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# Assessing Climatic Stress in Vegetation: A Statistical-Driven Approach to Predict Thermal "Degradation" Parameters via Passive Thermography

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**Vertical green structures (VGS) increase green spaces in compact urban areas offering benefits as an improved thermal insulation of the building envelope, and a decrease of the Urban Heat Island effect. Efficient species selection and quantitative evaluation of species' reaction to hygro-thermal variations are needed to optimize VGS benefits. This study proposes a novel methodology to discriminate the thermal behavior between healthy and unhealthy leaves under hygrothermal stress. To this aim, the surface temperature on region of interests (ROIs) of target leaves of the *Heuchera villosa* species is measured using passive thermography (pIRT). Besides, an additively manufactured leaf is used as a reference shape for assessing geometrical changes between healthy and unhealthy leaves. The thermal data analysis procedure extracts a vegetative health index based on the third-order centered momentum of thermal data distribution, encompassing temperature anomalies, and geometric variations. The study demonstrates high potential to be further extended to a data-driven approach to automatically and non-destructively detect the healthy and unhealthy status of vegetation in VGS by pIRT. The findings contribute to advancing understanding of vegetative responses to environmental stressors and provide insights for effective monitoring and management of VGS.**

## 1. Introduction

Vertical green structures (VGS) are vertical surfaces covered with vegetation which allow to increase the number of green areas in densely built cities. A VGS can be constituted by supporting elements, growing media, drainage, irrigation, depending on the typology and the level of complexity.[1] However, the living component, i.e., the vegetation that exists in all the VGS types still remains more challenging to optimally choose due to its varying requirements (e.g., light, water, and nutrients) for specific environmental conditions (e.g., temperature and relative humidity), the need for ongoing maintenance and long-term viability.

Utilizing the additive manufacturing (AM) technology can contribute in VGS development in many ways. First, AM technology can be used to build some VGS components as structural support. AM also enables the rapid prototyping and iterative refinement of VGS components, streamlining the research and development process. As presented in this article, AM encompasses both technological and mathematical aspects that play a significant role in vegetation stress assessment. Thanks to AM, VGS components can be intricately designed considering different needs of diverse vegetation, e.g., water distribution and nutrient delivery in a customized manner.

Previous ecological studies[2–7] but something is still unknown about how to evaluate the health of vegetation quantitatively. In

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the work of Zia et al.,[8] the grapevine crop water stress index was evaluated using the temperature directly assessed on thermal maps. Even if the approach was very practical, more effort should be paid in selecting dry and wet leaf reference threshold temperatures to avoid any inclusion of non-leaf objects in the image analysis. As well as on the sensitivity of thermal maps with respect to the changing environment conditions in terms of weather conditions (e.g., variation in wind speed, radiation and temperature, and the influence of leaf angle variation). InfraRed Thermography (IRT) is a full-field, and contactless experimental technique that could provide the needed quantitative information and level of accuracy on the living component of a VGS, in addition, an in-depth analysis of thermal signal could also account for the limitations in current temperature data processing procedures.[10]

The aim of the present research is to demonstrate the capability of the passive IRT (pIRT) of assessing climatic stress in *Heuchera villosa* (HV) species. This is accomplished through the development of a novel data processing procedure to 1) to elaborate IRT data of vegetative components; 2) to select reference leaves; and a novel statistically driven procedure to 3) calculate and index for discriminating healthy leaves from the unhealthy ones. The final purpose being the support to decision-making process during the vegetation selection in VGSs.

## 2. Experimental Section

### 2.1. Plants Selection

The procedure to select the vegetative component in this contribution was the same as that carried out in Ogut et al.[7] where four different species were investigated. The selection was made by considering the following parameters: 1) water requirement, 2) light requirement, 3) varying leaf geometry, 4) availability to purchase in plant nursery. In this contribution, only *HV* was finally selected and tested due to its largest leaves and hence larger region of interests (ROI) which might provide more data and statistical assessment capability. Moreover, this species was the only plant which—within laboratory conditions—may have unhealthy leaves to monitor.

### 2.2. Additive Manufacturing (AM) Production

To assess the stress on vegetation, first it had been necessary to create a reference object—insensitive to environmental stimuli—to compare with the leaves of the studied species (i.e., HV). This had been done using a fused deposition modeling (FDM) printer (3ntr A4V4 printer) in Additive Manufacturing (AM) technology. The extruded material was a filament of polylactic acid (PLA) and 3ntr SSU04 for the artificial leave and the supporting structure respectively.[11,12] The reference artificial objects were based on the simplified designs of leaves and 2D vector graphics were generated by using AutoCAD software.

The printing parameters for the AM process included: a layer thickness of 0.2 mm, an extruded bead width of 0.4 mm, a checkerboard infill pattern with a density of 33.3%, a printing bed temperature set at 80 °C, an extruder temperature adjusted to 245 °C for a soluble support material SSU04 and 210 °C for PLA, respectively. Then, to ensure precise geometry and achieve a high surface quality in the process, the printing speed was set to 30 mm $s^{-1}$ for the top and bottom layers, as well as the skin, and 40 mm $s^{-1}$ for all the other layers. The production procedure had been explained in detail in Ogut et al.[7]

### 2.3. Thermographic Setup and Data Analysis

The thermographic camera used in this study was the microbolometric FLIR A70 with a matrix of 464 × 348 pixels, and noise equivalent temperature difference less than 35 mK. The camera was positioned in front of the test object (**Figure 1**) and several thermal images were acquired at specific time intervals (**Table 1**).

By analyzing the total power of the radiation hitting the IRT camera it had been possible to distinguish between unhealthy (deteriorated) and healthy (functional) leaves, since they presented significantly different thermal characteristics (hence, temperatures).

Two plants of HV were used in this contribution. One was placed in the isolated chamber (CH), whereas the other one was placed in the room (R) condition as a reference plant. The AM artificial leave was placed next to the plant in the CH. The experiment lasted for 48 h with two watering cycles (at $t_{w1}$ and $t_{w2}$) conducted with a spray bottle in every 24 h. The water amount sprayed on the leaves was circa 3 mL. During the experiment, the thermal image acquisition was done for 13 times, and 26 thermal images were acquired as listed in Table 1.

Once thermal data were collected, a specific Matlab code had been developed to smooth the data and select the regions of interest (ROIs) accounting for the leaf characteristics. ROI1 and ROI3 were chosen on healthy and unhealthy leaves in CH whereas ROI2 was selected on the healthy leaf in R conditions. The analysis was both qualitative and quantitative. The qualitative analysis (**Figure 2a**) focused on thermal maps and histograms to graphically draw considerations on leaves behavior. It addressed different stages: the mean signal of ROI1 and ROI3 was normalized by the mean value ROI2 signal (R conditions); then the histogram of normalized matrices ROI1 and ROI3 was plotted; and after that, levels and frequencies of histogram were considered to evaluate the third momentum index ($M_3$)[9] following Equation (1). $M_3$ was an index that evaluated the skewness of thermal data distribution in each ROI and allowed to discriminate healthy from unhealthy leaves. $M_3$ was defined by the following formula:

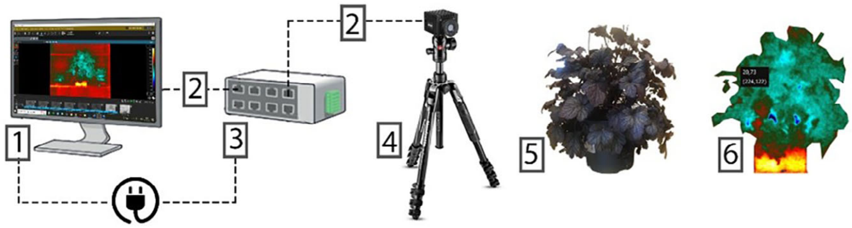
$$M_3 = \frac{\sum \left(x_i - \mu\right)^3 n_i}{n} \tag{1}$$

where $x_i$ were the levels of the histogram, each level represented a specific temperature range, $n_i$ were the frequency associated to $x_i$, $\mu$ was the mean value of the frequencies $n_i$, $n$ was the sample size.

In the results section the values of the evolution of M3 were presented for the ROI1 and ROI3 (in CH conditions).

### 2.4. Geometrical Indexes

In addition to the IRT data, geometrical attributed analysis of the leaves was conducted to detect the impact of watering in the



1. Computer running FLIR Research Studio software.
2. CAT 6 Ethernet cable.
3. Industrial power over Ethernet (PoE) switch.
4. FLIR A70 IR camera set with tripod.
5. Object to be monitored, i.e., plant
6. Example of thermal image

**Figure 1.** The infrared camera setup to monitor HV. Numbers stand for the components of the setup reported in the legend.

**Table 1.** Test plan.

| Watering cycle | Day (dd.mm.yyyy) | Time (hh:mm) | Image acquisition time | Condition | *HV* image [*n*] |
|---|---|---|---|---|---|
| 1 | 23.05.2023 | 15:00 | $t_{i1}$ ($\approx t_{w1}$) | CH | 45 |
| | | | | R | 55 |
| | 23.05.2023 | 15:15 | $t_{w1}$ + 0.25 h | CH | 69 |
| | | | | R | 61 |
| | 23.05.2023 | 16:15 | $t_{w1}$ + 1.25 h | CH | 76 |
| | | | | R | 82 |
| | 23.05.2023 | 17:15 | $t_{w1}$ + 2.25 h | CH | 94 |
| | | | | R | 92 |
| | 24.05.2023 | 09:00 | $t_{w1}$ + 18 h | CH | 101 |
| | | | | R | 109 |
| | 24.05.2023 | 11:00 | $t_{w1}$ + 20 h | CH | 121 |
| | | | | R | 119 |
| | 24.05.2023 | 15:00 | $t_{w1}$ + 24 h ($t_{i2} \approx t_{w2}$) | CH | 127 |
| | | | | R | 134 |
| 2 | 24.05.2023 | 15:15 | $t_{w2}$ + 0.25 h | CH | 148 |
| | | | | R | 144 |
| | 24.05.2023 | 16:15 | $t_{w2}$ + 1.25 h | CH | 154 |
| | | | | R | 160 |
| | 24.05.2023 | 17:15 | $t_{w2}$ + 2.25 h | CH | 172 |
| | | | | R | 170 |
| | 25.05.2023 | 09:00 | $t_{w2}$ + 18 h | CH | 178 |
| | | | | R | 185 |
| | 25.05.2023 | 11:00 | $t_{w2}$ + 20 h | CH | 197 |
| | | | | R | 195 |
| | 25.05.2023 | 15:00 | $t_{w2}$ + 24 h | CH | 204 |
| | | | | R | 210 |

$t_i$ and $t_w$ refer to initial time and watering time respectively whereas CH and R are the chamber and room conditions.

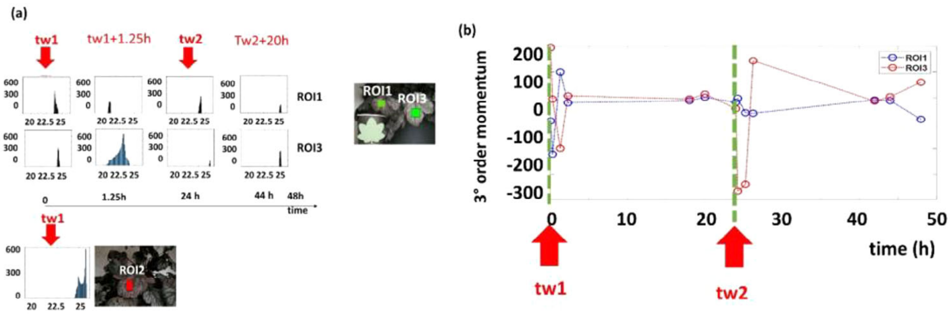


**Figure 2.** Evolution a) of histograms of the ROIs obtained by analyzing thermal maps. b) 3° order momentum through the time for ROI1 and ROI3.

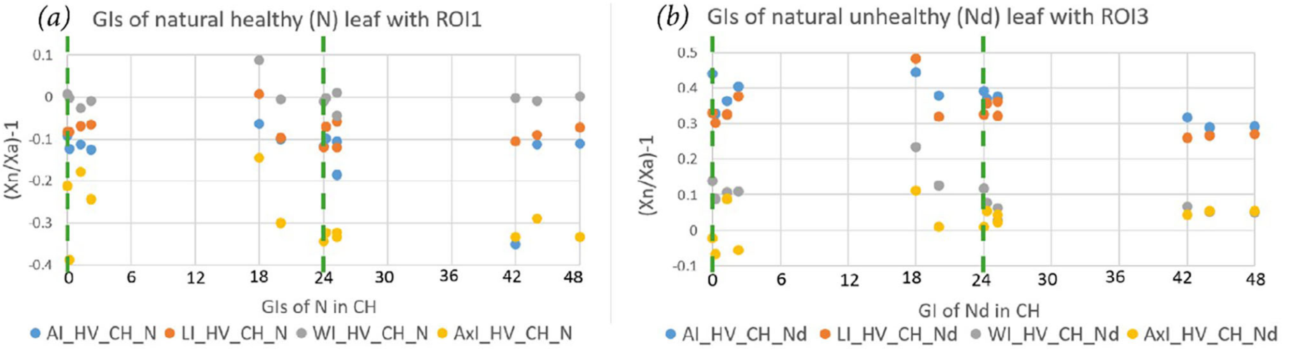


**Figure 3.** *Heuchera villosa* (HV)'s GI of natural a) healthy leaf at chamber (CH) condition, b) unhealthy at the CH. Watering times are presented with green lines. An acronym system has been developed to represent geometrical attributes of leaves. Each acronym corresponds to specific measurements: "AI" for "Area Index," "LI" for "Length Index," "WI" for "Width Index," "AxI" for "Angle Index." The system further distinguishes the plant species (HV) and between healthy (suffixed with "_N") and unhealthy (suffixed with "_Nd") leaves.

selected leaves' form. The considered Geometrical Indexes (GI) were: 1) area ($A_I$), 2) maximum length ($L_I$), 3) maximum width ($W_I$), and 4) angle with $x$ axis ($A \times I$). The geometrical indexes were calculated with Equation (2) for each species:

$$GI = \frac{X_n}{X_a} - 1 \tag{2}$$

where $n$ and $a$ standed for natural and artificial leaf respectively. $X_n$ and $X_a$ were geometrical attribute ranging from (1) to (4) for natural and artificial leaves, respectively.

## 3. Results and Discussion

### 3.1. Statistical-Driven Approach to Analyze Thermographic Data

In Figure 2a, the histograms and in Figure 2b the 3° order momentum resulting from thermal data analysis are shown. Each histogram of Figure 2a refers to a specific thermal map of ROI1 or ROI3 in a specific time instant of the experiment (from 0 to 48 h of time, see Table 1). ROI1 (healthy leaf) and ROI3 (unhealthy leaf) show, generally, an opposite behavior. In effect, immediately after the watering (red arrows with labels $t_w1$ and $t_w2$) ROI3 experienced a negative skewness while ROI 1 presented a positive one.

This result is also confirmed by the curves in Figure 2b, where, after each watering (red arrows), significant decrease in $M_3$ index is present for the unhealthy leaf (ROI3, red line, and markers).

Such a statistical based approach to assess the health of the vegetative component seems to be very promising as it could be a powerful discriminant compared to classical methods based only on the analysis of the mean temperature trends in ROIs.

### 3.2. Geometrical Indexes

**Figure** 3a,b shows the geometrical indexes of healthy and unhealthy leaves in CH respectively and how they change over time, showing trends that may be related to the impact of watering. The area index has a more significant range of values compared to other geometrical attributes. Notable changes occurred over time for both leaves' area, with the highest values observed after 18 h from the watering. After the second cycle, the unhealthy leaf had less geometrical modification than after the first cycle. Both leaves showed same way of variation for length and width, but the numerical values of healthy leaf were always higher than the unhealthy one.

On the other hand, the angle index fluctuates over time but does not show a clear common trend. Specifically, the healthy leaf reacts less in the second cycle, however the unhealthy one reacts more significantly. This can be explained through optimal turgor pressure, i.e., a measure of the water pressure within plant cells.[13] Healthy leaves may maintain this pressure due to intact cellular structure which makes the cells in healthy leaves more rigid. As the turgor pressure causes the plant cells to absorb water, hence swells, the different trends of geometrical attributes can be explained with this phenomenon as well.

## 4. Conclusion and Future Works

This contribution introduces a methodological approach for distinguishing between the thermal and geometrical behavior of healthy and unhealthy leaves under hygrothermal stress for advancing the selection and health monitoring of vegetation in VGS. It introduces innovative methods for thermal analysis, potentiality of automated detection, and real-time monitoring, contributing to the sustainability and efficiency of VGS. The suggested methodology supports plant species selection for VGS by offering both qualitative and quantitative assessment of how different species respond to hygrothermal variations. It provides data-driven insights for the identification of species well-suited to environmental conditions. This approach can also promote biodiversity and ecosystem health within VGS to enhance thermal regulation benefits and mitigate climate change. Instead of commonly used measure like mean or maximum temperature, the third-momentum index gives the opportunity to investigate, in a more robust way, multitude of effects such as environmental and surface conditions. Thanks to the pIRT, the adopted approach is full-field, contactless and non-destructive, and the data analysis is very rapid, so it presents potentials for automatic detection in remote sensing. These facts make pIRT utilizable not only in the decision-making, but also in the maintenance of the VGS so that the health state of vegetation can be detected, and precautions may be taken before the plants become irreversibly compromised. Finally, further development of the technique will involve the use of ML to automatically identify those unhealthy leaves when inspecting large areas or large vegetative components.

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## Conflict of Interest

The authors declare no conflict of interest.

## Data Availability Statement

Data will be made available from the authors on request.

## Keywords

asymmetry index, passive infrared thermography (pIRT), thermal stress, vertical green structures, water cycle

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