Using thermography to assess vertical greening canopies

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ABSTRACT: *A warming climate and the heat island effect are expected to increase the environmental thermal load on urban buildings. To address the resulting heat-related risks, green infrastructure enhancements have been widely encouraged since the turn of the century, while the difficulty of implementing enhancements in densely built cities has necessitated the development and inclusion of vegetated architectural features. Although early efforts focused on horizontal greening, 'vertical greening' has gained increased attention in recent times. This paper demonstrates the application of a thermography coupled methodology for examining their canopies, which enhances opportunity for the sustainable monitoring and maintenance of such installations. The approach is exemplified in this paper by using it to describe and quantify the canopy features of a case study indoor living wall.*

KEYWORDS: *Vertical greening; vertical greening assessment; thermography; thermal imaging; living wall maintenance*

1. INTRODUCTION

Urban green infrastructure enhancements are widely advocated to address risks from a warming climate. Surface greening approaches such as vertical greening as a result have received increased attention as a way to achieve enhancements in cities with high built environment densities [1,2]. Vertical greening describes green infrastructure enhancements that seek to cover any vertical built structure with plant life, and are further differentiated as 'green facades' and 'living walls'. While green facades including the growth of climbing plants are well-established, recent interest is directed at the newer living wall category. The growth substrates in these are placed on a vertical host building wall, where plants root into a substrate carrying support-work that includes an embedded closed-loop fertigation network. The greater prominence gained by living walls is mainly attributed to the aesthetic appeal of their flourishing canopies, which has encouraged installations to be introduced to a diverse range of building typologies and scales, as well as outdoor and indoor environments [3,4]. The purpose of this conference paper is to demonstrate the application of a thermography coupled pathway for examining their canopies, and highlight opportunity to enhance the efficient maintenance of such installations. The approach is applied in this study to describe and quantify the canopy features of an indoor living wall case study.

This case study is an installation located in the atrium of the David Attenborough Building (DAB), which is sited in Cambridge, England (temperate climate, Cfb). The building atrium's northwest surface hosts the three-storey living wall installation, which is 13 m-high and 91 m^2 in area, and includes circa 9,000 evergreen plants from 24 species planted onto a modular interlocking crate system with a soil-based 100 mm deep substrate zone [5], (see Figure 1).

2. METHODOLOGY

The DAB case study thermography exercise was carried out during a single wintertime inspection (given that climate variability within a near-closed indoor system and over a limited campaign is minimal), with atrium conditions immediately preceding the exercise detailed in Table 1. Given the area and vertical span of the installation, it was split by floor level (#03), with each further subdivided into three sectors to present #09 sectors in total for image capture. Following best practice guidelines (presented in [6]), all images were captured at ~2 m above floor level (AFL).

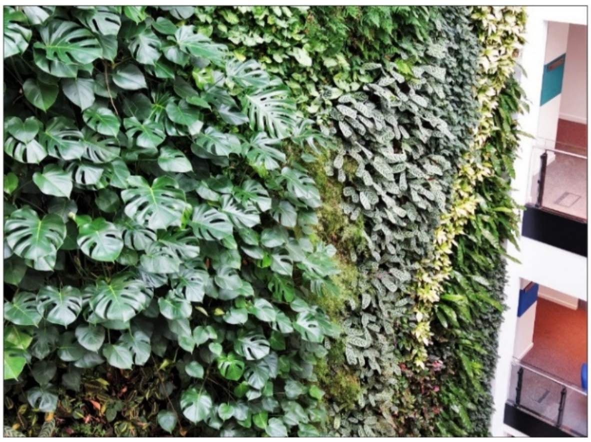


Figure 1. The DAB living wall in its current flourishing state.

Table 1. The DAB atrium conditions preceding the exercise.

Outdoor weather conditions:	Cloudy with scattered rain; T_{air}: 4°C; RH: 7%; and moderately windy: V_{air} ~7.6 m·s^{-1}
Surfaces:	Vegetation leaves visibly dry
$\boldsymbol{D_{IR}}$:	~6 m (Horizontal FOV: 5.00 m; Vertical FOV: 3.75 m; IFOV: 7.79 mm)
$\boldsymbol{T_{air}}$:	21.6°C
$\boldsymbol{T_{ref}}$:	21.5°C
$\boldsymbol{RH}$:	53.9%
$\boldsymbol{V_{air}}$:	0.13 m·s^{-1}

The apparatus used for the exercise included a FLIR T640 camera (see Table 2 for specification); Environmental Meter (manufacturer: PCE); surface temperature probes and logger (HOBO); and a M8475 air velocity transducer (TSI). Analysis was carried out using FLIR Tools V6.4 and ResearchIR V4.40 (FLIR), and MATLAB R2019a (MathWorks).

Table 2. FLIR camera specification.

Parameters	**FLIR T640**
Focal plane array (FPA):	Uncooled microbolometer
Spectral range:	7.5-14.0 µm (within atmospheric window)
Infrared resolution:	640 × 480 (307,200 measurement points)
Standard temp. range:	-40 to 2000°C
Sensitivity:	0.03 K at 30°C
Accuracy:	±2°C or 2%, whichever is greater, at 25°C
Lens focal length:	13.0 mm
Field-of-view (FOV):	45 × 34°

The prerequisite input parameters included: object emissivity (ε_{obj}) of 0.95 (typical for vegetation 0.91-0.97); measured reflected temperature; atmospheric transmissivity (τ_{atm}), calculated from apparent atmospheric temperature (T_{atm}) and relative humidity (RH), measured using the Environmental Meter; and distance to target canopy (D_{IR}), measured with tape-measure.

To characterise the canopy of the case study living wall, six plants with significant coverage area and comparable planting height were selected (see Figure 2). The metrics of *Leaf Size* and *Protuberance* were then defined for each canopy. The *Leaf Size* metric was defined by 'very small/VS' (<50 mm length), 'small/S' (>50 mm and <150 mm), 'medium/M' (>150 mm and <250 mm), 'large/L' (>250 mm and <500 mm), and 'extra-large/EL' (>500 mm) ordinal categories; while *Protuberance* off the host wall surface was defined by 'prostrate/P' (<150 mm), 'medium extension/ME' (>200 mm and <500 mm), and 'extensive extension/EE' (>500 mm) ordinal categories. Blade and needle leaf canopies were considered independently, given their distinct leaf morphologies.

The captured thermogram processing included pre- and post-processing tasks. An example of these steps for a thermogram is presented in Figure 3. Pre-processing prepared captured thermograms for data extraction, which involved enhancement, calibration adjustment, and cropping using FLIR Tools software. Post-processing was achieved using the image processing tools included in FLIR ResearchIR. Segmentation tasks involved partitioning the thermogram into simplified segments for analysis, with the 'thresholding method' used to segment the histogram into temperature ranges of interest [7]. The cooler substrate background was removed to segment out only canopy temperatures of interest. These were refined using user-prescribed 'regions of interest' (ROI), and then averaged to characterise their leaf temperatures [8]. When selecting canopy regions of interest for averaging, self-shaded areas were thresholded out during the segmentation step of post-processing.

The final processing of the data involved the input of thermogram data to the validated *Vertical Greening Model* (VGM) described by [4,9,10], to calculate and present hygrothermal maps for the canopies.

Figure 2 .Plant species examined at the DAB, with 'Leaf Size' and canopy 'Protuberance' categorisation.

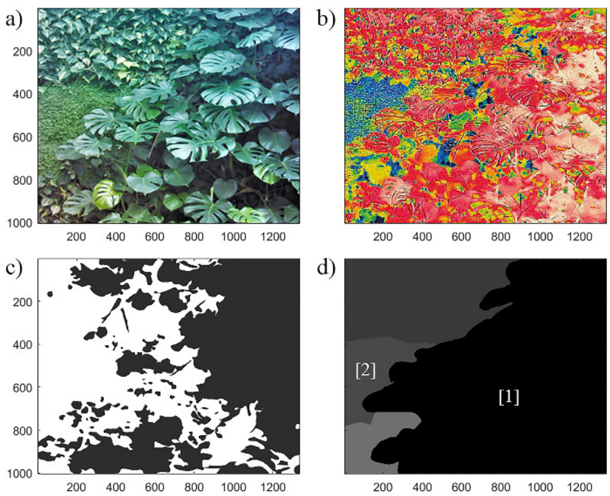
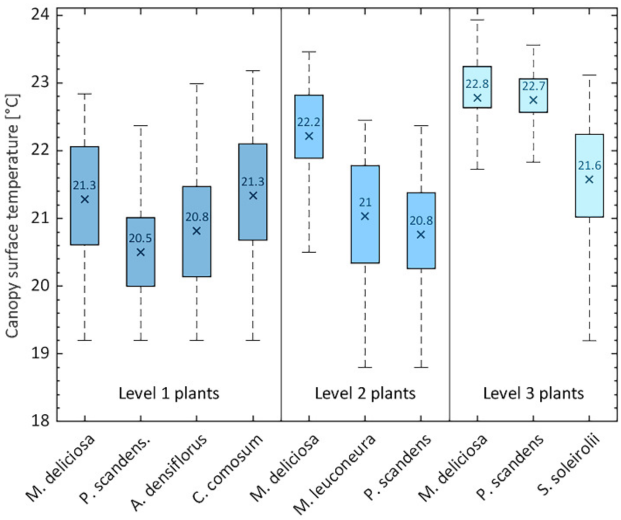


Figure 3. Pre-processed thermogram from level 3 (b); after threshold segmentation (c); and applied user-defined ROI template (d), with M. deliciosa [1] and S. soleirolii [2] ROIs.

3. FINDINGS



Background means	Air temperature (T_{air})	Relative humidity (RH)	Air velocity (V_{air})
Level 3	21.4°C	57.0%	0.08 m·s^{-1}
Level 2	21.5°C	55.5%	0.08 m·s^{-1}
Level 1	21.2°C	59.4%	0.09 m·s^{-1}

Figure 4. Daytime canopy surface temperatures of plants at each installation floor level; ('×' = mean value).

3.1 Canopy observations

The canopy temperatures captured at the DAB case study included ~7.5 million datapoints from nine sectors. The overall canopy temperature means demonstrated stratification over the height of the installation (see Figure 4), with the highest at Level 3 or the top-third section of the installation (21.5°C, standard deviation/SD = 5.60), relative to the Level 1 bottom-third section (18.2°C, SD = 7.41). Notably, the *M. deliciosa* canopy, with its 'extra-large/EL' and 'extensive extension/EE', presented the warmest mean temperatures at each floor level, with the highest at Level 3.

Canopy morphology influence characterised by the *Protuberance* metric presented a weak correlation for daytime canopy temperature means (Spearman's rank-order $r_{s\,(3,\,n\,=\,5)} = 0.224$, $p = 0.718$), while the influence of the *Leaf Size* metric presented a moderate correlation ($r_{s\,(3,\,n\,=\,5)} = 0.527$, $p = 0.361$). These correlations however were statistically insignificant given the limited dataset (only five plant canopies assessed).

3.2 VGM processed results

The exercise of coupling the *Vertical Greening Model* (VGM) with the segmented canopy analysis approach presented high-resolution mapping of sensible and latent flux, as well as vapour flux distribution. Figure *5* presents these plots for the same section of the wall as in Figure 3. It highlighted again the *M. deliciosa* canopy, with its 'extra-large/EL' and 'extensive extension/EE' to present relatively higher vapour flux, which in turn translated to relative humidity mapping nearer to the ambient environment.

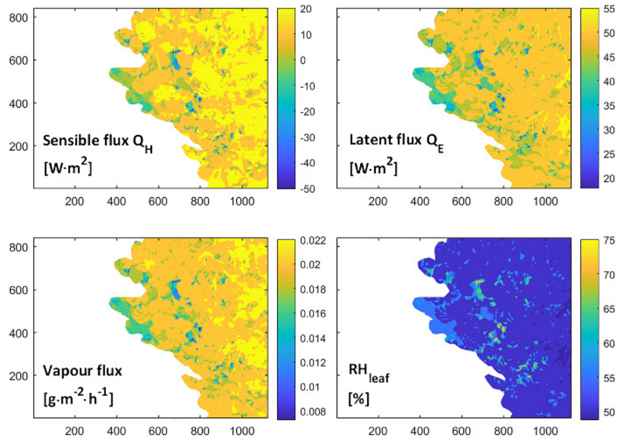


Figure 5. VGM coupling with thermography application to assess M. deliciosa canopy vapor flux.

4. DISCUSSION

Surface temperature is a standard parameter measured when assessing the thermal influences of vertical greening installations. As with plant science studies, preceding vertical greening studies have taken measurements as either point or limited array thermocouple readings of representative canopies. There is good representation of such thermocouple-based studies in both laboratory and on-site settings dating from the 1980s [11], with several having highlighted significant surface temperature reductions resulting from green cover presence relative to untreated control conditions [12]. The use of thermography for such assessments however has received modest attention at present, despite its established advantages of offering higher-resolution arrays of quantitative data, non-invasive capture, and near instantaneous outputs. All such benefits could be considered advantageous when considering in-situ assessments, where invasive contact methodologies are challenging to implement. This is of relevance to current living wall studies in particular, where attention is diverting from laboratory work to in-situ assessments to identify applied performance and maintenance related issues [3,11].

The qualitative application of thermography has ample precedent in vegetation performance and maintenance diagnostics. It provides the opportunity for an experienced assessor to visually examine canopy temperatures to qualitatively diagnose stress. Furthermore, it facilitates the location of fertigation network routes and any flow disruptions to support system maintenance, as well as assess substrate properties to determine dynamic thermal influence. The latter is attributed to substrate moisture retention affecting the medium's thermal resistance (increased conductivity and heat capacity), as well as increasing evaporation to cool its surface. In this study for example, the coolest surface temperatures were captured where the soil-based substrate was exposed to highlight its evaporative cooling influence and function as a high moisture retentive growth medium. Maintaining elevated moisture availability is particularly critical for hydroculture or felt-based systems with moderate retention capacity, as they rely on a permanently saturated growth medium to sustain plant health. The detection of relatively warmer substrate temperatures could indicate a moisture deficit resulting from irrigation shortfalls. The qualitative detection of such conditions present useful early warning that enables prompt remedying action. The effectiveness of this however is still dependent on the thermographer's experience and judgment, which may not always be available. Stress detection relevant for automated precision fertigation responses in contrast require higher accuracy data gathering and processing, which is best achieved with approaches including quantitative thermography application.

4.1 Surface temperature effects of canopy features

In this study, quantitative thermography was used to characterise the plant canopy of an indoor installation, described by the variables of *Protuberance* off the vertical surface and *Leaf Size*. The quantitative assessment confirmed broad and larger-leaf canopies that project off the wall surface (i.e., with higher *Protuberance*), to present much warmer temperatures relative to smaller-leaf surface spreading (prostrate) canopies.

Canopy morphological properties are identified by studies to affect the typically dominant shading effect of vegetation cover (i.e., the irradiance interception function), while to a lesser extent affect evapotranspiration efficiency [13]. Canopy density is characterised in such studies by a leaf area index value (LAI between 0-10), while cover extent is characterised by 'percentage cover' (0-100%). With vertical greening applications, the LAI definition is modified to represent the ratio between the total leaf area and exposed vertical wall area. In this study, the focus was the canopy itself with the background wall surface segmented out to isolate only the target plant canopies. The percentage cover was therefore near-100% (segmentation error), while the vertical LAI for each canopy was always >1.

The varying three-dimensional projections of the considered canopies were simplified for analysis by defining three categorical levels of *Protuberance*. Higher *Protuberance* represented conditions where canopies would be decoupled from the wall substrate to be in increased contact with the ambient atmosphere, while prostrate canopies would be well-coupled with the substrate and its moisture-rich surface climate. At the same floor level of the installation and elevational planting height, the most prostrate of canopies presented the highest canopy-to-air temperature differences (i.e., negative ΔT_{veg}), while the most *Protuberant* canopies presented the lowest (predominantly positive ΔT_{veg} values). The floor level of the installation is a relevant consideration given the presence of a stratified microclimate in the atrium, with proximity to the skylight affecting the radiation loading received and resultant influence on surface temperatures.

In addition to *Protuberance*, the proportions of leaves also influence canopy surface temperatures. There is ample observational evidence from plant science studies that highlight warmer temperatures for larger-leaved canopies relative to smaller-leaved ones from the same environment [8]. A few vertical greening observations have also highlighted agreement, with Charoenkit & Yiemwattana [14] for example, having observed the smaller leaves of *Cuphea hyssopifolia* to demonstrate higher cooling efficiency relative to the larger-leaved *Excoecaria cochinchinensis*. This is explained by the way individual leaves aid the coupling of the canopy to the ambient atmosphere. *Leaf Size* and leaf morphology, together with prevailing airflow speed, determine the leaf boundary layer depth, with the latter inversely related to the leaf boundary layer conductance. Higher boundary layer conductance allows for leaves to be well-coupled with the atmosphere to facilitate efficient latent and sensible convective heat dissipation to result in relatively cooler leaves [13]. Smaller (e.g., *S. soleirolii*), pinnated, compound, or dissected leaves, stay cooler in similar conditions as their boundary layer conductance is increased from a shallower boundary layer depth [15]. The rate of heat convection per unit area is therefore greater between the leaf and air for smaller leaves than larger leaves [16]. This smaller-leaf benefit is acknowledged in climate adaptation, with such leaves commonly seen on plants from hot and dry climates, where adaptations to minimise transpirational water loss necessitates reliance on enhanced sensible convection to dissipate the higher irradiance loading typically encountered.

Larger leaves in contrast generate a deeper boundary layer to result in reduced conductance, which in turn contributes to relatively higher leaf temperatures. The canopy-to-air temperature differences (ΔT_{veg}) for the *M. deliciosa* canopy agreed, with positive values presented at all three atrium floor levels. This increased leaf temperature also serves to increase the saturation vapour pressure within the leaf, which in turn increases the vapour gradient with the ambient atmosphere. This gives rise to a higher rate of transpiration and resultant latent heat loss. The lower convection efficiency of such larger leaves is therefore compensated by enhanced transpirational cooling, provided neither a water deficit nor irradiance stress exists. Well-hydrated larger leaves as a result cool more rapidly through transpiration to help dampen their higher temperatures [16], which is exploited by plants from hot and humid climates, where ample supply of water and growth factors are available (as exemplified by the large-leaved tropical epiphyte *M. deliciosa*).

Larger leaves however present complex morphologies, with their size and weight resulting in them distorting to present a convex geometry to radiation loading that leads to heterogeneous absorption. This together with the heterogeneity of hydraulic and stomatal function, can result in a larger range of leaf temperature distribution [17]. Leigh *et al.* [16] for example, found a positive correlation between the metrics of *Leaf Size* and the temperature range per leaf. This highlighted single-point thermocouple measurement of larger leaves to present nonrepresentative temperatures, while the higher resolution of thermography allows for this heterogeneity to be captured.

The significance of leaf convective boundary layer influence on heat dissipation however reduces at very low wind speeds (<0.25 $m \cdot s^{-1}$). In such near still conditions, forced convection gives way to the dominance of the less efficient dissipation from natural convection [16]. At the DAB case study, where the indoor airflow mean was 0.13 $m \cdot s^{-1}$, the dominant canopy cooling influence would thus be through transpiration. Given this, when tropical large broadleaved plants are used in such indoor environments, higher watering rates are likely to be required in the summer to alleviate leaf heat stress. Increasing summertime water supply in such conditions will also serve to increase the beneficial microclimate cooling contributions from the canopy, although it is likely to encourage aggressive growth that in turn would require frequent maintenance trimming to prevent canopy dominance and overshadowing (as experienced with the *M. deliciosa* canopy at the DAB study).

4.2 Quantitative application

Preceding plant science studies have applied quantitative thermography to detect stress in agricultural crops. This application is based on increased canopy temperatures observed with plant senescence, typically induced by disruptions in water and nutrient uptake and transportation triggered by biotic or abiotic stressors. Biotic stress induced by pest or pathogen attack result in distinct canopy temperature differences, with thermography used to locate and diagnose conditions, often prior to chromatic or morphological symptoms become apparent. The method is also used to assess abiotic stressors such as nutrient stress by examining radiation spectral properties, with studies having demonstrated most nutrient deficiencies to be clearly distinguished from water stress [18]. Water stress detection nevertheless remains as the dominant abiotic stress management interest of current quantitative thermography applications [8]. Such studies have demonstrated detected canopy temperatures to clearly differ between irrigated and non-irrigated states, as well as irrigation intensities [18]. The method therefore has the requisite sensitivity, with non-contact application utilised for scaled-up data collection of larger vegetated areas. It is worth noting that the thermography-based systems being developed at present focus on applying these benefits to monitor horizontally distributed agricultural or natural ecosystem canopies (e.g., [19]), while vertical greening canopies have yet to receive significant attention.

As thermography could be used to quantify the canopy-to-air temperature differences (ΔT_{veg}), a leaf energy balance could be formulated (see Equation 1) to quantify stomatal conductance, transpiration rate, and water status [19]; as well as vegetation associated microclimate cooling contributions [20,21].

$$\Delta T_{veg} = T_{leaf} - T_{air}, \qquad \textit{Equation 1}$$

$$= \frac{r_{HR}\,(r_W)\,\gamma R_{ni} - r_{HR}\,VPD\,\rho c_p}{\rho c_p[\gamma(r_W) + s r_{HR}]},$$

…where: T_{leaf} and T_{air} are leaf and air temperatures [K] respectively; r_{HR} is the parallel resistance to heat and radiative transfer [$s \cdot m^{-1}$]; γ is the psychrometric constant [$Pa \cdot K^{-1}$]; R_{ni} is net isothermal radiation [$W \cdot m^{-2}$], ρ is the density of air [$kg \cdot m^{-3}$]; c_p is the specific heat capacity of air [$J \cdot kg^{-1} \cdot K^{-1}$]; s is the slope of the curve relating saturation vapour pressure to temperature [$Pa \cdot K^{-1}$]; and VPD is the vapour pressure deficit of air [Pa].

The coupling of thermography data output with the VGM used this principle to calculate and present flux mapping for the living wall canopy examined. These maps highlighted latent flux and vapour flux to be at their highest at the most *Protuberant* parts of the canopy, where the leaves are well-coupled with the ambient atmosphere and its drying power. The relative humidity at the leaves (RH_{leaf}) was maintained in most areas at between 50-55%, which falls within the desired range to achieve occupant comfort in an indoor environment. The vapour flux generated by the canopy therefore did not contribute to undesirable RH enhancements beyond ambient atrium levels. This corresponds with previous observations that have highlighted vapor generation to be re-purposed by canopies to maintain foliage health in the first instance, leading to lower surrounding RH increases than expected [22]. Exclusive reliance on leaf relative humidity (RH_{leaf}) to determine irrigation demand must therefore be cautioned, as lower values do not necessarily indicate a substrate water deficit. This is particularly significant when considering tropical plants with recommended RH_{leaf} requirements between 85-95%, the strict adherence to which could result in oversupply, and given their adaptations to thrive in water abundant conditions, could increase growth-related maintenance burdens. To address this, thermography-based monitoring must be supported with substrate moisture detection to determine appropriate water demand.

5. CONCLUSION

In this study, surface temperature features of an indoor living wall canopy were assessed using quantitative thermography. The assessment revealed plant canopies characterised by large *Leaf Size* and substantial *Protuberance* to be well-coupled with the atrium atmosphere to present warmer surface temperatures proximate to ambient levels, while smaller-leaf and surface spreading canopies were much cooler and proximate to substrate temperatures. The increased vapor flux presented by the former highlighted potential for Increasing summertime transpirational cooling (and potentially reduce space-cooling loads) with increased water supply to such canopies; although this would also encourage aggressive growth that in turn would require frequent maintenance trimming to prevent root push-back and canopy dominance.

The study also demonstrated quantitative thermography use as an effective non-invasive methodology to assess living wall canopies. By coupling it with a validated *Vertical Greening Model* (VGM), the study demonstrated the method's viability for enhancing living wall maintenance and management pathways, with further development presenting opportunity to contribute to automated precision fertigation and real-time biotic stress detection. The development and deployment of such systems would mean that maintenance and resource costs could be lowered to promote the widespread application of such green infrastructure installations, which would in turn contribute towards enhancing the climate resilience of urban built environments.

6. ACKNOWLEDGEMENTS

The work described in this paper was part of a doctoral project funded by the UKRI | Engineering and Physical Sciences Research Council [1930753].

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