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Best practice:
thermography application in built environment studies

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Abstract

This method paper presents best practice guidance on qualitative and quantitative thermography application in built environment studies, with focus on the novel application of examining and monitoring vertical greening installations, an increasingly common solution implemented to enhance the climate resilience of urban buildings. Exemplar vertical greening studies have been presented here, with the qualitative application highlighting potential for identifying performance and maintenance issues, as well as providing *prima facie* indication of plant stress. Detailed aspects of plant performance assessment, as well as abiotic and biotic stress detection are however emphasised to require quantitative application using additional processing tools. The paper demonstrates that despite typical limitations concerning camera accuracy, usage errors, and interpretation cautions, the methodology to be an effective non-invasive approach pertinent not only for research purposes, but also long-term built environment management and maintenance applications.

Keywords: thermography; thermal imaging; surface temperatures; building thermography; monitoring vertical greening

1.0 Introduction

Thermography describes a methodology that captures the radiant infrared energy distribution emitted by a target object of interest [1]. Planck's Radiation Law states that every object with a temperature above absolute zero (0 K) emits electromagnetic radiation in the infrared (IR) region of the spectrum (wavelengths between 0.78 and 1000 µm). The Stefan-Boltzmann Law states that the amount of infrared radiation emitted by such an object to depend on its emissivity and absolute temperature, which is quantified by the Equation: $W = \varepsilon \, \sigma \, {T_s}^4$; where W is the total infrared radiation emitted [W·m^{-2}], ε is emissivity [dimensionless], σ is the Stefan-Boltzmann constant 5.67×10^{-8} [W·m^{-2}·K^{-4}], and T_s is the surface temperature [K]. Thermography captures this emitted infrared radiation by utilising camera optics to focus it onto an array of sensors described as the detector focal plane array (FPA), with the resulting electrical response signal converted and output as a thermogram. Typical infrared cameras capture radiation in the longwave wavelengths between 7.5-13.5 µm, which is described as the 'atmospheric window' where neither water vapour nor CO_2 interferes with infrared transmission [1–3].

The radiation flux captured by the camera (W_{tot}) includes radiation from the target object's surface (W_{obj}); radiation that was first emitted by the background and then reflected by the object (W_{ref}); and atmospheric influence, where the atmosphere between the object and the camera attenuates both the former radiation components by absorption, and adds radiation by atmospheric emission (W_{atm}):

$$W_{tot} = W_{obj} + W_{ref} + W_{atm}, \qquad \textit{Equation 1}$$

$$W_{tot} = \tau_{atm}\, \varepsilon_{obj}\, \sigma\, {T_{obj}}^4 + \tau_{atm}\left[1 - \varepsilon_{obj}\right]\varepsilon_{sky}\, \sigma\, {T_{ref}}^4 + \left[1 - \tau_{atm}\right]\sigma\, {T_{atm}}^4. \qquad \textit{Equation 2}$$

...where, T_{obj}, T_{ref}, and T_{atm} are the object surface temperature, reflected temperature (typically T_{sky} for outdoor conditions), and apparent atmospheric temperature (or ambient air temperature [4]), respectively; and τ_{atm} is atmospheric transmissivity, which is calculated from atmospheric air temperature (T_{atm}), relative humidity (RH), and the distance between the target object and infrared sensor (distance D) [1,3,5]. The contributions from W_{ref} and W_{atm} sources are compensated automatically by onboard processing, which assumes solar scattering in the atmosphere and stray radiation from intense radiation sources outside the camera's field-of-view (FOV [i]), as negligible. The emissivity of the object (ε_{obj}), reflected temperature (T_{ref}, measured or calculated), and above parameters for calculating atmospheric transmittance, must be known input quantities and recorded at site prior to capture [6].

Thermography application in thermal studies can be distinguished as either qualitative or quantitative, with some employing both [6]. With qualitative studies, the application is 'passive' and captures the temperature differences of the target object under conditions not modified by the thermographer (i.e., the assessor). The approach typically locates an anomaly, and a qualitative indication of severity may be expressed depending on the experience of the interpreting expert. Such assessments do not attempt to accurately quantify the degree of severity, and therefore may not require research grade infrared cameras [7]. Quantitative investigations however require infrared cameras with higher-accuracy that may be used under passive conditions, as well as 'active' conditions (dynamic; non-equilibrium; or non-steady-state), where the temperature differences of the target object are generated by using an external thermal stimulus [6]. The active approach is typically considered when the temperature contrast of the target object is difficult to distinguish, or for identifying deeper defects in object materials. The nature of the used stimulus further distinguishes (see Fig. 1) active thermography as either 'pulsed' (short pulsed thermal input), or 'lock-in' (sinusoidal input) [6,7].

[i] FOV is a measure of the angular view path of what the camera sees. It determines the thermographer's overall viewing area and is defined by horizontal and vertical angles, measured in degrees.

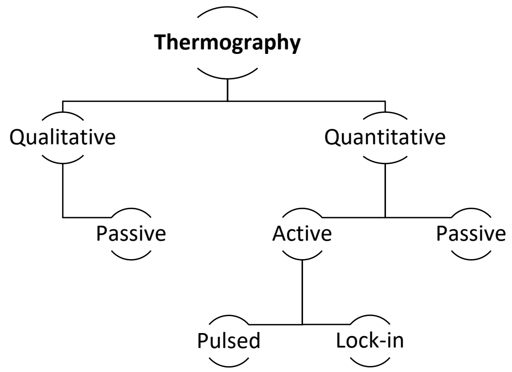


Fig. 1. Thermography application approaches.

2.0 Application in built environment studies

Thermography has been used in built environment research since the 1980s, and has gained increased prominence over the past two decades as a significant diagnostic tool in the drive to reduce building energy consumption [6–8]. It is typically used for qualitative passive diagnostics to identify defects in building envelopes such as insulation gaps, thermal bridging, cracks, voids, infiltration, and moisture issues, as well as to detect hot or cold anomalies of mechanical and electrical systems [6,9].

The commonly used passive assessment methodology is described in the British Standard BS EN 13187 [10]. It involves a thermographer (the person carrying out the exercise), examining all external and internal building components for thermal anomalies, and when found recording thermograms for qualitative analysis and eventual inclusion in a survey report. The British Standard prescribes that such assessments should be carried out when background wind speeds are less than 5 $m{\cdot}s^{-1}$; the temperature difference between indoor and outdoor spaces is at least 10 K; the surfaces examined are free from direct solar exposure both for hours preceding and during the survey; and undertaken during cloudy conditions to avoid reflecting a clear sky [10].

In addition to such qualitative applications, quantitative application is increasingly utilised for determining in-situ U-values during new build facade construction, as well as when retrofitting existing buildings [11]. This involves the translation of captured raw data using supplementary software, or may even involve the coupling of specific numerical models to process and deliver outputs for analysis.

3.0 Application in vegetation studies

Thermography has been widely utilised to characterise plant canopy temperatures in agricultural (e.g., [12]) and in natural ecosystem studies (e.g., [3,5,13]). The method has also been used for assessing soil moisture content (e.g., [14]), and levels of microbial activity (e.g., [15]); and thus is significant for managing abiotic and biotic plant stressors [6]. Some studies have investigated these aspects using large area applications such as aerial remote sensing to study large plant communities, while others have used ground-based in-situ applications often to consider specific plant canopies. The non-contact methodology is therefore well-established for monitoring physical and physiological characteristics of entire plant canopies to assess performance, as well as stress [16–18]. Recent years have seen this experience extended to study vertical greening installations (the intentional application of vegetation to vertical building surfaces, [19–21]), which combines vegetation and built environment considerations.

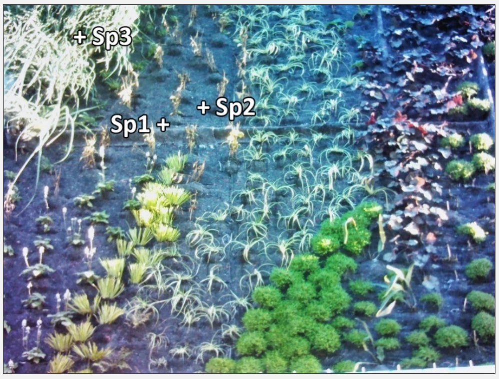
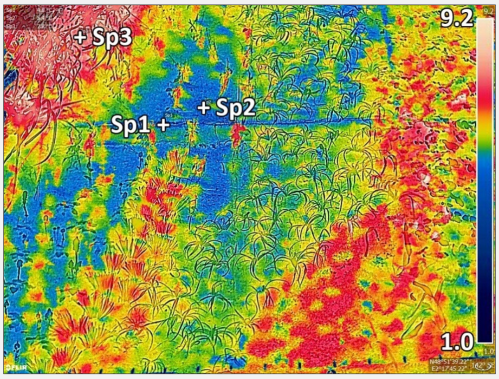
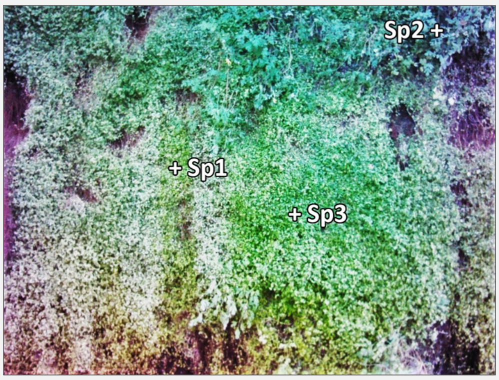
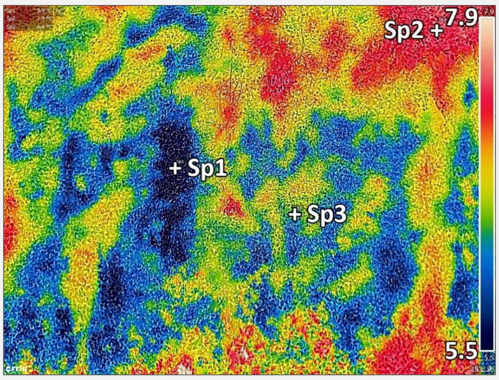
Much like early plant science studies (e.g., [22,23]), thermocouple-based assessments have dominated early vertical greening studies concerned with assessing the thermal influences of such installations. Typically, such measurements have been taken as either point or limited array thermocouple readings of representative sample canopies. There is good representation of studies in both laboratory and on-site settings dating from the 1980s [19,24], some of which had notably highlighted significant surface temperature reductions (up to 30 K), resulting from green-cover presence relative to bare control conditions (e.g., [25,26]). Notwithstanding this existing body of work and findings, the use of the methodology has been criticised for the limited number of point readings relied upon, which overlooks the widely acknowledged heterogeneity of canopy and leaf temperature distributions [22]. While thermography has gained attention as an approach that addresses this shortcoming, the uptake in vertical greening studies is relatively low at present. This is despite its advantages of offering higher-resolution arrays of quantitative data, non-invasive capture, and near instantaneous qualitative summaries. All such benefits could be regarded as particularly advantageous when considering in-situ assessments, where invasive contact methodologies may be prohibitive. This is of relevance to current living wall studies (the newer category of vertical greening applications including a fertigated vertical substrate zone into which plants are planted), where the focus is shifting from laboratory-based experiments to in-situ monitoring that aims to identify practical performance and maintenance issues [19].

Qualitative application presents its value when monitoring performance, as well as in maintenance diagnostics. With such tasks, the experienced assessor visually identifies canopy temperature observations and irrigation aspects to qualitatively determine areas of concern. From a living wall systems maintenance perspective, it provides the assessor with the opportunity to non-invasively identify and locate the embedded fertigation network, as well as identify any flow disruptions resulting from blockages or leaks (best detected with thin-substrate systems in contrast to deeper soil-based systems). Substrate properties of such systems can also be assessed to determine system thermal performance. This is associated with substrate moisture retention affecting the medium's thermal resistance (increased conductivity and heat capacity), in addition to evaporation influence [27].

3.1 Passive qualitative assessments

An example of qualitative application is presented in Table 1, which highlights significant observations of a living wall installation associated to point surface temperature readings. The coolest surface temperatures are noted where the substrate of the installation is exposed, which confirms its function as a moisture-rich growth medium. Moisture richness is particularly critical for such hydroculture or felt-based systems, as they rely on maintaining a permanently saturated growth medium to facilitate plant growth. The detection of relatively warmer substrate temperatures is therefore likely to be the result of an irrigation deficit, with substantially warmer temperatures indicating a critical fault requiring immediate attention. Although such qualitative detection is useful from a monitoring and maintenance point of view, correct diagnosis is dependent on the assessor's experience. Precision performance monitoring and stress detection, particularly when considering automated responses, requires quantitative methodologies to be implemented.

Table 1. Passive qualitative assessment of the Quai Branly Museum living wall.

Study	**Description**	The single inspection exercise was carried out at the Quai Branly Museum in Paris, on 25 November 2017, afternoon. Due to felt replacement and replanting works in progress at the time, only half the installation had plants at a mature stage of growth, while the other had exposed felt and some young plant-plugs in place. As examples, thermograms from each half of the installation are represented with corresponding qualitative observations.
	Apparatus	FLIR T640 infrared camera
Conditions	**Outdoor weather conditions**	Cloudy with intermittent sunny skies; and moderately windy: air velocity (V_{air}) ~4.18 m·s^{-1}
	Outdoor wall surface conditions	Morning rain had left the surroundings damp
	Distance D	~3 m (Horizontal FOV: 2.50 m; Vertical FOV: 1.90 m; and Instantaneous FOV/IFOV: 3.89 mm)
	Air temperature (T_{air})	5.4°C
	$T_{ref} = T_{sky}$	-16°C (calculated for 0.5 cloudiness [28])
	Relative humidity (RH)	80.6%
	Colour Image	**Composite thermogram**
Replanted half, mid-area - (a)		
Mature half, base-area - (b)		

Observations		
	▪ Vegetation generally showed cooler canopy surface temperatures relative to other surrounding building façade elements. ▪ The exposed felt (a) was significantly cooler (e.g., a-Sp2) relative to the surrounding canopy foliage. ▪ The dark blue horizontal and vertical lines evident with (a) highlight significantly cooler irrigation pipework embedded in the felt (e.g., a-Sp1). ▪ Some areas with mature foliage (e.g., b-Sp1) demonstrated ~2 K cooler surface temperatures.	**a-Sp1:** 4.77°C (cooler irrigation pipe below felt) **a-Sp2:** 5.38°C (exposed moist felt) **a-Sp3:** 7.80°C (warmest young foliage) **b-Sp1:** 5.41°C (coolest mature foliage) **b-Sp2:** 7.44°C (warmest mature foliage) **b-Sp3:** 6.37°C (relatively cooler mature foliage)

3.2 Passive quantitative assessments

Previous vegetation studies have applied thermography to quantitatively understand and assist stress management, particularly focusing on canopies with economic value such as agricultural crops. This is predicated on canopy temperature increases identified with plant senescence, which is typically induced by disruptions in water and nutrient uptake and transportation triggered by biotic or abiotic stressors [18,29]. Biotic stress induced by pest or pathogen attack for example can result in distinct canopy temperature differences, with the methodology presenting opportunity to locate and diagnose such conditions [16]. The temperature changes are triggered by stomatal deregulation [29,30], with stomatal aperture reduction observed as an innate immune response to restrict pathogen invasion [31]. The ability to detect the resulting temperature changes is very useful, as conditions of plant stress may be identifiable from even subtle differences, and critically, prior to typical chromatic or morphological symptoms become apparent [29,32,33]. Pest and disease influence is similarly detectable, as canopy physical properties are altered directly to modify the amount and direction of radiation reflected and emitted [32]. The methodology has again proved useful in identifying such infection or attack extents, as well as their distribution patterns [34], while at higher resolutions it can highlight the characteristics of inflicted damage (e.g., [35]).

Thermography can also be used to assess abiotic stressors such as nutrient stress, by examining the radiation spectral properties of canopies. Plant science studies have demonstrated deficiencies to be clearly distinguished between nutrient and water stress [16,36]. The latter aspect of water stress detection is by far the most significant and common abiotic stress management focus of quantitative thermography application at present [3,18]. Such studies have demonstrated clear temperature differences between irrigated and non-irrigated canopies, as well as between different intensities of irrigation. This existing evidence base has therefore presented thermography as a viable methodology for application in real-time vegetation maintenance and management plans [12,14,16].

An example of qualitative thermography application is presented in Figure 1. This single inspection exercise of an indoor living wall installation was carried out in Cambridge, England. The apparatus used included a FLIR T640 infrared camera (same as the qualitative example), with key specifications described in Table 2 (FLIR Systems Inc., Wilsonville, Oregon, USA); and a PCE Instruments Environmental Meter with hygrothermal probes. All processing and analyses were carried out using FLIR Tools V6.4 and FLIR ResearchIR V4.40, and MATLAB R2019a software.

Table 2. FLIR infrared camera specifications.

Specification	**FLIR T640**
	
Detector 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 temperature range	-40 to 2000°C
Sensitivity	0.03 K at 30°C
Accuracy	±2°C or 2%, whichever is greater at 25°C
Visible image	Integrated 5.0-megapixel camera
Lens focal length	13.0 mm
Field-of-view (FOV)	45 × 34°

The prerequisite inputs ε_{obj}, T_{ref}, and the parameters for calculating τ_{atm}, were recorded prior to thermogram capture. The applied values were determined as follows: ε_{obj} of 0.95 (typical for vegetation between 0.91-0.99 [17,37,38]); T_{ref} measured in the indoor environment using the crumpled aluminium reflector method; τ_{atm} calculated from T_{air} and RH measured with the Environmental Meter; and distance D measured with a measuring tape. The thermograms were taken during a single inspection, at ~2 m above finish floor level (AFFL), and in conditions with no interference from overshadowing or intense irradiation from surrounding objects. The thermography also followed best practice guidelines of allowing for an adjustment period prior to capture; avoiding framing the target at acute angles (perpendicular to target surface where possible); and capture in focus. The captured thermograms were then subjected to pre- and post-processing tasks, with the algorithm for a single thermogram represented in Figure 1.

Pre-processing tasks prepare the captured thermograms for data extraction, which could involve enhancement, cropping, and adjustment of the reflected temperature and infrared temperature scale. This can be achieved using the camera manufacturer's standard software (i.e., FLIR Tools). This would also allow for spot temperature extraction, which can be used to inform and support qualitative observations (e.g., see Table 1).

Post-processing is required to extract and translate data for detailed quantitative analysis. The captured thermograms could be post-processed using image processing models (e.g., MATLAB 'Image processing toolbox'), or by using compiled software with equivalent functionality such as FLIR ResearchIR (used for this exemplar application). The former MATLAB-based approach uses greyscale values to calculate pixel temperatures, an example of which was presented by Cohen *et al.* [12]:

$$T_{(x,y)} = T_{min} + \frac{T_{grey}}{255}\,(T_{max} - T_{min}) \qquad \textit{Equation 3}$$

...where $T_{(x,y)}$ is the pixel-specific (x, y) temperature calculated; T_{grey} is the greyscale intensity of the (x, y) pixel ranging between 0 to 255; T_{min} and T_{max} are the minimal and maximal values of the thermogram temperature scale (corresponding to greyscale '0' for black, and '255' for white). Using the more advanced FLIR ResearchIR software however allows for thermogram temperature data to be extracted and processed directly. The key steps include pre-processing, segmentation, and region of interest (ROI) extraction:

1. Pre-processing prepares thermograms for data extraction, which may involve enhancement, calibration adjustment, and cropping.

2. Segmentation involves partitioning the thermogram into simplified segments for analysis. Typically, the 'thresholding method' is used to segment the histogram of the thermogram into temperature ranges of interest [6]. In this exercise for example, the background including the cooler substrate was removed to segment-out only canopy temperatures relevant for further analysis.

3. Region of interest (ROI), or feature extraction may be determined by data analysis (e.g., connected pixels within a certain intensity range), or user prescribed. In this exercise for example, the latter user prescribed approach was used to extract temperatures of specific plant canopies.

As demonstrated by Kim *et al.* [3], the ROI pixel temperatures could be averaged to characterise temperatures for each canopy. However, care must be taken when selecting canopy ROIs for averaging, with distinction made between irradiated and self-shaded areas [39]. Typically, self-shaded areas are thresholded out during the segmentation step of post-processing to include only irradiated regions of interest.

The data extracted from such an exercise could be utilised directly to study surface temperature associated trends. This could be achieved with static thermography (i.e., single or series image capture), as well as with dynamic thermography (i.e., high frame-rate capture). The latter certainly requires advanced cameras with such capability, as well as computational power to pre- and post-process the captured data. The computational demand would also require significant enhancement if real-time capture and processing is desired. Furthermore, surface temperature associated assessments could be extended when processing data by coupling advanced processing models. With canopy assessments, as with the examples presented in this paper, there is opportunity therefore to couple transpiration and productivity models to offer complete vegetation assessment pathways.

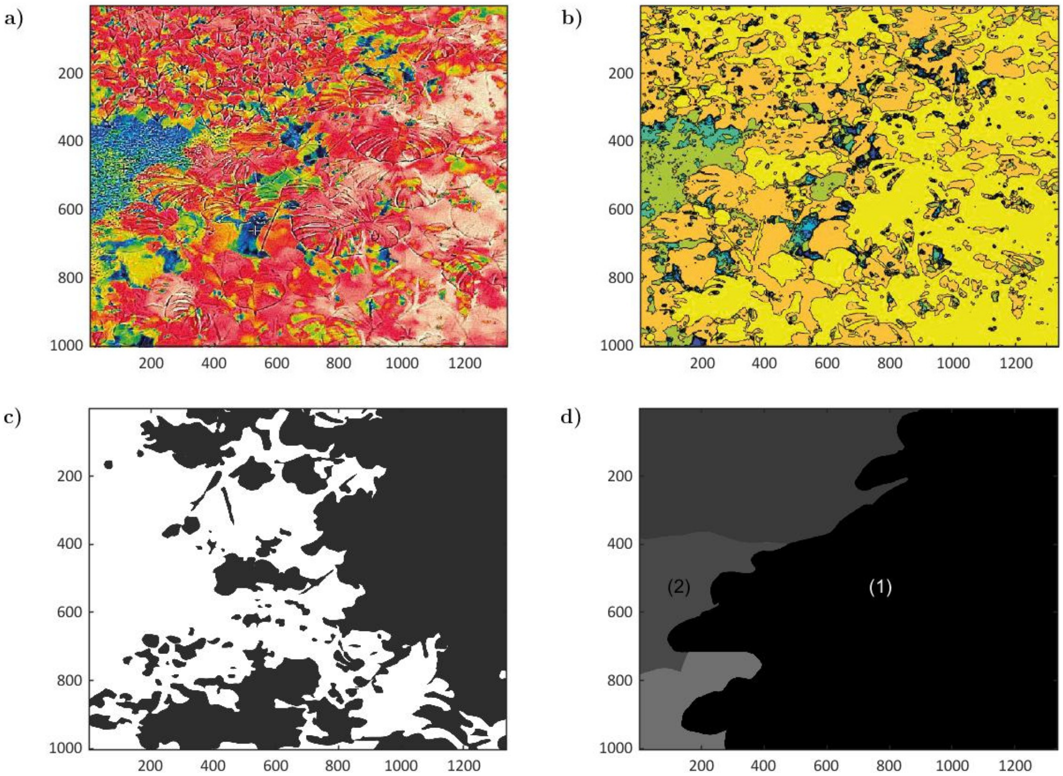


Figure 1. Pre-processed thermogram of a living wall section (a); same thermogram after threshold segmentation (b); segmented canopy data of interest (c); user-defined ROI template for data extraction (d), with e.g., Monstera deliciosa (1) and Soleirolia soleirolii (2) canopy ROIs.

3.3 Thermography application to estimate transpiration

Evaporative cooling from transpiration represents the dominant component of the vegetation latent flux, and the principle means by which canopies lose heat to manage heat stress [39,40]. Transpiration therefore affects the leaf and canopy energy balances to reduce their sensible flux and temperature, while being dependent on the water status. The plant leaf-to-air temperature difference (ΔT) is a key transpiration driver and has an inverse proportional relationship to the transpiration rate. Quantifying this temperature differential could therefore be used for estimating the transpiration rate, stomatal conductance (g_s), water status, and vegetation associated microclimate cooling [16,18,20,37,41].

As thermography could be used to quantify ΔT of canopies, the methodology has been utilised previously to calculate plant water status, develop a crop water stress index (e.g., energy balance-based CWSI, [37,42]), and a stomatal conductance index (e.g., I_G defined by Jones [37]), to support the precision irrigation of agricultural crops [18,43,44]. The ΔT relationship to stomatal conductance (g_s), or its inverse of stomatal resistance (r_{lW} is the leaf resistance to water vapour loss that is assumed to be dominated by stomatal resistance), is presented by the leaf energy balance, which was defined by Jones [37,40] as:

$$\Delta T = T_{leaf} - T_{air} = \frac{r_{HR}\,(r_W)\,\gamma R_{ni} - r_{HR}\,VPD\,\rho c_p}{\rho c_p[\gamma(r_W) + s r_{HR}]}, \qquad \text{Equation 4}$$

...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·m^{-1}]; γ is the psychrometric constant [Pa·K^{-1}]; R_{ni} is net isothermal radiation (net radiation for a leaf at air temperature) [W·m^{-2}], ρ is density of air [kg·m^{-3}]; c_p is the specific heat capacity of air [J·kg^{-1}·K^{-1}]; s is the slope of the curve relating saturation vapour pressure to temperature [Pa·K^{-1}]; and VPD is air vapour pressure deficit [Pa].

For 'amphistomatous' leaves (i.e., stomata on both sides), r_W is the sum of boundary layer and stomatal resistances to water vapour $(r_{aW} + r_{lW})$ [s·m^{-1}], while for 'hypostomatous' leaves (i.e., stomata only on one side) it is $2\,r_{aW} + r_{lW}$ [37,45]. Care must be taken to correctly identify the stomatal distribution, as well as the response behaviour for the plants concerned [16,39]. Those displaying 'isohydric' behaviour (i.e., regulates plant water potential by closing stomata in response to a decrease in soil water and/or an increase in VPD), provide better indication of water status or stress than those displaying 'anisohydric' behaviour (i.e., poor stomatal control and leaf water potential decreasing with increasing evaporative demand), as with the former, stomatal conductance (g_s) is a better indicator of soil moisture than leaf water potential [16,46].

In addition to the requirement for correct input of data to the transpiration model, thermographic detection sensitivity to background climate conditions must be considered. Hot, dry conditions typically present the greatest temperature differences between stressed and non-stressed canopies, while humid, cooler, and low leaf-to-air vapour pressure difference (VPD) conditions present the lowest. Encouragingly, the latter conditions have still been shown to present detectable differences to demonstrate application validity [16,43]. The study by Kim *et al.* [3] found ground-based thermography to present reasonably accurate leaf temperatures (1.3-1.6 K mean error) in moderate and warm climates (background temperatures between ∼10 - 25°C), while in contrasting cooler or very hot environments, further correction was recommended.

4.0 Typical sources of error and limitations

- Infrared camera or sensor used:

The accuracy of infrared cameras is continually improving with typical cameras having an accuracy of ±2% (used for the examples), while advanced models have an accuracy of ±1% for a defined temperature range. Quantitative research requires the highest degree of accuracy, given that no available camera has been validated to be as accurate as a contact temperature measurement method [6]. A key consideration is the spot-size-ratio (SSR), which describes the ratio between the focal plane array (FPA) of detectors and the field-of-view (FOV) of the camera optics. The highest FPA and narrowest FOV offers the best infrared resolution for a given target, which in turn presents the highest detail typically necessary for quantitative research tasks [47]. The Infrared camera spectral range must also be assessed to ensure that detection is within the 'atmospheric window', which is necessary for interference-free capture.

- Inaccurate characterisation of relevant environmental variables:

Key variables include solar radiation intensity, air temperature, relative humidity, wind speed, and pollution at the time of capture [6,16]. Pollution for example is relevant for atmospheric attenuation or the W_{atm} component compensation (air density assumption), and has been identified by studies to contribute significant errors with increased distance D, particularly with aerial remote sensing applications [2]. With ground-based studies, sensitivity analyses have revealed relative humidity and distance D to be the least sensitive, while ε_{obj}, T_{ref}, and T_{atm} are the most, particularly with quantitative applications [3,4]. From the latter three variables, target ε_{obj} has the greatest influence, and is a common source of error when very low values (<0.3) have been used [2,5]. With high target ε_{obj} values (>0.9) as with typical vegetation, the W_{ref} component and implicit T_{ref} is less significant. This reflected component's compensation and associated error could also be reduced in outdoor environments by carrying out thermography under cloudy conditions, when T_{sky} is much warmer relative to a clear sky [10].

- Thermographer's approach:

When framing the target object, it is important to avoid too shorter distance D, as this is likely to add the reflection of the thermographer onto the resulting thermograms [6]. The distance D also affects the FOV and thermogram resolution. Greater distances reduce resolution (increases the 'instantaneous field-of-view' / IFOV [ii]), which reduces detail by averaging a greater area of temperatures per pixel [47]. Furthermore, attention should be paid to how the camera's FOV is targeted. If water status quantification is the principal objective, the FOV should be directed to cover the vegetation canopy as much as possible, or else readings would have to be compensated for partial canopy cover [18]. This is significant for living wall assessments as it adds the task of having to segment-out substrate temperatures during post-processing, while this may not be a straightforward task given that surface spreading or prostrate plant canopies with smaller leaves tend to remain closer or equal to substrate temperatures; thereby contributing to segmentation errors. Typically, thermograms taken with a narrow FOV, moderate distance D, perpendicular to the target object, and in focus, present the most detailed and accurate information [6,47].

- Application validations:

Validation of novel application areas, such as in the measurement of vertical greening surface temperatures, requires further investigation. The measurement error for plant-based assessments should ideally be within 1-2 K, given that ΔT gradients in many environments are between 0-5 K (and gradients as high as 10-15 K). Accuracy correction measures are at present in development, with the need for correction critical when measuring in extreme cold and hot ambient conditions, or when considering target objects with expected extreme surface temperatures (e.g., [3]). For the assessment of vertical greening surface temperatures in non-extreme climates (between ~10-25°C), thermography remains

[ii] IFOV describes the spatial resolution of a camera, i.e., the smallest target size it can detect at a given distance with a given lens type and detector size, typically specified as an angle measurement in milliRadians or mRad. The smaller the IFOV value, the narrower the viewing angle, and better the resolution. E.g., an IFOV of 2.0 mRad would differentiate details as small as ~12 mm in size, at a distance of ~6 m.

as a viable methodology. In temperate climates, this means that it could be effectively used for critical summertime water status monitoring, while less critical wintertime readings are likely to require adjustment prior to interpretation. When applying this methodology for stress detection, it must be understood that the potency of the stressor must lead to detectable canopy temperature changes, which may not always be true with minor shortfalls, or at early stages of adverse influence. Diagnosis of the causal agent stressor is also not always obvious from temperature related observations alone, as a combination of stressors can affect the potency of temperature changes [16,32].

5.0 Summary

Good practice checklist:

- ✓ Check camera accuracy and resolution to determine suitability of application.
- ✓ Ensure the use of calibrated apparatus to record the prerequisite inputs ε_{obj}, T_{ref}, and the parameters for calculating τ_{atm} (recorded prior to capture).
- ✓ Avoid overshadowing or intense irradiation from surrounding objects and sources.
- ✓ Avoid framing the target at acute angles (i.e., perpendicular to target surface where possible), and opt for a narrow field-of-view (FOV).
- ✓ In outdoor settings, avoid capture when background air velocity exceeds ~5 $m \cdot s^{-1}$, as higher values enhance convective heat losses to underestimate surface temperatures.
- ✓ Avoid shaded or self-shaded areas (if unavoidable these can be thresholded out during post-process segmentation).
- ✓ Allow for adjustment period prior to capturing, and always capture in focus (the adjustment period should facilitate this requirement).

Typically, thermograms taken with a narrow FOV, moderate distance $\mathbf{D}$, perpendicular to the target object, and in focus, present the most detailed and accurate information.

In this paper, qualitative and quantitative thermography application in relation to built environment studies was discussed. Special attention was paid to the novel application of examining and monitoring vertical greening installations, an increasingly common green infrastructure solution implemented to enhance the climate resilience of urban building fabrics. With the exemplar studies presented, the qualitative assessment highlighted potential for identifying performance and maintenance issues, as well as providing a *prima facie* indication of plant stress conditions. However, detailed aspects of plant performance and abiotic and biotic stress detection were highlighted to require further quantitative assessment, using additional processing tools.

Despite limitations concerning camera accuracy, application errors, and interpretation cautions, quantitative thermography is a reasonably accurate, non-invasive, and non-contact methodology that facilitates the empirical assessment of vertical greening installations. Furthermore, as the coupling with stress detection modelling improves, it could be integrated into installation management and maintenance pathways, with further development leading to automated precision fertigation systems including 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, which would in turn contribute to urban heat risk mitigation.

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