Contribution of thermal imaging to fertigation in soilless culture

Isidro Morales · Juan E. Álvaro · Miguel Urrestarazu

Abstract Thermography is a tool used in many scientific disciplines, including agriculture. This paper describes the application of thermography as a rapid diagnostic method of adequate watering. Two experiments were conducted. In experiment 1, *Philodendron erubescens* and *Anthurium andraeum* were transplanted to pots in a greenhouse in Almeria (Spain). The vegetative growth parameters of these plants were measured. In experiment 2, two areas of vegetative cover were established on green walls: one with a combination of aromatic plants and another with ornamental indoor plants. The thermographic images were recorded using a compact infrared camera, which had a spectral infrared range of 7.3–13 μm, microbolometer of 320×240 pixels, and the resolution was 0.01 °C at 30 °C. Three irrigation treatments were applied in both experiments, consisting of a control treatment (CT), a deficit irrigation [1/3 less volume, deficient irrigation (DI)] treatment, and an excess irrigation [1/3 greater volume, excess irrigation (EI)] treatment. In both experiments, the sample temperatures were recorded by thermography for each irrigation treatment. In experiment 1, the vegetative growth parameters were greater under CT than under DI or EI. The data of the reference thermographs over the leaves of the potted plants were significantly correlated with the superior growth parameters under the optimal irrigation treatment. A continuous vegetative canopy was formed on both of the green walls in experiment 2, and the average temperatures were correlated with the irrigation treatments in this experiment. The temperatures reflected in the reference thermographs allowed for the determination of the most appropriate irrigation treatment. These results suggest that thermography can be a useful method to provide an early diagnosis of water stress in potted plants and green walls.

Keywords Green wall · Thermography · Thermometry · Sensor techniques · Fertigation · Non-invasive monitoring

Introduction

Infrared thermography is used in many fields of science [1] and technology [2], including agriculture and horticulture [3–8] and plant physiology [9, 10]. The technology can be utilized specifically to monitor the efficiency of water resource use for both field applications [11] and potted plants in a soilless culture [12, 13]. The leaf temperature of plants is the result of both external and internal (physiological) factors. A correlation exists between leaf temperature and water status, as water is the primary source of infrared absorption in plant tissue [14]. The relationship between leaf transpiration and crop water stress is well-established [15]. Transpiration is regulated by a stomatal feedback control mechanism, which is in turn influenced by water deficits [12, 16]; due to the negative correlation between transpiration rate and leaf temperature, digital infrared thermography allows for the non-invasive monitoring and indirect visualization of potential stress. Several previous studies have employed digital infrared thermography in horticulture for disease control [17–22], but relatively few studies have proposed the use of thermography for the early diagnosis of issues with a fertigation distribution system [12], water stress [8], or salt tolerance in crops [13, 23].

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A real need exists for sensitive, easy, economic, and robust techniques for the detection of water and other plant stresses, especially before these stresses manifest as crop damage.

The present work investigates the potential of infrared thermography as a tool for fertigation. The study evaluates the capability of infrared thermography as an early, rapid, and simple method for diagnosing the volume of fertigation by soilless culture under pot and green wall conditions.

Materials and methods

Experiment 1

Crop

The experiment started on 25 February 2013 in a greenhouse at the University of Almeria (Almeria, Spain). Seedlings (65 days old) of philodendron (*Philodendron erubescens* K. Koch and Augustin cv. Imperial red) and anthurium (*Anthurium andraeanum* Linden Ex André) were transplanted to 0.5–L pots filled with a mixture of peat and coir fiber (1:2 vol:vol). Each pot (crop unit) was fertigated with a standard nutrient solution [24] for 90 days to anthurium and syngonium, using a self-compensating, non-draining dripper with a flow rate of either 2, 3, or 4 L h^{-1}. For all treatments, new fertigation was supplied whenever a pot had absorbed between 10 and 20 % of the

easily available water, as determined from the control treatment (CT) [25, 26]. The flow rate of the CT was 3 L h^{-1}, while the flow rate for the deficient irrigation (DI) treatment was 2 L h^{-1}, with a fertigation volume 1/3 less than the CT. The flow rate for the excess irrigation (EI) treatment was 4 L h^{-1}, with a fertigation volume 1/3 more than the CT.

Thermometric measures

The thermographic images were recorded using a compact infrared camera, the Fluke® Ti32 Thermal Imaging Scanner (Janesville, WI, USA), which has a spectral infrared range of 7.3–13 μm, a temperature range of −40 to +600 °C, and an accuracy of ±2 %. The detector was a focal plane array (an uncooled microbolometer of 320 × 240 pixels), and the field of view was 20°, with a minimal focus distance of 0.3 m. The resolution was 0.01 °C at 30 °C. The emissivity was 0.95. The thermal measurements were obtained at midday according to the methods of Inagaki and Nachit [5] and Fernández-Bregón et al. [12]. The measurements were taken from leaves on half of the stem at a constant, pre-determined orientation and position in the plant (Fig. 1d) from an approximately 3–5 cm^2 area, in agreement with the criteria of Urrestarazu [13] (Fig. 1b). The lens was perpendicular to leave surface.

A thermographic image was taken from each plant in each of the three treatments at the same time (Figs. 1, 2, 3, and 4).

Fig. 1 **a** is a thermograph of the three irrigation volumes, where CT is the control, DI has 1/3 less irrigation, and EI has 1/3 more irrigation. Dripper irrigation occurs at flow rates of 2, 3, and 4 L h^{-1}, respectively, in each pot. **b** Thermographic measurement of the average (Avg), minimum (Min), and maximum (Max) temperatures of a representative leaf area. **c** Thermographic data of a pot with the same irrigation volume. **d** is the reference photograph
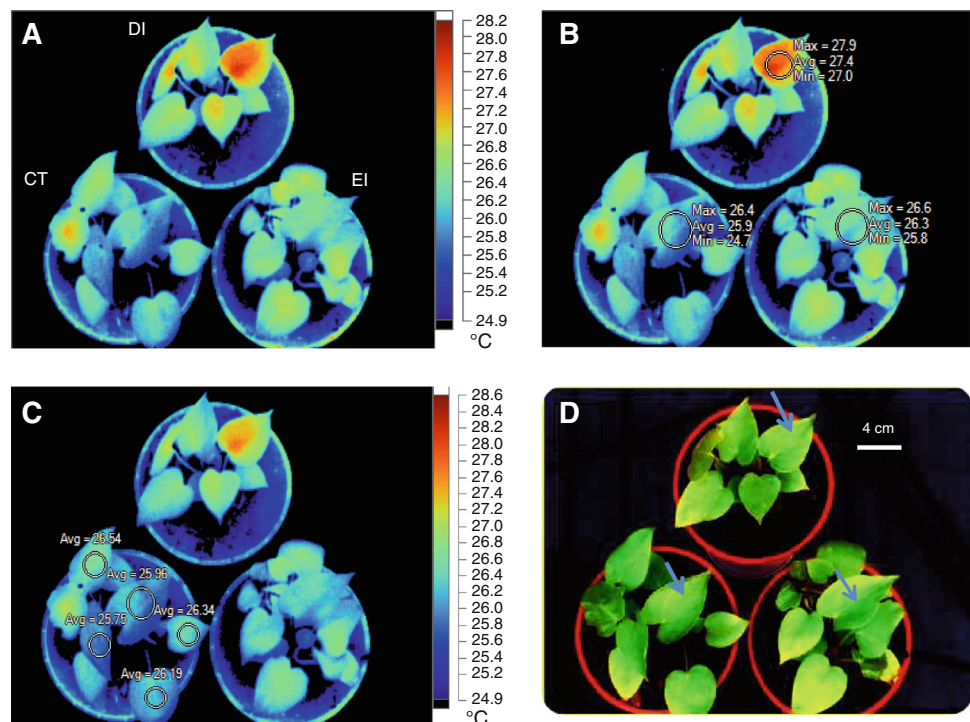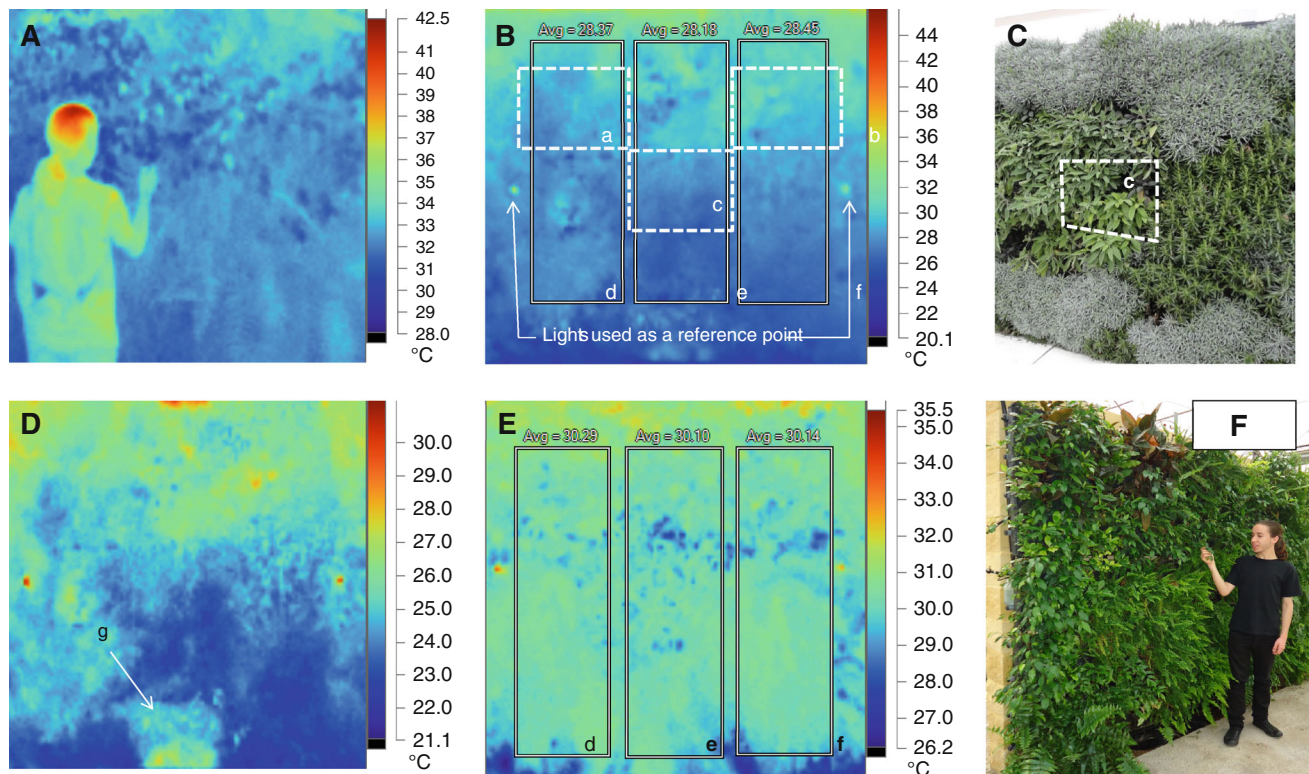
Fig. 2 **a** is a reference thermograph, **b** is a thermograph of a vegetative wall of aromatic plants, and **c** is a photograph of a wall of aromatic plants. **a**, **b**, and **c** are the spaces that occupy three of the cultivated modular units covering the vegetative wall; **d**, **e**, and **f** are the areas used to measure thermograph temperatures for each treatment (2,3 and 4 L h^{-1} drippers). **d** is a reference thermograph where irrigation was stopped for 3 days in one cultivated modular unit, bottom center (**g**). The numbers represent the average temperature of the respective boxes. **e** is a thermograph and **f** is a reference photograph of a vegetative wall of ornamental indoor plants

Thermometric analysis

The camera used in this study is supported by the software package SmartView 3.2^{TM} Researcher Pro (Fluke Thermography, Plymouth, MN, USA) and a Microsoft Windows XP platform, which offers analytical functions including point temperatures, profiles, histograms, isotherms, and the determination of the maximum temperature in the image (Figs. 1, 2, 3, and 4).

Growth parameters

Ninety days after the transplant, the plants from each treatment and repetition were divided into roots, stems, and leaves. After the measurement of the fresh mass for each portion, the dry mass of the roots, stems, and leaves were determined after drying at 85 °C until reaching a constant mass (Table 1).

Experimental design and statistical analysis

Four replicates were used for each measurement and treatment. The experiment was conducted using a completely randomized design with eight pots in replicates for each treatment.

A Tukey's multiple range test at $P \leq 0.05$ was used to differentiate the means. The experimental design and data analysis were based on the procedure described by Little and Hills [27]. A Statgraphics R_Plus 5.0 statistical package was used to process the data [28].

Experiment 2

A second experiment conducted on a green wall under similar conditions in relation to thermal measurement system and statistical processing of the data as experiment 1. The experiment was conducted at the University of Almeria (Almeria, Spain). A wall 2.5 m high and 3.5 m long was built with concrete blocks. Each block was made of precast concrete and measured 200 mm high by 190 mm wide by 400 mm long.

Green wall

Two types of vegetative cover were established on the concrete block wall: an aromatic plant cover on the south

Fig. 3 Thermographs corresponding to 2, 3, and 4 L h^{-1} irrigation flow rates in Philodendron plants; *top*, *left*, and *right*, respectively, in philodendron and syngonium. Avg: Average temperature
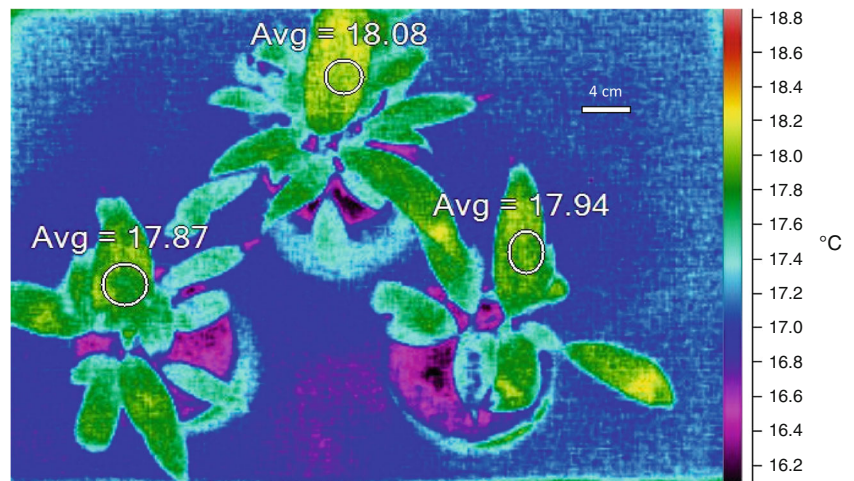
Fig. 4 Relationship between fertigation volumetric flow rate (L h^{-1}) and temperature decrease recorded by thermography. **a** is the leaf temperatures of potted *Philodendron*, **b** is the leaf temperatures of potted *Anthurium*, **c** is the vegetative wall of aromatic plants, and **d** is the vegetative wall of ornamental indoor plants
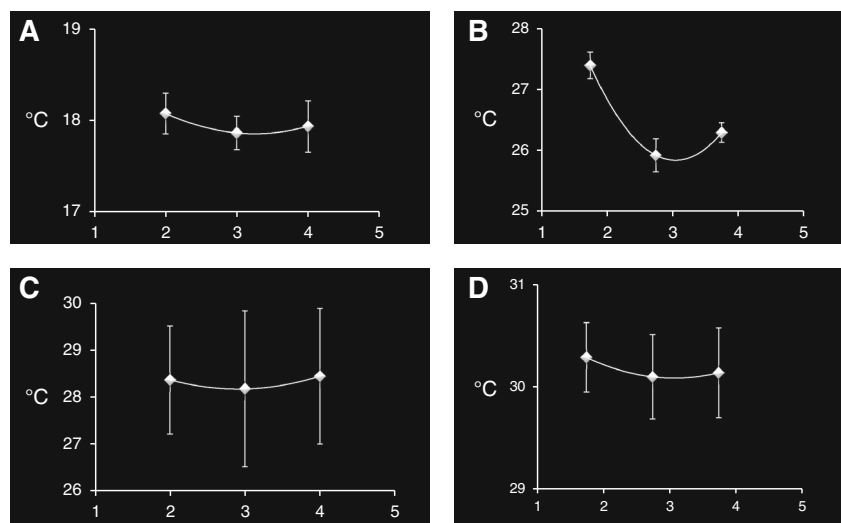
face and an indoor ornamental plant cover on the north face. The covering consisted of modular vegetative units (CMU) measuring 600 mm long, 400 mm high, and 100 mm wide that were fastened to the concrete wall by metal anchors, as in the methods of Urrestarazu and Burés [29] (Fig. 2).

This experiment was conducted according to Fernández-Bregón et al. [30]. The cultivated CMUs consisted of a combination of six or ten species of aromatic and indoor plants, respectively.

Indoor plants:

– *P. erubescens* K.Koch and Augustin cv. Imperial red
– *Ficus benjamina* L. cv. Exotica
– *Nephrolepis cordata* Hort.
– *Nephrolepis cordifolia* (L.) C. Prel cv. Duffii
– *Nephrolepis biserrata* (Sw.) Schott. cv. Macho
– *Nephrolepis exaltata* (L.) Schott cv. Montana
– *Nephrolepis exaltata* (L.) Schott cv. Ariana
– *Nephrolepis exaltata* (L.) Schott cv. Teddy Junior
– *Dryopteris erythrosora* (D. C. Eaton) Kuntze

– *Syngonium podophyllum* Schott cv. Robusta

Aromatic plants:

– *Helichrysum thianschanicum* L.
– *Salvia officinalis* L.
– *Lavandula angustifolia* Mill.
– *Lavandula stoechas* L.
– *Rosmarinus officinalis* L.
– *Thymus vulgaris* L.

The plants were distributed in the CMU based on esthetic criteria; when the plants were fully developed, the plant cover was continuous, and it was not possible to identify the specific position of each CMU (Fig. 2c). Therefore, when considering an area larger than that of a CMU, the analysis included several of the species, as seen in Fig. 2b, c.

The CMUs were grown in a greenhouse and transported to the test location for installation on the wall. These plants provided 100 % CMU coverage and an average canopy height of 250 mm. The CMUs were allowed to acclimate in

Table 1 Parámetros de crecimiento (g plant^{-1}) en función de régimen de riego

Plant	Treatment	Fresh mass					Dry mass				
		Leaf	Stem	Shoot	Root	Total	Leaf	Stem	Shoot	Root	Total
Philodendron	DI	7.95 b	6.93 c	14.39 b	10.92 c	25.31 c	2.67 b	2.47 a	5.04 c	1.18 b	6.22 c
	TT	10.79 a	9.67 b	20.46 a	12.75 b	33.21 b	3.41 a	2.48 a	5.89 b	1.36 ab	7.25 b
	EI	11.14 a	10.67 a	21.81 a	15.63 a	37.44 a	3.57 a	3.17 b	6.73 a	1.63 a	8.36 a
Anthurium	DI	6.50 b	6.82 a	13.32 b	13.67 a	26.99 a	1.22 b	0.93 a	2.10 b	1.15 a	3.25 b
	TT	7.14 a	6.92 a	14.06 a	12.86 a	26.92 a	1.28 b	1.03 a	2.44 a	1.12 a	3.56 a
	EI	7.31 a	6.57 a	13.88 ab	12.76 a	26.64 b	1.43 a	1.13 a	2.57 a	1.37 a	3.94 a

Within each cultivar, means with different letters are significantly different at $P \leq 0.05$ by Tukey's multiple range

TT, DI, and EI son el tratamiento testigo, 1/3 less, and 1/3 more irrigation, respectively

this location for 4 weeks before the thermal measurements were taken.

Each CMU on the green wall was considered as an independent fertigation circuit for the quantification of the input (irrigation) and output (drainage) volumes [29]. The fertigation for each CMU was supplied by one non-draining dripper with a flow rate of either 2, 3, or 4 L h^{-1}, in correspondence with the treatments of experiment 1. The treatments were vertically distributed as columns of CMUs in the middle of the green wall (Fig. 2b), and each column of CMUs was fertigated by one dripper with a flow rate of either 2, 3, or 4 L h^{-1}.

Thermometric measures

The thermographic images were recorded in a similar fashion to those of experiment 1. The thermographs were recorded (three replicates per wall type) when there was a continuous vegetative layer in which the CMUs could not be identified individually (Fig. 2c, f). An area larger than a group of three CMUs was measured for each treatment (Fig. 2b, e).

The rest of the parameters and methods were similar to those of experiment 1.

Results and discussion

Experiment 1

Almost all of the growth parameters evaluated in the two crops were significantly affected by the irrigation volume (Table 1). The philodendron was affected in all of its growth parameters. The DI treatment led to a greater than 15 % reduction in all parameters (except for stem height) compared to the CT. Conversely, the EI treatment did not yield a significant difference for the fresh and dry mass of the leaves; a lower percentage differences was observed for EI than for DI between the fresh and dry nass of the shoot.

Similar trends were also found in the anthurium, for which plants under DI had lower growth than those under CT or EI (except for the fresh nass of the root and the nass of the stem). However, the percentage differences in anthurium were significantly less compared to those of the philodendron (5 compared to 15 %).

The average transpiration of a leaf is determined by its temperature [15, 31]. A thermograph of several pots (Figs. 1a, 3) with different irrigation treatments indicated a wide range of leaf temperatures. This wide temperature range was maintained even when measured on various leaves of the same plant under the same irrigation treatment (Fig. 1c). However, temperature is closely correlated with the state of available water from the pot when comparing equally developed leaves with the same spatial orientation toward incident radiation on the same plant [12, 13]. The thermographs of the philodendron (Figs. 3, 4a) and the anthurium (Figs. 1b, 4b) recorded the lower temperature for the highest transpiration rate, when the irrigation treatment was most appropriate (CT vs. DI and CT vs. EI); this result is consistent with the observations of Fernández-Bregón et al. [12]. A higher growth reduction between DI and CT for the philodendron, compared to the difference between CT and EI, was also recorded by the thermograph; the temperature difference between DI and CT was approximately ten times greater than that recorded between CT and EI.

Under tightly controlled transpiration conditions, such as those employed in this experiment, the thermograph is closely correlated with the final vegetative growth results obtained during the crop cycle. Therefore, the thermograph can be a useful tool for the rapid, sensitive, easy, economic, and robust diagnosis of water and other plant stresses, especially before they manifest as crop damage.

This method was based on measuring only an appropriate leaf fraction under similar environmental conditions [12, 13]; therefore, the technique avoided the errors in estimated temperature incurred when infrared thermography includes surfaces other than the desired area [3, 32].

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