had 3 non-planted pots placed in front of it – but used the same (pre-wetted) growing-medium. The position of the control panel was also randomly altered between recording sessions. All pots (planted and control) were covered with white vinyl sheeting during the experiment to minimize solar radiation absorption by the black pots (and hence extra localised heating and alterations to root hydraulic conductance). In addition, the top of the growing media was covered in straw (10 mm thick)– again to reflect light and reduce heating of the substrate itself.

Plant leaf temperatures were measured using a non-contact thermography technique with an Infra-Red Thermal camera (Flir T460) with high resolution imaging (320X240 pixel and ± 1 % accuracy). However, thermal readings can vary considerably within the same image, as factors such as leaf position in the canopy, angle of leaves towards solar radiation, and leaf thermal traits can all affect the amount of radiation absorbed by a specific leaf. This leads to variations in energy absorption among leaves of the same plant [50]. To account for this variation, measurements were taken from 24 different leaves from various parts of each species, standardising where possible for location, relative leaf size and incidental angle to the camera. Canopy temperature was derived from the mean leaf temperature at any one time. In addition to all 24 taxa being recorded for their leaf temperature at *ad hoc* periods throughout the summer, a subgrouping of nine taxa were more systematically assessed, with greater replication, for leaf temperature between May 2021 and October 2021. This sub-group being chosen for

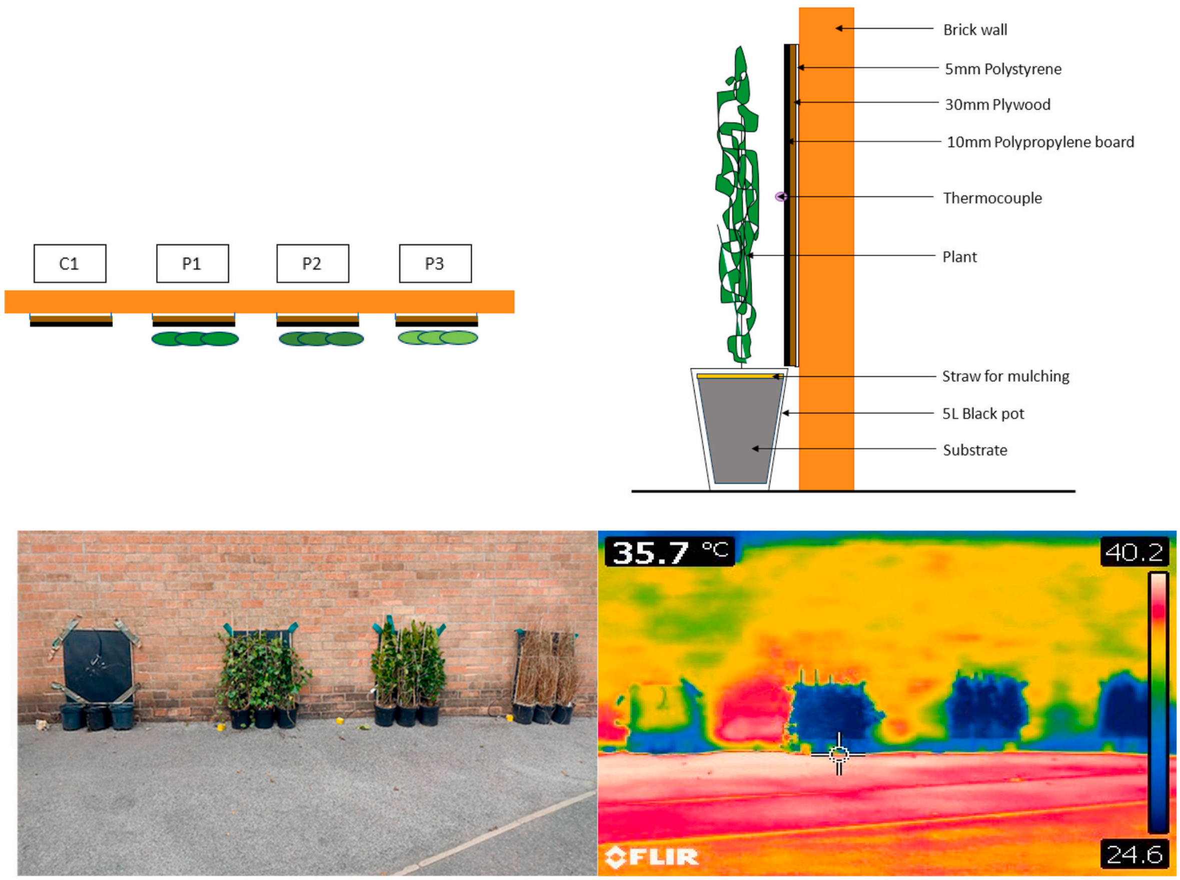

Fig. 1. Top view (left) of plant positioning with respect to wall panels (plants are green - with plant taxa P1, P2 and P3 and non-planted control – C1). The wall is brown, and the insulated panels are black. Side view (right) shows plant spacing with respect to the wall, the position of the thermocouple, and the different sections of the insulation panel (10 mm black polypropylene board in front of 30 mm plywood and this in front of 5 mm polystyrene insulation board). Photograph (bottom left) of experimental set up and wide range thermal image (bottom right). Note the white vinyl cloth has been removed to help show the position of the pots. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

contrasting leaf types, i.e. large 'silver-white' leaves – *Senecio*, small grey-green leaves – *Nepeta, Cistus, Dianthus,* medium-sized hirsute 'silver-grey' leaves – *Stachys*, glaucous/lustrous dark-green leaves – *Griselinia, Camellia,* soft dark-green leaves – *Hydrangea petiolaris* and succulent green-purple leaves – *Hebe* cv. Mrs Winder.

Ambient air temperature, wind speed and precipitation were recorded throughout the experimental period, using the Weston Park Weather Station (Sheffield City Council; within 300 m of the experimental site). Data from the experimental wall was collated with that of the Weather station on an hourly basis.

Leaf area per plant was calculated by taking photographs of individual specimens at 90° to the side of the plant and level with it (i.e. to determine the area of leaves that were directly in front of the wall). Photographs were converted to pixels on a computer [51,52] and the area of leaves calculated as a percentage of the wall area behind it (correlated with a ruler to allow conversion to an area measured in m^2). This 'side-view' leaf area index was then used to assess the proportion of the wall, and the proportion of the panel that was shielded by the plant. Temperature data being divided by the leaf area to give a cooling ratio per unit of leaf area in front of the wall. This ratio being used to compare taxa with a standardised leaf area, and thus less affected by the size and total leaf number of individual plants.

2.2. Plant material handling

All plant taxa were grown in 5 L pots and were approximately 2 years old, but there were natural differences in leaf canopy dimensions across the taxa. As wall plants are often trimmed in practice to keep the canopy close to a wall, and not grow away from it; the same principles were adopted here. Plants stems were trained into bamboo canes and plastic twine to create a fan or cordon shape that mimicked a 2 dimensional rather than 3 dimensional plant canopy. This allowed for a more valid comparison across the plant taxa, while acknowledging there were still differences in the number of leaves present, their individual sizes, their orientation and leaf area indices across the taxa. The experiment was conducted during peak sunlight hours with high irradiance and white vinyl cloths was used to cover the plant pots to minimize the influence of substrate heat transfer. Data was not collected on days with rain or overcast cloudy skies. Plants were irrigated the evening before each experimental period. This allowed the pots to be at or near container capacity (field capacity) in terms of water availability, but avoid any surface water being present on the pots or leaves at the time temperature recording commenced. Soil moisture content was checked at the start and end of each experimental period (ML3 ThetaProbe Soil Moisture Sensor, Delta-T Devices, Cambridge, UK) and stayed within a range of 0.45–0.35 m^3 m^{-3} i.e. wet to damp throughout. The growing media was a 90 % composted wood fibre; 10 % coir mix with controlled release fertiliser giving 330 g N, 104 g P and 339 g K m^{-3} and pH of 6.6–7.0 (Miracle-Gro Peat Free All Purpose Compost, Evergreen Garden Care (UK) Ltd, Frimley, Surrey, UK). For this study, 24 common landscape plant taxa were selected based on leaf colour, size, and special traits (Table 1).

2.3. Data presentation and statistics

The experiment ran from 27th March to 2nd October 2022, with each

Table 1
Plant taxa used in experiment and their traits.

Species	Plant type	Leaf colour	Leaf length range smallest/ largest (mm)	Leaf texture	Special traits
Camellia japonica cv. Doctor King	Evergreen shrub	Dark green	72–110	Smooth	Lustrous leaves
Ceanothus cv. Concha	Evergreen shrub	Dark green	6–14	Smooth	Glaucous leaves
Cistus purpureus	Evergreen shrub	Grey/green	47–69	Smooth	
Griselinia littoralis	Evergreen shrub	Dark green	33–72	Smooth	Lustrous leaves
Hebe cv. Mrs Winder	Evergreen shrub	Green/purple	37–75	Smooth/ succulent	Compact, bushy growth, Lustrous leaves
Lavandula angustifolia	Evergreen sub-shrub	Grey/green	21–56	Smooth	Narrow, linear or lanceolate leaves
Photinia fraseri cv. Little Red Robin	Evergreen shrub	Dark green	47–97	Smooth	Lustrous leaves, light green or bronze colour on lower surface
Hedera helix	Evergreen climber	Green	30–68	Smooth	Glaucous leaves
Hedera hibernica	Evergreen climber – vigorous growth	Dark green	34–85	Smooth	Glaucous leaves
Jasminum polyanthum	Evergreen climber – vigorous growth	Dark green	29–45	Smooth	Pinnate compound leaves
Lonicera japonica var. *repens*	Evergreen climber – vigorous growth	Dark green	25–68	Smooth	Dense and lush foliage
Fuchsia cv. Midnight	Deciduous shrub	Dark green	32–55	Smooth	Broad leaves
Hydrangea paniculata cv. Tardiva	Deciduous shrub	Dark green	24–65	Rough	Coarse, dense panicles
Hydrangea petiolaris	Deciduous climber	Dark green	37–75	Smooth	
Jasminum nudiflorum	Deciduous climber	Dark green	19–33	Smooth	Ovate shape/ Lustrous leaves
Alchemilla mollis	Herbaceous perennial	Med. green	84–139	Velvety	Hirsute leaves
Acanthus mollis cv. Morning Candle	Herbaceous perennial	Dark green	330–550	Smooth	Lustrous/serrated leaves
Dianthus plumarius	Herbaceous perennial	Green	45–89	Smooth	Lustrous/ Lanceolate leaves
Heuchera micrantha cv. Palace Purple	Herbaceous perennial	Purple/Red-brown	75–154	Rough	
Nepeta racemosa	Herbaceous perennial	Grey-green	10–43	Rough	Hirsute leaves
Stachys byzantina	Herbaceous perennial	Silver-grey	35–75	Velvety	Hirsute leaves
Senecio candicans cv. Angel wings	Succulent	Silver	86–205	Velvety	Hirsute leaves
Carex buchananii cv. Red Rooster	Perennial sedge	Red-bronze	800–1100	Rough	Narrow leaves (3–7 mm in width) growing in dense clumps
Miscanthus sinensis cv. Flamingo	Perennial grass	Green	800–1050	Rough	Long, narrow leaves, growing in dense clumps

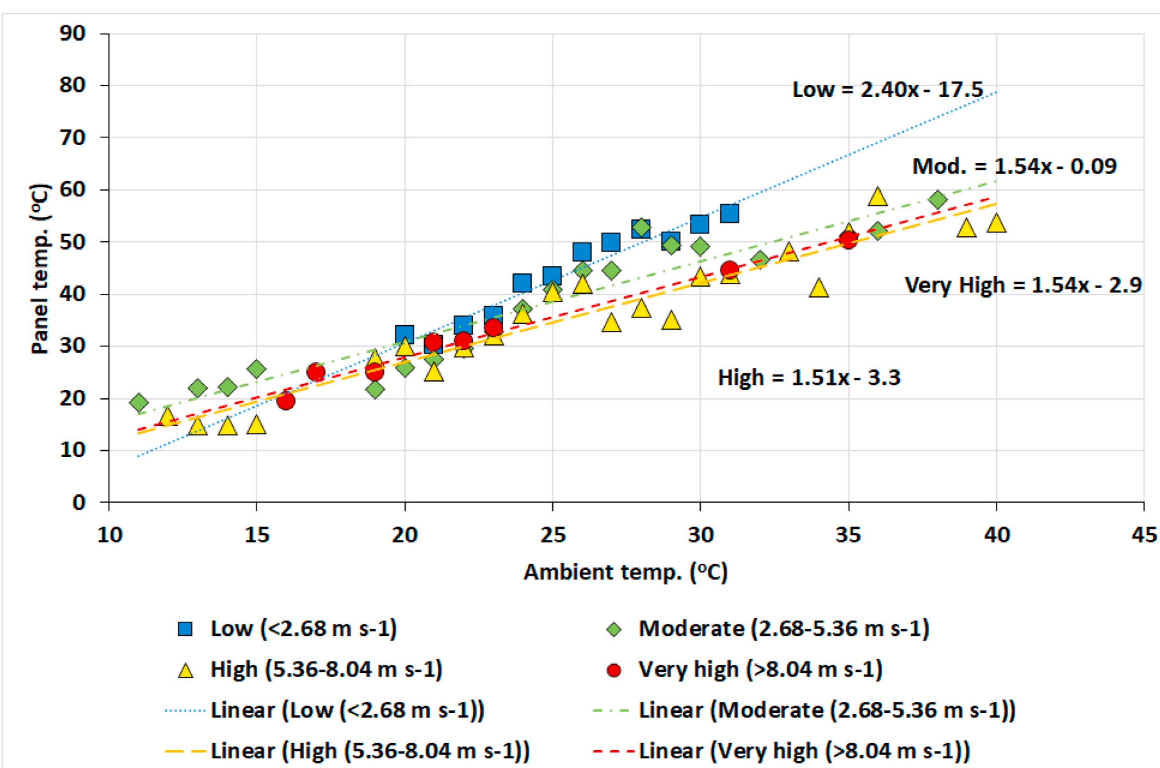

Fig. 2. Mean control (un-planted) panel temperature (°C) against ambient air temperature (°C) at various wind speeds.

plant taxa being assessed for cooling on more than 20 different occasions. For each recording period, temperature of the plant shaded panels were compared to the temperature of the control panel and the difference in temperatures recorded. These temperature differences were used in subsequent statistical analyses to determine the effects of taxa, wind speed and ambient temperatures on a plant's capacity to cool the wall panels.

A mean value of temperature (and temperature differentials; i.e. bare wall panel value minus planted wall panel temperature) was based on 5 min recording intervals (the Tinytag recorded every 30 s and the mean value for every 5 min was based on these). For presentation purposes, the data was then divided based on control panel temperatures (i.e. different ambient temperatures). So data sets associated with periods of very warm weather (when the bare panel temperature itself was 55 ± 5 °C) were pooled together for analyses, irrespective of the date of recording. Likewise, temperature profiles are depicted when bare panel temperatures were 45 ± 5 °C, 35 ± 5 °C and 25 ± 5 °C, and the relative capacity of different taxa to cool the panels at the temperature ranges presented. To allow for balanced ANOVA analyses, 50 data sets per taxa (reps) were chosen at random (using a randomisation command in Excel) for each time interval. Thus the ANOVA for the 55 ± 5 °C was based on 24 taxa × 50 reps (i.e. 1200 differential readings), but the data the reps represented could be taken from different days and/or times in the day. Data for mean cooling (i.e. the differences in temperature between the bare panel and the planted panels are depicted in Figs. 3–6. ANOVA was used to determined significant differences based on taxa at each temperature range, and post-hoc Bonferroni tests were used to identify which taxa had significantly greater cooling effect than others; different letters denoting statistical differences between means.

3. Results

3.1. Meteorological effects – wind velocity, air temperature and surface wall temperature

For the period of data collection, the range of parameters were air temperature = 11–40 °C; wind speed = 0.44–10.28 ms^{-1}; dew point = 2.7–16.6 °C; humidity = 12–65 %, and atmospheric pressure = 0.0992–0.1023 MPa. Recording wall panel temperatures were only undertaken under fair or sunny weather conditions (58 days in total). This equates to <40 % opaque cloud cover and no precipitation. As ambient air temperatures increased so did bare wall panel temperatures, e.g. 20 °C air ≈30 °C wall; 25 °C air ≈40 °C wall; 30 °C air ≈50 °C wall and 30–40 °C air ≈50–60 °C wall (Fig. 2). Wind velocity though could affect bare wall panel temperature, with some evidence that stronger winds were providing greater wall cooling for any given ambient air temperature (Fig. 2).

3.2. Cooling patterns at different ambient temperatures

The presence of vegetation significantly reduced the wall panel temperatures compare to the bare panel. Plant taxonomic choice significantly affected cooling at all the temperature scenarios presented (P < 0.001, df = 1176 in each case). Under moderately warm days (control panel temperature 25 °C), greatest wall panel cooling was associated with *Hebe, Carex, Acanthus, Jasminum polyanthum* and *Lonicera* (Fig. 3). All these taxa reduced panel temperatures by 4–5 °C. On warmer days (control panel temperature 35 °C), greatest cooling was associated with *Lonicera, Lavandula, Acanthus* and *Hebe* (Fig. 4). Here, reductions in panel temperature were in the region of 12–14 °C. As temperatures rose further (control panel temperature 45 °C), taxa providing the most effective cooling were *Hebe, Alchemilla, Senecio, Heuchera, Lonicera, Griselinia, Hedera helix, Acanthus* and *Nepeta* (Fig. 5). These taxa reduced wall panel temperatures by 16–20 °C. At the hottest

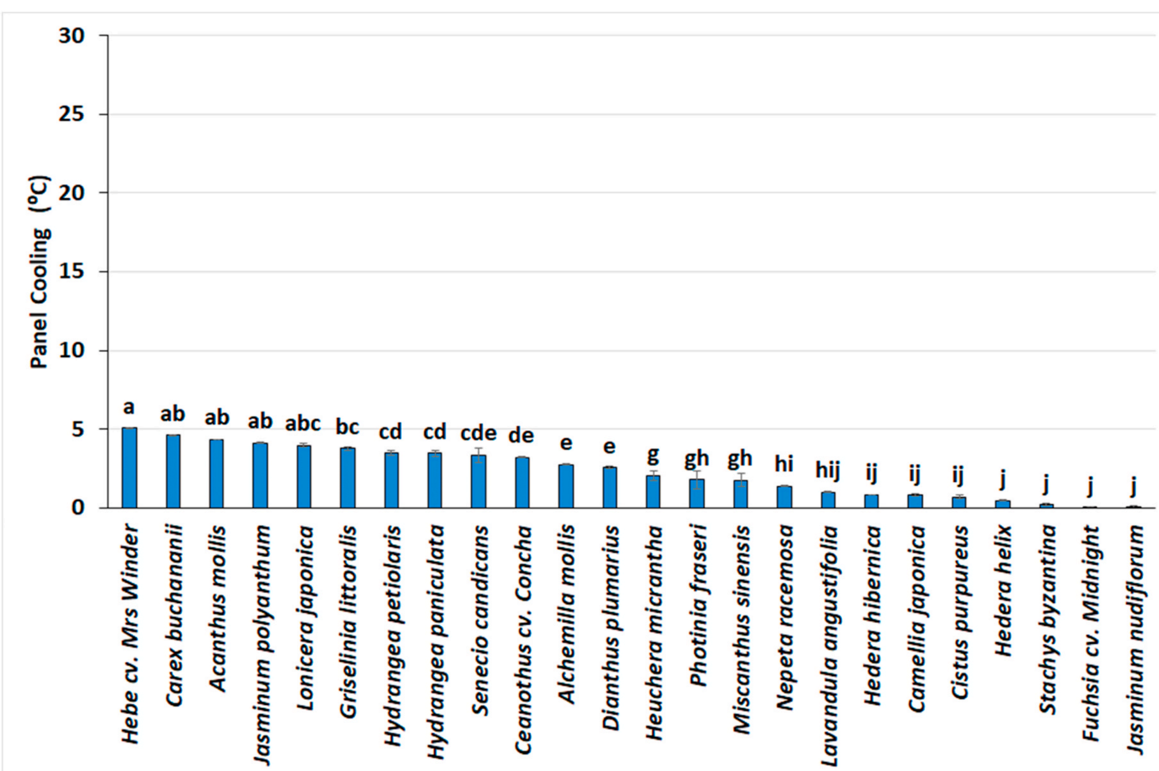

Fig. 3. Mean panel cooling (°C) by taxa, when control panel temperature was 25 ± 5 °C. Different letters note significant different between mean values, based on Bonferroni post-hoc tests, e.g. a mean value with an 'a' is significantly different to a value with a 'b', but not one with an 'ab' depiction.

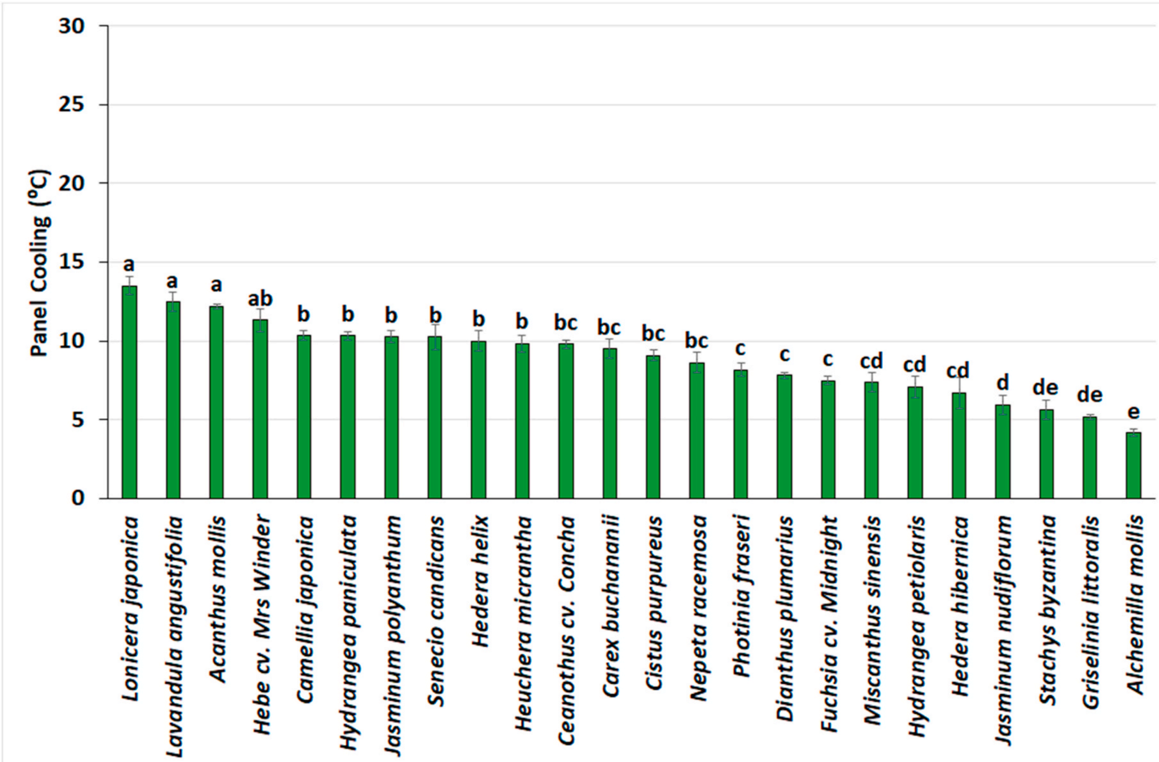

Fig. 4. Mean panel cooling (°C) by taxa when control panel temperature was 35 ± 5 °C. Different letters note significant different between mean values, based on Bonferroni post-hoc tests, e.g. a mean value with an 'a' is significantly different to a value with a 'b', but not one with an 'ab' depiction.

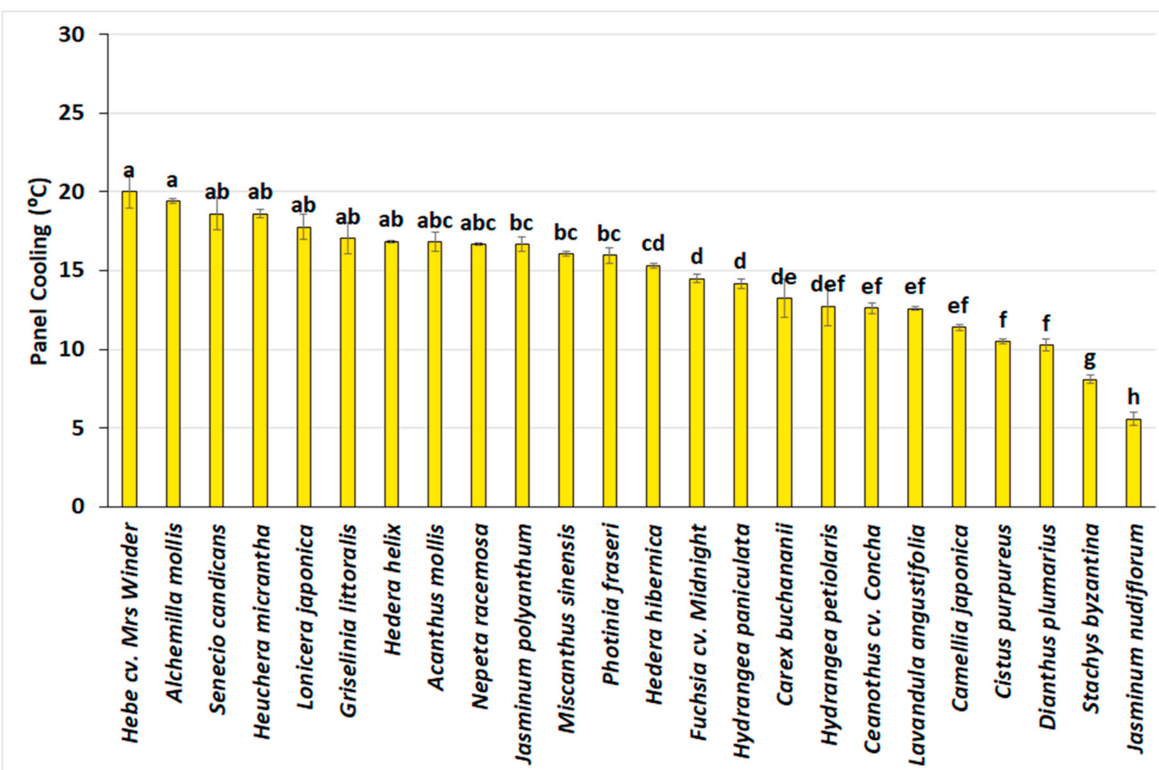

Fig. 5. Mean panel cooling (°C) by taxa when control panel temperature was 45 ± 5 °C. Different letters note significant different between mean values, based on Bonferroni post-hoc tests, e.g. a mean value with an 'a' is significantly different to a value with a 'b', but not one with an 'ab' depiction.

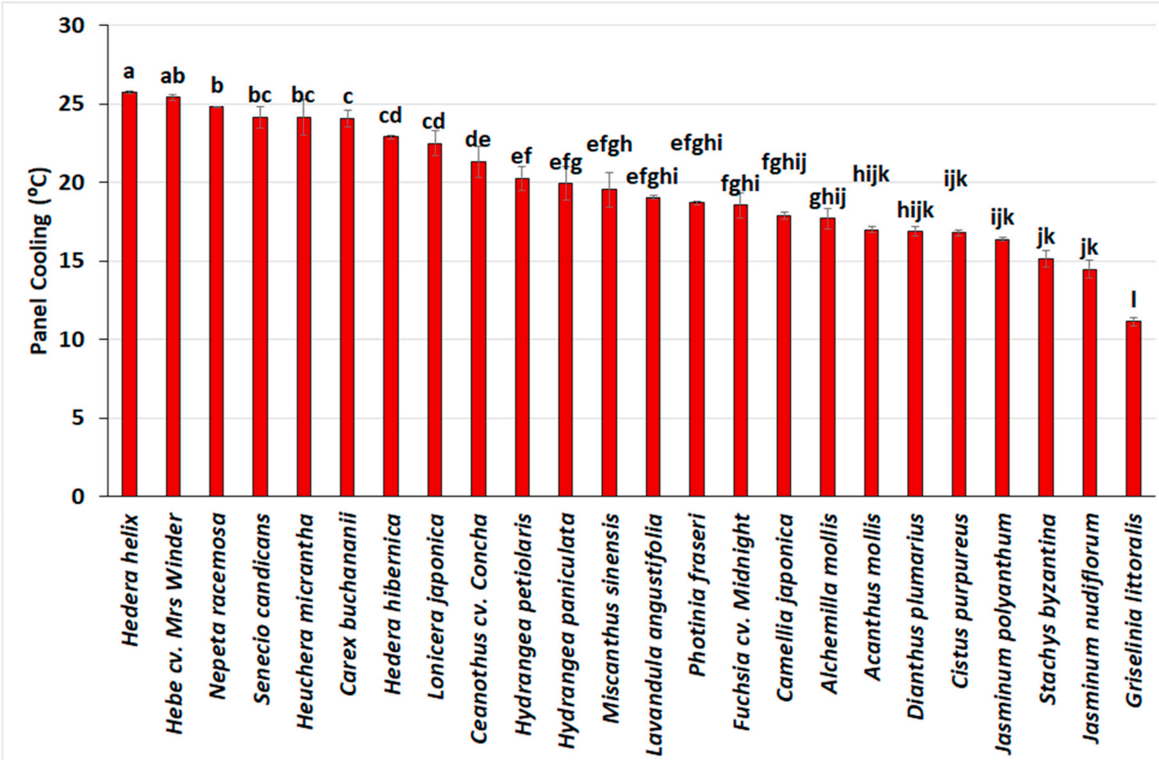

Fig. 6. Mean panel cooling (°C) by taxa when control panel temperature was 55 ± 5 °C. Different letters note significant different between mean values, based on Bonferroni post-hoc tests, e.g. a mean value with an 'a' is significantly different to a value with a 'b', but not one with an 'ab' depiction.

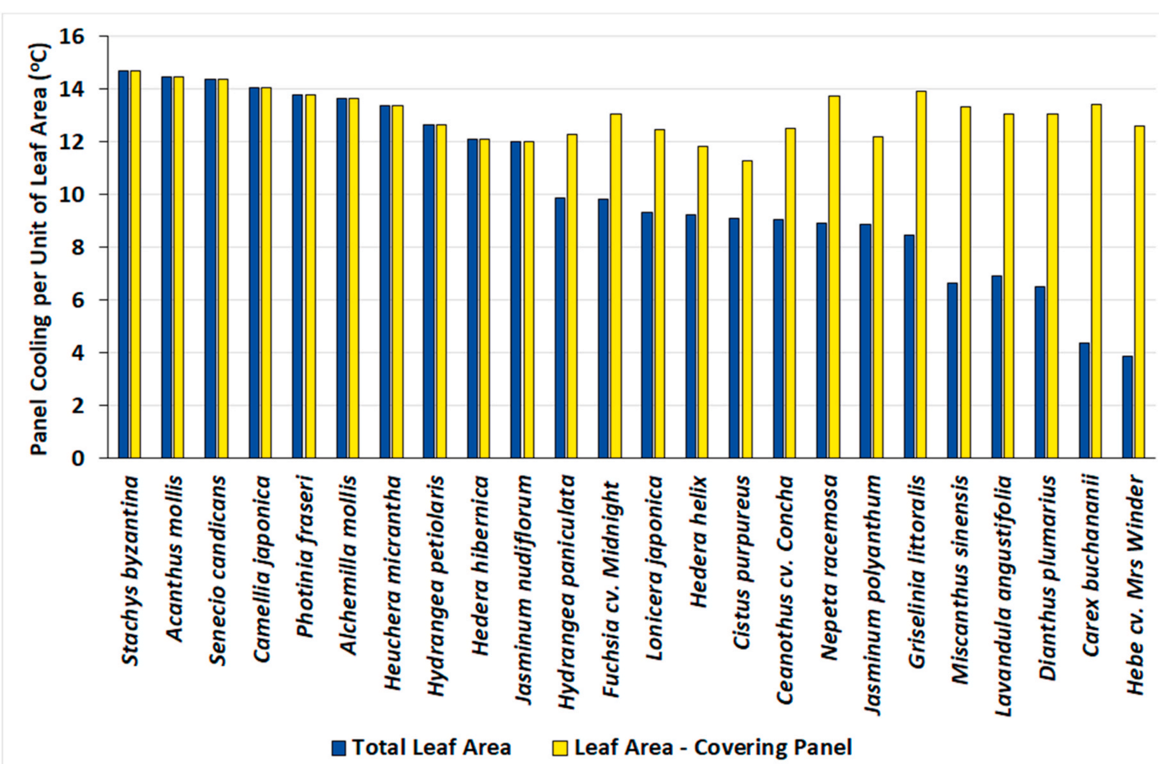

Fig. 7. Mean panel cooling per unit of leaf area (°C) by taxa when the unscreened control panel temperature was 55 ± 5 °C. Dark bars relate to panel cooling when the total canopy leaf is estimated, and pale bars denote cooling when only the leaf area directly in front of the black panel is considered. Note there are no statistical comparisons as leaf areas are estimates of mean values per taxa used, not actual individual specimens used at each temperature scenario.

temperatures (control panel temperature 55 °C), cooling was greatest with *Hedera helix* and *Hebe* (Fig. 6); both providing >25 °C of cooling to the wall panels. All plant taxa provided some panel cooling effect, with minimum cooling of 0.02 °C, 4.17 °C, 5.59 °C and 11.13 °C when the control wall panel temperature reached to 25 °C, 35 °C, 45 °C and 55 °C, respectively. Generally, *Stachys, Jasminum nudiflorum* and *Cistus* were the least effective wall panel cooling plants.

3.3. Wall cooling per unit of leaf area

An estimate of leaf area per taxa based on i. the whole plant, and ii. the area of leaves directly in front of the black panel, were used to give an estimate of cooling potential per unit of leaf area. This indicated that taxa such as *Stachys, Acanthus* and *Senecio* had good wall panel cooling attributes when based on a single unit of leaf area (Fig. 7 shows wall panel cooling per unit leaf area, when the wall panel was at 55 °C). Similar effective cooling per leaf area was apparent when the leaf area directly in front of (directly at right angles to) the panel was considered alone (Fig. 7 – pale bars). Under this circumstance, taxa such as *Griselinia, Nepeta* and *Carex* also showed good cooling potential per unit of leaf area.

3.4. Taxon performance

Overall, the taxa that gave consistent cooling included *Hebe, Lonicera* and *Senecio* whereas *Dianthus, Cistus, Stachys, Camelia and Jasminum nudiflorum* showed consistent low cooling potential (Table 2). Taxa that performed well at higher temperatures but were relatively ineffectual at lower temperatures included *Hedera helix* (ranking varying between 1st and 21st), *Nepeta* (ranking between 3rd and 16th) and to some extent *Hedera hibernica* (ranking between 7th and 20th) (Table 2). Conversely, taxa that provided greatest cooling at lower wall panel temperature, but lost this potential as temperatures rose included *Acanthus, Jasminum polyanthum, Dianthus, and Griselinia* (Table 2).

There were no clear physiological or morphological traits associated with the types of plant that provided the greatest cooling to the wall (Fig. 8). Plants with grey or hirsute foliage ranged from those with greatest cooling capacity (*Hebe* 'Mrs Winder') to those with almost least

Table 2
Ranking of taxa based on optimal coling at the different bare wall panel temperatures, with 1 = the taxa that had greatest cooling.

Taxon	Mean bare wall panel Temperature/Ranking at that temperature			
	25 °C	35 °C	45 °C	55 °C
Hebe cv. Mrs Winder	1	4	1	2
Lonicera japonica	5	1	5	8
Senecio candicans	9	8	3	4
Heuchera micrantha	13	10	4	5
Acanthus mollis	3	3	8	18
Carex buchananii	2	12	16	6
Hedera helix	21	9	7	1
Hydrangea paniculata	8	6	15	11
Nepeta racemosa	16	14	9	3
Jasminum polyanthum	4	7	10	21
Ceanothus cv. Concha	10	11	18	9
Lavandula angustifolia	17	2	19	13
Hydrangea petiolaris	7	19	17	10
Alchemilla mollis	11	24	2	17
Photinia fraseri	14	15	12	14
Miscanthus sinensis	15	18	11	12
Hedera hibernica	18	20	13	7
Griselinia littoralis	6	23	6	24
Camellia japonica	19	5	20	16
Fuchsia cv. Midnight	23	17	14	15
Dianthus plumarius	12	16	22	19
Cistus purpureus	20	13	21	20
Stachys byzantina	22	22	23	22
Jasminum nudiflorum	24	21	24	23

(*Stachys byzantina*) (Fig. 9). Medium-sized, soft leaves provide effective cooling (*Lonicera japonica*) or limited cooling (*Fuchsia* cv. Midnight). Rather, the strongest factor associated with cooling was total leaf area between the incoming solar irradiance and the wall, with taxa with greatest total leaf area providing the greatest mean cooling (Fig. 10). This factor, however varied in terms of its influence, as total leaf area only explained 25 % of the variation when wall panel temperatures were 25 °C, 44 % at 35 °C, 50 % at 45 °C but notably 66 % of the variation when wall panel temperatures were 55 °C (Fig. 11).

3.5. Leaf temperature

Some taxa showed the capacity to keep their leaves relatively cool, when the nearby wall panel (and wall) became warmer. (Fig. 12 shows typical leaf temperature for all taxa, and Fig. 13 for those selected for contrasting leaf types). Taxa that tended to show the warmest leaves as wall conditions got hotter were *Camellia* (Fig. 12B) and *Stachys* (Fig. 12A), with some suggestion that *Jasminum nudiflorum* (Fig. 12C) and *Carex* (Fig. 12C) lost their capacity to cool their leaves when the control wall panel temperatures exceeded 60 °C. Taxa with the coolest leaves as ambient and wall panel temperatures rose included *Hebe, Cistus, Senecio* and *Nepeta* (Fig. 13), with some evidence for *Lavandula* (≤60 °C wall panel temp, Fig. 12A) and *Heuchera* (Fig. 12B) also having some capacity to keep their leaves cool.

Taxa such as *Senecio, Lavandula* (Fig. 12A), *Heuchera, Acanthus* (Fig. 12B) and *Carex* (Fig. 12C) had leaf temperatures ≤25 °C, when the panel itself was 60 °C. *Miscanthus* similarly maintained a 31 °C leaf temperature when the nearby panel was recording 66 °C (Fig. 12C). In contrast, leaf temperatures tended to be higher for taxa such as *Stachys, Dianthus* (Fig. 12A), *Camellia* (Fig. 12B) and *Jasminum nudiflorum* (Fig. 12C) as ambient temperatures continued to rise.

4. Discussion

4.1. Plant cooling capacity as affected by ambient and panel temperatures

Plants were effective at reducing wall panel temperatures. Using our black panel system, we observed façade temperatures in the UK (max. 65.1 °C) comparable to building masonry wall temperatures experienced in warmer geographical regions, e.g. 61 °C in Greece [53] and Australia [54] and 55 °C in China [55,56]. By placing plants in front of our panels, temperature reductions of 26 °C, were recorded on the warmest days. This is comparable to the degree of cooling observed in planted walls in warmer Mediterranean climates (30 °C – Spain [27]). Due to the black panels interacting with solar irradiance in different ways to that of (pale coloured) building materials we cannot make direct analogies to specific buildings or building types, but we did manage to develop an experimental system that allowed a wider range of temperatures to be analysed, than would otherwise be the case in the UK (our brick walls reached a maximum of 48 °C, and only for short-periods of time). Overall, the data shows that plants have the capacity to significantly cool façade temperatures, and the warmer the ambient conditions, the more effective the vegetation was in reducing the panel temperatures.

The innovative result from this research, however, is the fact that the ranking of cooling capacity of the different taxa changed as conditions became warmer and wall panel temperatures increased. Taxa that optimised cooling at 25 °C did not necessarily optimise cooling when the bare wall panel was much warmer at 55 °C. At the warmest temperatures, *Hedera helix* and *Hebe* outperformed other taxa in their capacity to keep the wall cool, yet at the lower 25 °C scenario, *Hedera helix* was only ranked 21st out of 24 in its capacity to cool the wall panels. A similar trend was noted with *Hedera hibernica* – ranked 7th at 55 °C, after being ranked previously at the lower temperatures between 13th and 20th. In stark contrast, *Hebe* always remained in the top four plants for cooling capacity irrespective of the relative heat the plants were experiencing

Fig. 8. Leaf morphology of the taxa that provided geatest cooling at 55 ± 5 °C. Note the lack of consistent traits across the leaf types.

(Table 2).

4.2. Factors contributing to wall panel cooling

A large proportion of the cooling could be explained by the leaf mass present in front of the wall (Fig. 10), and for some taxa the localised cooling can be attributed to the fact that these were simply larger plants, with more (e.g. *Carex*), or larger (e.g. *Senecio, Acanthus*) leaves, or had a more-dense canopy (e.g. *Hebe*). This was especially so at the higher ambient temperatures (Fig. 11). At lower temperatures this relationship broke down, implying that factors other than simple leaf mass/shading is affecting the wall panel temperature.

The relative uniformity of individual leaves to cool the black panel (by 12–14 °C; Fig. 7) suggests that for this area immediately behind the central plant, most leaves or combinations of leaves are effectively shading the panel from the direct rays of solar irradiance – and as such giving relatively consistent cooling per leaf irrespective of taxa. Taking data as the total leaf area of the plants however (blue bars, Fig. 7), alludes to other morphological/physiological factors at play (e.g. see points below about leaf morphology, wider shading effects and evapo-transpiration). Interestingly, a number of taxa were effective at both cooling the adjacent wall panel and at the same time ensuring their own leaves remained cool. These included *Hebe, Senecio* and *Nepeta*. Others such as *Cistus* and *Lavandula* were effective at keeping their foliage cool at higher ambient temperatures, but not the adjacent wall panel.

Unfortunately, the data did not indicate any uniform broad traits that could help predict cooling potential across different taxa. The grey-leaved 'Mediterranean' flora, for example, comprised both those that were very successful at wall panel cooling (*Senecio*; and at the highest temperature *Nepeta*, Fig. 6) and those that were relatively ineffective, at least at the whole plant level, e.g. *Cistus* and *Stachys* (Fig. 9). Similar trends were noted with taxa that possessed thick, glaucous leaves – *Hedera helix* being successful at higher ambient/wall panel temperatures, but *Camellia*, and *Griselinia* much less so. In the case of *Camellia*, individual leaves actually had good cooling capacity, but the overall low leaf density of the canopy meant a high proportion of solar irradiance passed through to heat the panel and adjacent wall behind, thus undermining the functionality of this taxon. Variation within the one genus was also noted. *Jasminum polyanthum* was more effective at keeping the wall panel (Fig. 9) and its leaves (Fig. 12C) cool compared to *Jasminum nudiflorum*; this latter taxon always being ranked in the bottom four taxa for cooling potential. *Jasminum nudiflorum* is quite sparsely covered in leaves – thus potentially letting more solar radiance through to the panel [57]. It also had quite warm leaves at high ambient temperature, suggesting perhaps limited evapo-transpiration compared to other taxa [50,58,59]. In contrast, *Jasminum polyanthum,* whilst possessing similar small, pinnate leaves, is a fast-growing evergreen twiner with positively phototropic leaves. The leaves of *Jasminum polyanthum* orientate themselves in a way to maximise light absorption thereby intercepting more of the incoming irradiation [60,61].

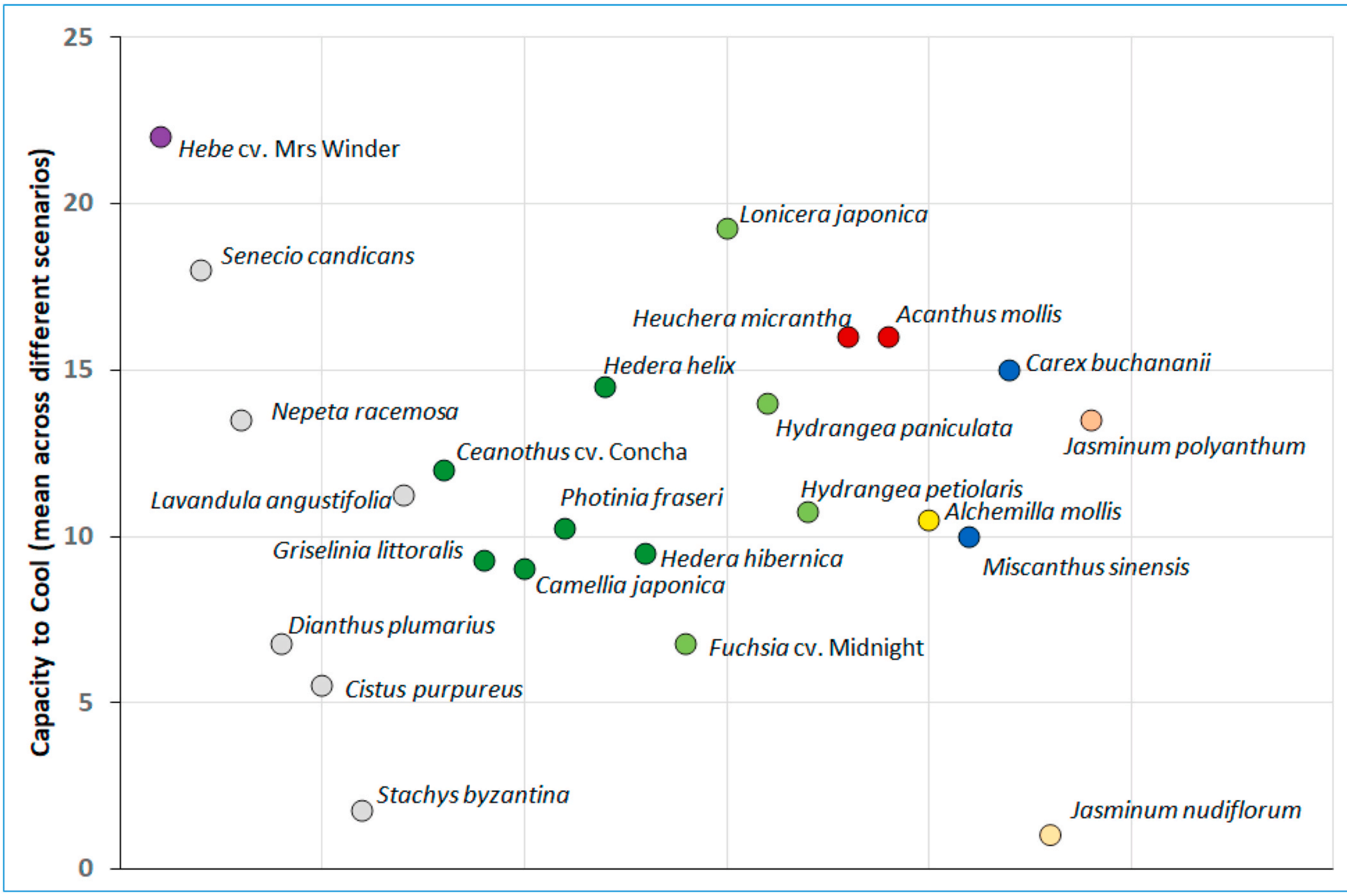

Fig. 9. Mean cooling capacity (°C) of different taxa (mean value across different scenarios).

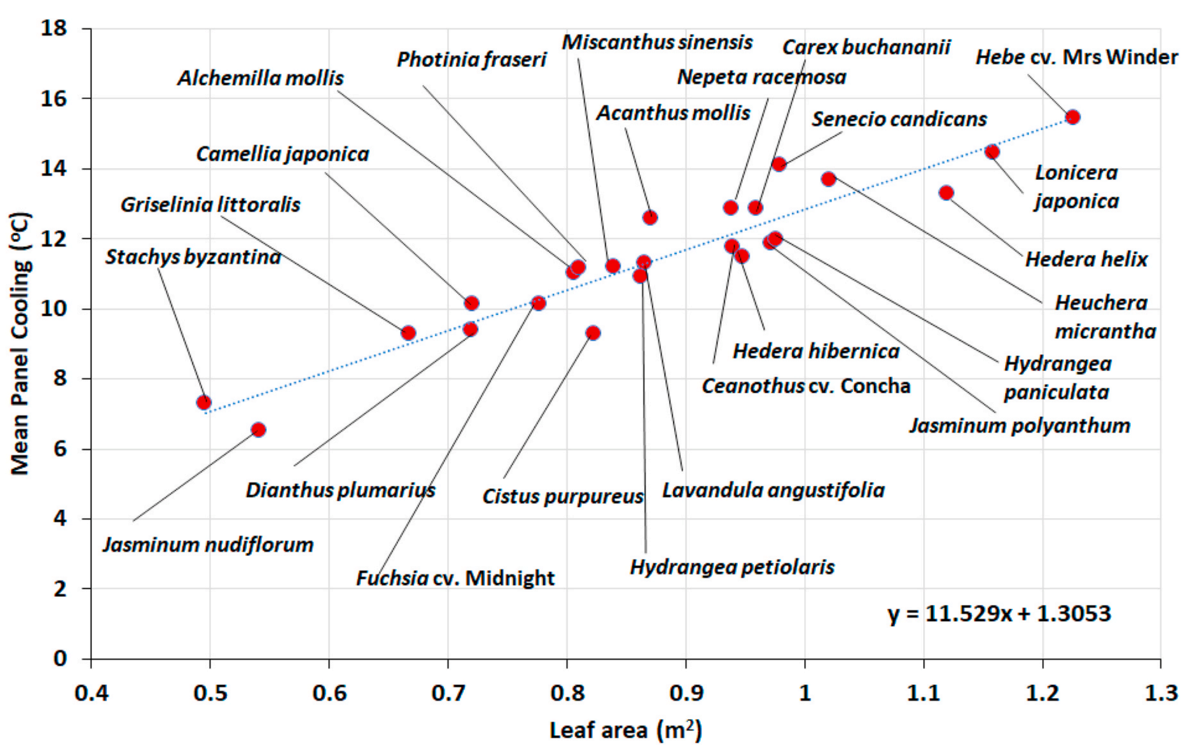

Fig. 10. The relationship between estimated leaf area per plant per taxon and wall panel cooling (mean of all temperature (°C). Correlations explained 89 % (r^2 = 0.89) of the variance.

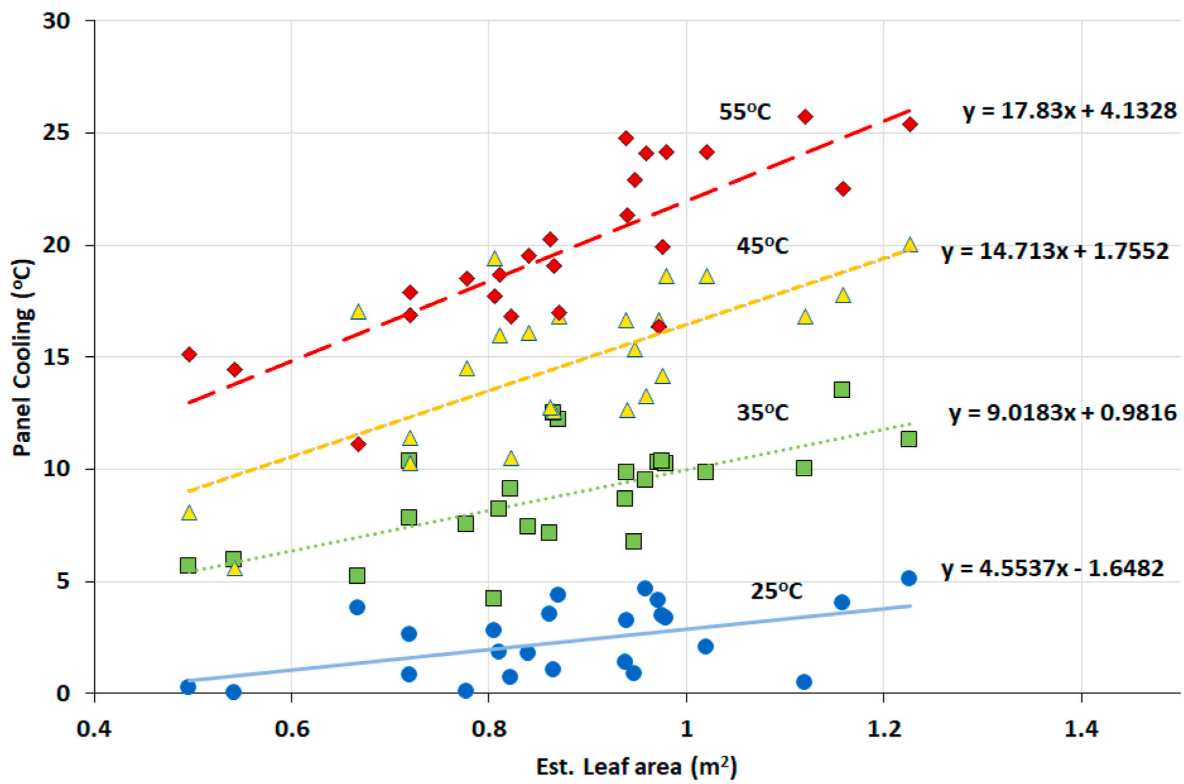

Fig. 11. The relationships between estimated leaf area per plant per taxon and wall panel cooling (°C) under different scenarios. Correlations explained 25 % ($r^2 = 0.25$) of the variance at 25 °C bare panel temperature; 44 % of variance at 35 °C; 50 % of the variance at 45 °C and 66 % of the variance at 55 °C.

4.3. What taxa can we recommend?

The fact that we failed to detect generic traits that allude to cooling potential (other than overall leaf mass), means that more effort is required to evaluate individual genotypes before recommending them for urban cooling capability. It also indicates that cooling capacity between taxa may relate to quite subtle factors around leaf morphology, canopy geometry, physiological processes and adaptations to the conditions the plant finds itself in, as well as overall plant dimensions. Based on the data generated here, positive cases can be made for *Hebe, Lonicera, Senecio*, and under certain circumstances for *Hedera helix, Nepeta* and *Heuchera*. *Hebe* cv. Mrs Winder provided effective cooling across a range of different scenarios; this compact, evergreen shrub with its dense canopy of purple/grey-green leaves remained consistently near the top in cooling potential rankings throughout (Table 2). Cooling with this taxon may be due to the large number of small leaves it possesses – either providing really effective shade when acting as the entire canopy – or the combined effect of many small leaves all evapo-transpiring at once (data not measured). Either way this taxon is cooling through a group leaf (i.e. entire canopy) effect, as the cooling attributes to individual leaf area is quite low (Fig. 7). The use of compact plants, with numerous small leaves, and a dense leaf canopy may have specific application on modular green walls systems – when many such taxa can be grown in close proximity. Indeed, Perini et al. [62] showed that mixed community plantings dominated by such species (e.g. *Cistus, Hebe, Phlomis. Buxus* and *Viburnum* spp.) could reduce the reliance on artificial air conditioning in Italy by 26 %. As *Hebe* is a relatively common genus on green walls – further *in situ* studies could help identify this taxon's specific contribution.

In terms of taxa used on green facades, *Lonicera japonica* var. *repens* proved promising, with this genotype being in the top best five cooling taxa in the 25–45 °C range. This corroborates previous studies where climbing *Lonicera* have been cited as a useful screening plant due to a high leaf area index acting as a shield against incoming radiation [63, 64]. Cameron et al. [16] attributed effective cooling with *Lonicera* due to a relatively even contribution of shade cooling and evapo-transpirational cooling. *Heuchera* is another taxon that showed effective cooling in this study. A previous study by Gräf et al. [65] indicated that the cooling potential of *Heuchera* is strongly dependent on water availability, i.e. transpiration being important; there being a 6 °C difference in leaf temperature between well-watered and drought stressed plants. *Heuchera* was one of the more successful species here in keeping its leaves cool; again suggesting evapo-transpiration is an important cooling mechanism with this taxon. The cultivar we chose in this study was particularly interesting as it has dark purple leaves; yet the leaves themselves remained relatively cool until adjacent panel temperatures exceeded 60 °C (Fig. 12B). Leaf colour itself gave no overall hint of cooling capacity as the palest leaves were associated with *Senecio*, yet this plant also provided very effective cooling. Thus leaf colour, again, does not appear to be a broad trait we can rely on for determining localised cooling.

4.4. Relationships between leaf and wall panel cooling

As outlined above, there was some variation in the Mediterranean taxa evaluated in terms of their capacity to cool the wall panels, but also to keep their own leaf temperatures low. The pale and hirsute nature of the leaves in *Senecio, Nepeta, Cistus* and *Lavandula* may explain their capacity to reflect solar irradiance and keep their foliage cool under warm conditions, but only *Senecio* and *Nepeta* conferred any local cooling influence on to the panels themselves. This may relate to the large individual leaves of *Senecio* providing effective shade; and perhaps a retained capacity in *Nepeta* to evapo-transpire at high temperatures, as possible explanations, but these aspects need verifying. Surprisingly, an additional Mediterranean taxon – *Stachys*, was deemed relatively ineffective at cooling the wall panel (Fig. 9) or its own leaves (Fig. 13) – despite also possessing hirsute, pale leaves. This is in contrast to previous studies on this taxon on green roofs [45] – where it has been shown

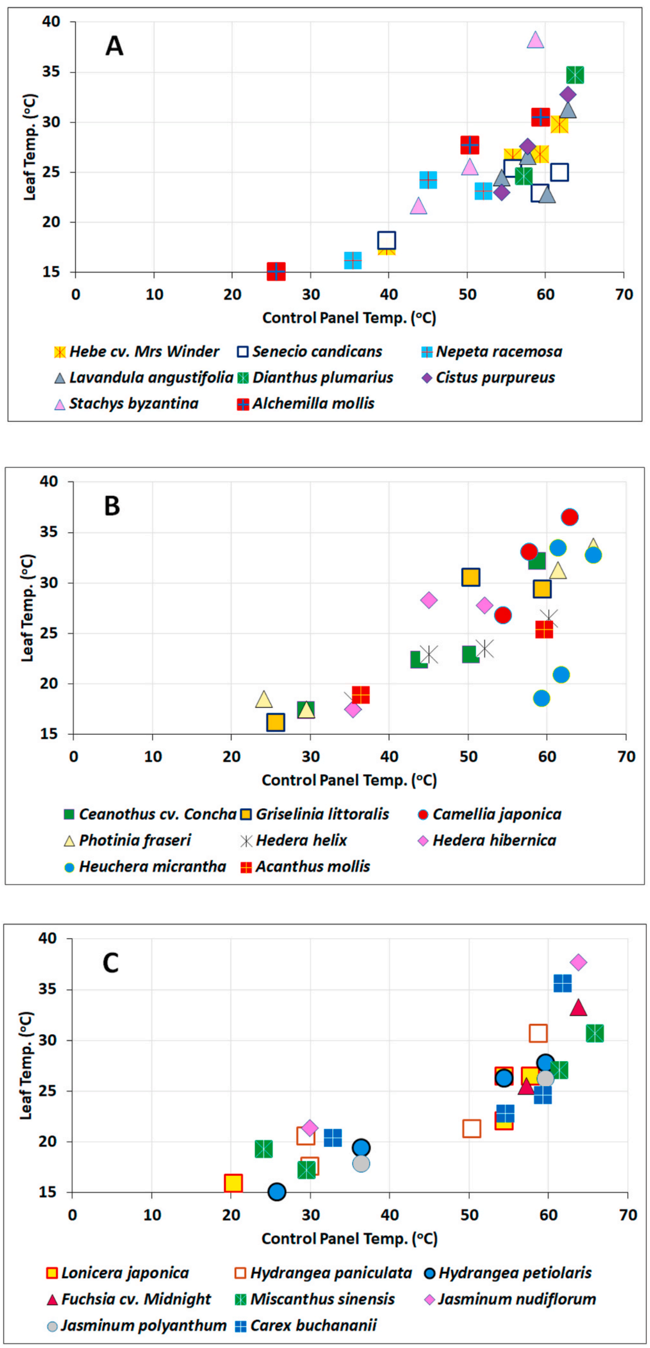

Fig. 12. Recorded leaf temperatures (°C) compared against the control black panel temperatures (°C) at specific periods of the experiment. (All taxa).

to provide effective localised cooling. In our study here, however, the plant was orientated differently with respect to where temperature was being measured – the wall-mounted thermocouple being parallel to the horizontal, strap-like leaves of the plant in this case, rather than placed directly below the whole canopy (as occurred on the green roof studies). This may have compromised its capacity to cool the wall panel as reported here.

The other taxa, that proved ineffective in keeping its leaves cool under higher ambient air temperatures was *Camellia*; and despite this species being known as a wall shrub in temperate climate (where the warm wall microclimate is useful in initiating flower buds in summer and reducing frost damage to open blooms in spring), its future use in very warm, unshaded urban conditions may be questionable, if it fails to keep its leaf tissues below 40 °C.

Overall, our data suggests that leaf number and canopy density are key factors determining wall panel cooling, and these factors become more important as ambient temperatures rise (Fig. 11). Taxa that rely strongly on shading to promote cooling, such as *Hedera helix* [16,66] may increase in relative prominence as solar irradiation intensity increases, partially because other taxa stop or slow down evapotranspiration as heat increases [67,68]. Taxa vary in their sensitivity to higher temperatures, in terms of regulating their stomatal behaviour [69]. Under warm conditions, demand for water in the leaves, can exceed that being able to be supplied by the roots even when substrate moisture status is high – with stomata subsequently closing [70]. Some plant species may close their stomata at lower temperatures than others, and thus lose their evapo-transpirational cooling abilities earlier than their counterparts. Von Caemmerer and Evans [71] showed species varied in stomatal behaviour as leaf temperatures increased from 30 °C to 40 °C with some taxa increasing and others decreasing transpiration. The relatively high 'jumps' observed in leaf temperatures (e.g. 25–35 °C – *Dianthus*; 27–33 °C - *Cistus*; 20–34 °C - *Heuchera*, 25–35 °C - *Carex* and 25–34 °C – *Fuchsia*; Fig. 12) when the wall panel reached ≈61–62 °C, may relate to stomatal closing [65,72], but this needs further evaluation in more detailed studies embracing leaf porometery [73]. An understanding of plant ecophysiology may be beneficial here too, as stomatal behaviours can relate to ecological adaptions to survival in natural habitats (e.g. Ref. [74–76]). Thus, more research is required linking ecological adaptations by plants to their capacity to provide ecosystem services in urban contexts [77,78].

4.5. Meteorological effects on wall panel temperature

Wall panel temperature was not just affected by the cooling influence of plants. Often wall panel temperatures were proportional to the mean air temperature (although often about 15 °C warmer), when external variables such as wind speed, wind direction, and cloud conditions were constant. Wind was a cooling factor, however, and highest wall panel temperatures were associated with calm days, especially when cloud cover was absent. Conversely, on days with strong winds and gusts, the wall panel surface temperature showed a sudden drop compared to a calm day with the same air temperature. When the wind came from the north, northwest or north-east wall panel temperatures could be warmer, presumably due to the protection afforded by the building we used – shielding our experimental area from the north.

4.6. Limitations of the study

This research utilised an insulated black panel system rather than the brickwork of the wall itself to ensure temperature readings were not influenced by thermal energy migrating along the wall (for example, for parts of the wall not shaded/influenced by the plants). A black surface was also chosen to allow maximum solar irradiance absorbance and heat gain on the panel, thus allowing plant response to higher temperatures to be examined within the context of the (relatively cool) climate of the UK. Although black façade buildings exist in the UK and elsewhere, care is required when comparing data here for absolute temperature data with other studies on *in situ* buildings, where façades may be composed of other (lighter-coloured) building materials, with their own thermal absorbance and emission properties.

In this study there was also a necessary compromise between evaluating a relatively wide range of taxa (24) and having time/resources to carry out detailed physiological studies in the field, to fully understand the relationship between cooling and stomatal behaviour/evapo-transpirational cooling for each taxon. We have done this for smaller numbers of taxa previously (e.g. Ref. [45,59]), but similar approaches may now be necessary for new genotypes identifying in this and allied studies to verify how other, less-studied taxa are cooling their micro-environment. In this study, we partially controlled for leaf area by training our plants to a set geometrical pattern, but further controlled,

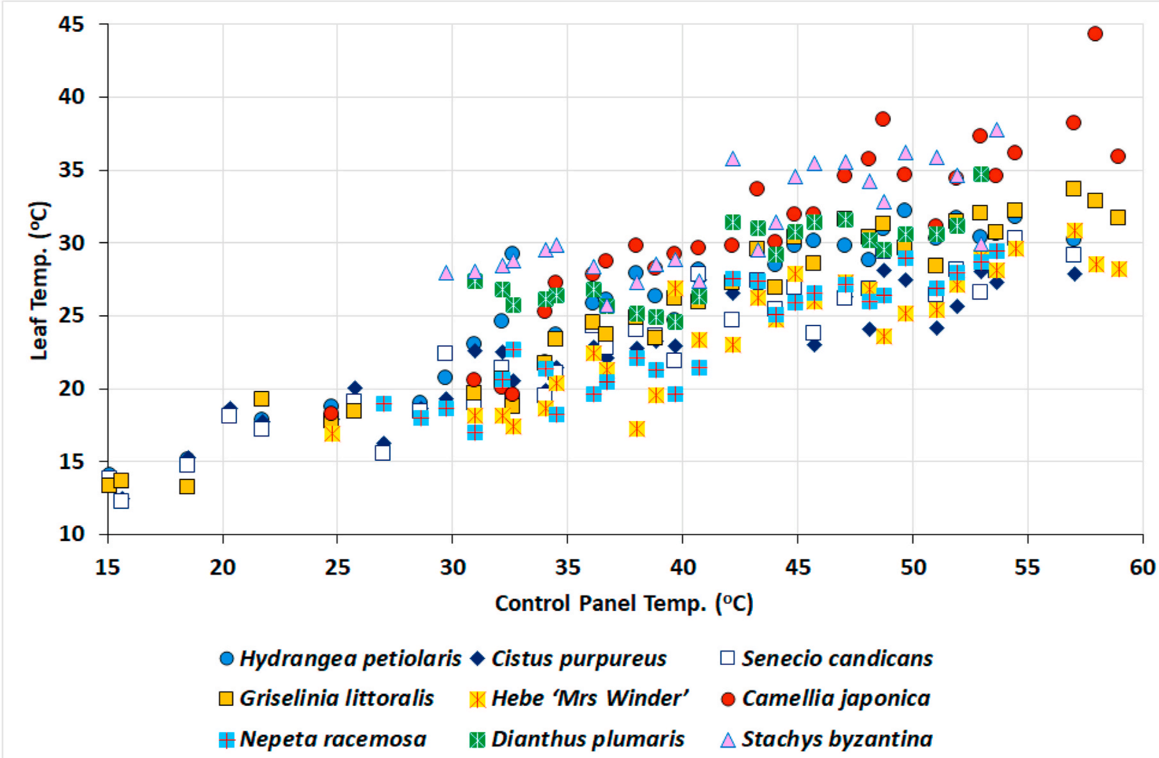

Fig. 13. Recorded leaf temperatures (°C) compared against control black panel temperatures (°C)at specific periods of the experiment. (Selected taxa).

more refined studies are warranted to understand better the relationships between leaf factors (area, orientation; interception of radiation, and indeed leaf to leaf interactions) in an attempt to better explain cooling under different circumstances. Finally, all the data was collected over a single calendar year, and similar procedures over additional years, with different meteorological patters, are warranted.

5. Conclusions

Plants demonstrate their unpredictable nature when it comes to identifying key factors linked to atmospheric and surface cooling. Their capacity to cool is to some degree dependent on the temperatures they themselves are experiencing. We believe this is the first piece of research to demonstrate this for landscape shrubs, climbers and perennials. It is likely that cooling is conferred by factors such as degree of shading [79], evapo-transpiration rates [80,81], albedo effects [18] and alterations of air movement over and around the leaves and wall [73]. Shading levels are likely to remain proportionate as solar irradiance and ambient temperatures increase, but the other factors may be affected by the thermal environment the plant finds itself in. This may explain the alteration in plant ranking as thermal loads on the wall panels increased. The poor correlations between broad plant traits (e.g. leaf texture and colour, stem orientation etc.) and cooling capacity across taxa, is problematic in practical terms, as it means every genotypes needs to be evaluated for its cooling potential, rather than key principles helping us choose the most effective plants. On the other-hand, the fact that different but specific genotype factors are influencing cooling, points to the need for landscape architects to ensure plant communities used for urban cooling remain diverse, and that the different mechanisms for cooling (shade, evapotranspiration, high albedo) are accommodated through this diversity. A point that may be important for other ecosystem services too.

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CRediT authorship contribution statement

Powshana Kunasingam: Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Andy Clayden:** Writing – review & editing, Supervision. **Ross Cameron:** Writing – original draft, Validation, Supervision, Conceptualization, Formal analysis, Funding acquisition, Methodology, Resources.

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

A summary of the results will be placed within the University of Sheffield PhD data repository.

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