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Contribution to Trees Health Assessment Using Infrared Thermography

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Abstract: Trees are essential natural resources for ecosystem balance, regional development, and urban greening. Preserving trees has become a crucial challenge for society. It is common for the use of invasive or even destructive techniques for health diagnosis of these living structures, and interventions after visual inspection. Therefore, the dissemination and implementation of increasingly less aggressive techniques for inspection, analysis and monitoring techniques are essential. The latest high-definition thermal cameras record thermal images of high resolution and sensitivity. Infrared thermography (IRT) is a promising technique for the inspection of trees because the tissue of the sap is practically on the surface of the living structure. The thermograms allow the identification of deteriorated tissues and to differentiate them from healthy tissues, and make an observation of the tree as a functional whole body. The aim of this study is to present, based on differences in the temperatures field given by the thermal images, a qualitative analysis of the status of two different arboreal species, *Quercus pyrenaica* Willd and *Olea europaea* L. The results show the IRT as an expeditious, non-invasive and promising technique for tree inspection, providing results that are not possible to reach by other methods and much less by a visual inspection. The work represents a contribution to make IRT a tree decision-making tool on the health status of trees.

Keywords: trees inspection; trees monitoring; infrared thermography; IRT; VTA; sustainability

1. Introduction

The tree is an essential natural resource for ecosystem balance. It regulates nature, climate and urban greening. Trees play a key role in local biodiversity as they release oxygen and reduce global warming. Trees regulate climate by mitigating urban heat islands. Trees behave as barriers for noise pollution and wind. They provide moisture to the atmosphere, which favours precipitation. They facilitate water infiltration into the soil contributing to the formation and maintenance of groundwater aquifers. They are also essential for soil building as their roots fix the soil preventing erosion. All trees are of importance, whether by their age, type, size and shape. Some of them are classified as remarkable or even monumental trees, and the law protects them [1]. Therefore, it is fundamental to act for the preservation and sustainability of these living beings. This is a current social challenge [2–5]. It is decisive to move from the anthropocentric conception of trees to ecocentric conception, that is, all living beings including humankind are interrelated and interdependent to keep the ecosphere equilibrium.

Contrary to what people thought for many years, trees react to physical and biological damages that lead to deterioration. The compartmentalization of decay in trees (CODIT) is a good example of this [6]. Therefore, trees must be cared for in a way that enhances their own defence systems [6]. In order to verify the health status of trees especially when more detailed information is required, invasive and even destructive techniques [7] are used. Unfortunately, they interfere with the structural integrity of this living being. Therefore, it is urgent to disseminate and implement non-aggressive inspection techniques that preserve biological integrity and functionality [3,4]. The basic rule must always be to start with less invasive techniques and only if required, to utilise the most aggressive ones, so that the damage produced in the tree [4,5,8] is minimized.

Infrared thermography (IRT) is a non-invasive non-contact technique that relies on the detection of body heat emission [9–11]. It measures continuously surface temperature in real-time [9]. Aerial surveillance of the canopies to detect the distribution and spread of forest damage was the first use of IRT in trees [4]. Later, this technique was applied to tree bark (branches and trunks). Now, it allows the evaluation of some types of damage in the lower trunk and to estimate the presumable cause that affects roots (the root system) [4]. The latest thermal cameras capture thermal images of high resolution and sensitivity. It has been demonstrated that IRT in conjunction with visual inspection when applied to assessment, and monitoring of tree health provides reliable data [2–4,12]. The IRT capabilities for tree inspection have not been exploited sufficiently yet, since the elaborate sap conductive tissues are practically on the surface of the living structure. The reading of tree surface temperature reveals specific variations when there is deterioration and voids inside the tree. The IRT observes the tree as a functional whole body and thermograms provide information to differentiate deteriorated tissues from healthy tissues. Other methods do not have this assessment capacity, much less the naked eye inspection. Other non-invasive methods survey the body by points, and then extrapolation applies to have an idea of the functional whole body. Through the naked eye, only advanced deterioration is detected, then a corrective measure is hardly effective, and the solution is tree felling.

Thermography allows the early detection of damage, while it is still not visually noticeable. Even more, it monitors the progress of pathology. The IRT is expeditious and non-invasive [2–5,12]. It is, therefore, a powerful, fast and efficient tool to detect changes in the integrity of trees and branches, identifying if one of them should be removed. The differences in the thermal patterns of the tree surface indicate the deteriorated areas of the tree. The greater the differences in the thermal patterns of the trunk and branches, the worse the tree health condition [2–5].

The methods different from IRT that acquire data for diagnosis are time-consuming, and require more hand labour, especially if the part of the tree to be examined cannot be reached from the ground [2–4]. Some techniques, such as the resistograph, require perforation, and these holes may become pathways for pathogens [2–4]. Other methods use X-rays or γ. A short summary of the other main methods for detecting tree deterioration is presented in Table 1. The ionising radiation used in some methods conveys the perception that they are not safe for the health of living beings [3]. Moreover, when IRT is compared to more sophisticated techniques, such as X-ray and γ, as well as tomographic acoustic techniques such as Picus and ArborSonic 3D, or even nuclear magnetic resonance [7,13–15], IRT is the only one able to evaluate the health condition and functionality of tree tissues. That is, the assessment of the structural integrity to detect voids and deterioration inside the tree is possible because the tree is analysed as a functional whole body [4,5]. IRT analyses the tree as a whole, in a holistic way, while other techniques provide information only on specified points, and the whole is obtained by extrapolation after a series of investigations [2–4]. The authors raise concerns about avoiding errors when selecting the emissivity value for temperature reading calibration. However, more parameters are required for IRT quantitative readings. It is necessary to assess the value of reflected (or reflective) apparent temperature, which varies according to the angle between the camera and the tree surface, and the direction of radiation from the environment and sunrays. In some studies, the tree is cut into logs, and then the logs are perforated to simulate deterioration after the logs are sealed at both sides to maintain the water content. When observing the logs in thermograms, it is difficult to detect the holes and the larvae introduced inside them. Even with the same water content, the temperature of the logs does not behave like the tree because there is no flow of the sap, as this happens when the tree structure is alive [16,17]. Some studies analyse trees of the same species affected by several pathologies. The main aim was to look for similar temperature patterns on the surface all along the trees applying IRT [18]. The statistical analysis showed that there was no correlation [18].

Table 1. A brief summary of the other main methods for detecting tree deterioration (adapted from [19]).

Method	Principle	Key Highlights
Increment borer	Visual inspection	Measures growth rate, age and soundness. Invasive method (it may itself be a decay factor) and needs experience on decay causes.
Boroscope	Remote visual inspection	Visual analysis from inside. Same disadvantages of the "Increment borer".
Resistograph	Penetration resistance	Fast, easy to execute and interpret. Does not detect early to intermediate decay stages; requires comparison with known patterns.
Shigometer	Electrical resistivity	Detects deterioration in early stages. Information is limited by the probe length.
Fractometer	Strength and stiffness	Small device and easy to carry. Portable compression meter has depth limited.
Stress wave velocity	Single-path acoustic wave velocity	Quickly performed; defines the location and extent of internal decay. Difficult to determine early stages of decay.
Electrical resistance	Electrical.	Effective to detect advanced decay stages.
Stress wave tomography	Multiple path acoustic wave velocity	Detects internal decay; accurately locates the anomalies; sensitive to early stages of decay. High cost and difficult to operate.
Electromagnetic tomography	Electromagnetic wave permittivity	Higher frequencies provide better resolution but penetration depth decreases. High cost and difficult to operate.
Nuclear magnetic resonance (NMR)	Magnetic properties	Non-ionising radiation; very detailed images that facilitate the analysis. High cost and difficult to operate.
Electronic nose	Odour	High levels of accuracy and reliability. Difficult to determine early stages of decay.
Gamma-ray computed Tomography	Gamma-ray transmissivity	Reliable and non-invasive. Ionizing radiation; high cost, and difficult to carry and operate.

Considering the above, IRT is a well-established technique in a range of fields, such as industrial and building maintenance. Despite its merits, it is still a relatively recent technique in assessing tree health [4,5] and remains residually implemented in agriculture. Due to the relatively scarce studies in this field [5], more research to ensure its potential and applicability on a large scale is required. Thus, it is crucial more studies focus on contributing to show and analyse the complexity of the technique applied to trees, the new and atypical aspects of the problem and respond to some knowledge gaps. Accordingly, the present paper intends to detail some relevant features related to the applicability of the technology, thus contributing to turning the IRT technique as a decision-making tool to assess the health status of trees. To accomplish this, two sample trees, one of species *Quercus pyrenaica* Willd and another of species *Olea europaea* L., are qualitatively analysed from their thermal images.

2. Materials and Methods

2.1. Background

The fundamental aim of thermographic surveying is the heat transfer process shown in Figure 1. When the IRT camera aims at the target, it receives radiation from the object itself, radiation reflected on the surface of the object coming from the emissions of neighbouring bodies, and radiation emitted by the atmosphere. In fact, the atmosphere results in interfering in some way with radiation that arrives at the camera [20]. The total power of the radiation arriving at the IRT (W_{tot}) camera is equal to the sum of the emission of the body ($\varepsilon\ \tau\ W_{obj}$), the emission reflected in the object coming from sources of the near ambient ($(1-\varepsilon)\ \tau\ W_{refl}$), and the emission of the atmosphere itself ($(1-\tau)\ W_{atm}$). That is:

$$W_{tot} = \varepsilon \tau W_{obj} + (1-\varepsilon)\tau W_{refl} + (1-\tau)W_{atm}, \quad (1)$$

where:

ε	Emissivity
τ	Coefficient of atmosphere transmission
W_{obj}	Energy radiation emitted by the object
W_{refl}	Reflected energy from surrounding bodies
W_{atm}	Atmospheric energy

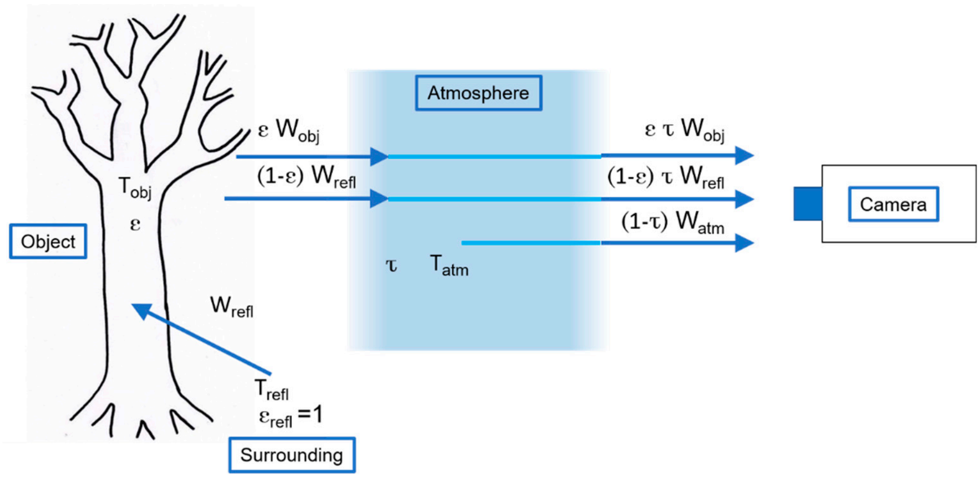


Figure 1. A schematic representation of infrared thermography (IRT) basics (adapted from [19]).

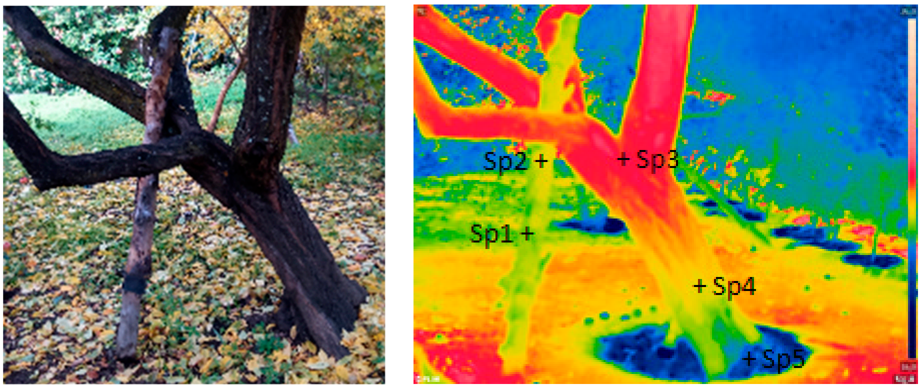
The thermal regime of a tree is determined by the heating of the surface by solar radiation and the transport, by conduction, of sensible heat to the interior. During the day, the surface heats up, generating a sensible heat flow towards the tree (a relatively slow process). The transportation of the elaborated sap promotes the convective transport of heat and ensures more tree thermal uniformity (a faster process of energy exchange). At night, the surface cooling by the emission of radiation (long waves) reverses the flow direction that changes from the interior to the surface leading to the cooling of the entire structure. The sap circulation causes the temperature gradient to vary along the trunk, and trees with more water available have better sap circulation [16]. This characteristic allows the differentiation between functional and dysfunctional tissue since the transport is done through the functional tissue. This feature allows health and vitality to be verified by IRT [16].

The density, the specific heat and the thermal conductivity play an important role in these processes. High specific heat leads to a smaller thermal stimulation for the same amount of heat. Thermal conductivity expresses the ability of the material to allow the heat to pass through it. It is commonly used in steady-state heat transfer analysis. Thermal diffusivity is much more relevant for transient heat transfer processes because it shows how well the heat could diffuse through the material. Thus, the diffusivity is a more important variable for the thermal characterization of a body than the conductivity (k), because it expresses how quickly the body adjusts completely to the temperature of its environment. In fact, the material thermal diffusivity (α) expresses how much easier the heat moves through its volume, that depends on the velocity conduction of the heat (k) and the amount of heat needed to increase temperature (ρC_p). It is given by the following equation:

$$\propto = \frac{k}{\rho C_p}, \quad (2)$$

where k is the thermal conductivity, ρ is the volumetric mass density, and C_p is the material specific heat. For instance, low diffusivity material delays the transfer of external temperature variations into the interior. Thus, it derives from the above, that damaged wood zones or unhealthy tissues have different thermal properties, leading to different heating and cooling times in relation to healthy zones. It is this principle that is explored in tree health analysis using IRT technology.

As mentioned above, wood (deteriorated/non-live tissues) and trees (functional tissues) have significantly different thermal characteristics, and as a consequence, different temperatures. This fact can be seen in Figure 2, that shows the difference in surface temperatures between a tree and a wooden stake supporting it [21]. The analysed tree was a specimen *Prunus domestica* L. (common name plum-tree) and the thermogram was obtained in the summer (air temperature 22.5 °C, relative humidity 55%), 4 h after the sunset, with an emissivity of 0.97 and a rainbow colour pallet. The wooden stake displayed a lower temperature as compared to the tree (except its lower part). The lower part shows slightly higher temperature values than the lower trunk because the tree was irrigated before the observation. The tree keeps a balanced relationship with the environment temperature, so the tree temperatures usually are lower than the atmospheric temperature when the sun heating effect is over [5]. Therefore, in Figure 2, the tree shows higher temperatures in the healthier parts and lower temperatures in the deteriorated parts, as well as in parts where the tree was recently wet with water [22]. The greater the differences in the thermal pattern of trunk and branches, the worse the condition of the tree health [2–5].



(**a**) (**b**)

Figure 2. A tree (*Prunus domestica* L.) and a wooden stake supporting it: (**a**) photograph; (**b**) IRT thermogram (passive mode). The temperature values (°C): Sp1 = 20.0; Sp2 = 20.5; Sp3 = 21.5; Sp4 = 20.5; Sp5 = 19.5. (Adapted from [21]).

Equipment

A thermohygrometer, FLIR MR 176 (Figure 3A) was used to measure the atmospheric temperature and relative humidity. The thermographic camera used in this study is the FLIR T1030sc (Figure 3B).

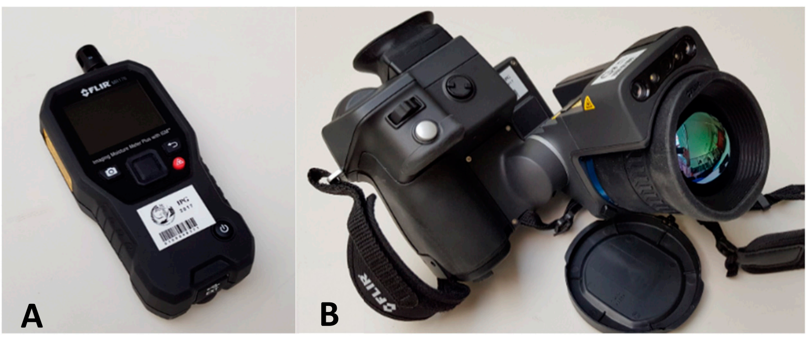


Figure 3. (**A**) Humidity meter FLIR MR 176; (**B**) Thermal camera FLIR T1030sc.

It is a HD imaging and measurement camera recording 1024 × 768 pixels. It has a focal plane array (FPA) detector type, uncooled microbolometer with a detector pitch of 17 µm. The T1030sc operates in a spectral range of 7.5–14 µm and offers a thermal sensitivity < 20 mK, at 30 °C (86 °F). The accuracy, at 25 °C, is +1 °C or +1%, for body temperatures from 5 °C to 150 °C. The camera was equipped with 28° lens, FOV 28° × 21° (36 mm) and number F 1.2. The thermal camera is equipped with a compass and GPS functions to locate the data on the thermogram [20]. The minimum focusing distance is 0.4 m for the standard 28° lens. The focus is manual, automatic or continuous. The continuous digital zoom from 1 to 8× can be used. It has a tactile screen of 800 × 480 pixels that facilitates the introduction of instructions. The software used to treat the thermograms were FLIR Tools + and FLIR ResearchIR Max 4 [23,24].

2.2. Sample Trees

Two trees were analysed: *Quercus pyrenaica* Willd (Figure 4), and *Olea europaea* L. (Figure 5). Table 2 shows their general characteristics. The common name of species *Quercus pyrenaica* Willd is Pyrenean oak. It is an autochthonous species of the Iberian Peninsula, from the mountain regions of continental climates [25]. This deciduous tree sprouts in acidic substrates preferably of granitic and schist origin. The immature subjects are marcescent with the capacity to sprout at the base of the trunk, as well as from the roots. The trunk is straight with opaque grey bark cracked in the form of panels. The specimen under study (Figure 4) is approximately 10 m in height. It consists of three trunks that arise from the base. The diameter at breast height (DBH) measured at 1.3 m in height, from south to north (south at the left of the photo) was: 0.20 m, 0.17 m and 0.17 m, respectively. The second tree is a perennial of the species *Olea europaea* L. It is native to the Mediterranean region (Southern Europe, North Africa and the Middle East) and the common name is olive (Figure 5). The olive tree is of exceptional longevity, being able to surpass 1500 years of age, and reaches a height of up to 8 m. It has greyish bark and branches. The specimen studied is approximately 3.5 m high. The branching begins at 1.75 m from the base, and the DBH measured at 1.30 m height is 0.35 m. Both specimens are located in the interior region of Portugal.

Figure 4. A photograph of the *Quercus pyrenaica* Willd tree taken at 2 p.m. under direct sunlight.

Table 2. Characteristics of sample trees.

Scientific Name	Common Name	Height (m)	HGB (m)	DBH (m)	Picture
Quercus pyrenaica Willd	Pyrenean oak	10.0	1.50	0.20/0.17/0.17	Figure 4
Olea europaea L.	Olive	3.5	1.75	0.35	Figure 5

HGB: Height from the ground (collar) to where branches begin (bifurcation); DBH: diameter at breast height.

Figure 5. A photograph of the *Olea europaea* L. tree taken at 5:30 p.m. under direct sunlight.

3. Methodology

The tree inspection was carried out applying qualitative IRT at the passive mode, that is, the heat source was the environment through solar radiation. The heat flows from the hotter to the colder zones of the tree. The irregularities of the thermal pattern on the tree surface can indicate the existence of defects, voids and deteriorated tissue. When it is found, deterioration as voids and defects occur in both the thermal properties of the constituents and the heat transfer process [2–5,7].

Thermograms were recorded at different times along the day, from when direct solar radiation was hitting the trees until after sunset. Besides the thermograms, photographs were taken to support the visual inspection and thermogram interpretation. The thermograms were processed running FLIR software [23,24]. The authors marked the spots at different locations over the tree trunk. The thermal patterns were analysed in order to correlate the temperature distribution with tree health. The atmospheric temperature and the relative humidity were measured at the time of the recording pf each thermogram, as well as the observation distance (between the thermal camera and the tree).

From a qualitative approach, although important, the value of emissivity is not preponderant. In fact, what is at issue is not the exact value of the measured temperature, but the temperature differences among the spots. The temperature values are comparable because the camera measured them with the same emissivity and reflected temperature.

Nevertheless, the emissivity value introduced was the one appropriate to the surface of the element under study. As the wood and bark are little reflective materials, the emissivity is high. Then, a high emissivity value was set in the camera. Thus, for both specimens, the emissivity value was 0.95. For each thermogram, the atmospheric temperature at the time of the capture was set in the camera. As it was a qualitative analysis, this study did not consider the reflected temperature. Further, it did not rain more than one week before surveying, then the thermograms did not register noises due to the humidity factor.

From the qualitative analysis, a more quantitative approach was taken, in particular, as regards to the comparison of recorded temperature values. It is important to understand thermal pattern differences among the trunks of similar diameter. The thermal patterns resulted from differences in the temperature along the surface. Naturally, this process introduces systematic errors that affect all points equally in each thermogram, whereby do not affect the result.

4. Results and Discussion

Figure 6 shows the thermogram of the *Quercus pyrenaica* Willd tree recorded from the same point of view and at the same time as the photo shown in Figure 4 (on 21 January 2018, 2 p.m., winter in the northern hemisphere). The southern part of the tree (left side of the thermogram) is exposed to sunlight. Figure 7 shows another thermogram of the same tree at the same day but it was taken at

9:45 p.m. (4 h after sunset) from the same point of view. Table 3 shows the observation conditions, and the parameters set in the camera to capture the thermograms. Table 4 contains the temperatures of the spots marked in the thermograms.

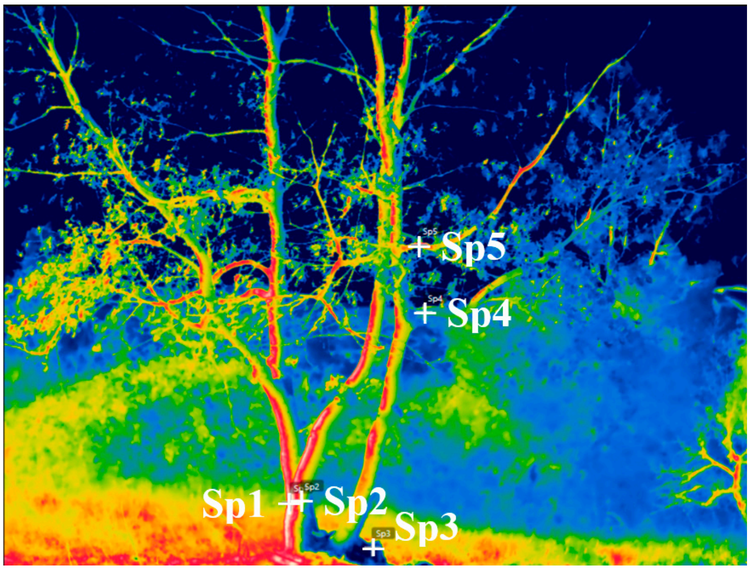


Figure 6. Thermogram *of Quercus pyrenaica* Willd tree taken at 2 p.m. under direct sunlight. (Spot's size out of scale for better visualization).

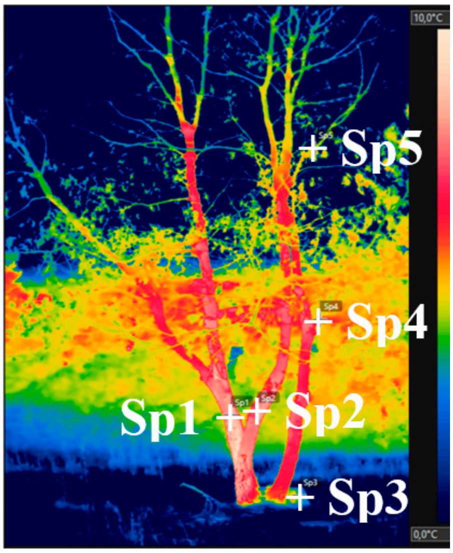


Figure 7. Thermogram of the *Quercus pyrenaica* Willd tree taken at 9:45 p.m., 4 h after sunset. (Spot's size out of scale for better visualization).

Table 3. The ambient conditions and parameters for the thermograms of *Quercus pyrenaica* (Figures 6 and 7).

Thermogram Image	Tree (Specimen)	Air Temperature (°C)	Relative Humidity (%)	Emissivity	Reflected Temperature (°C)	Observation Distance (m)	Colour Palette	Temperature Range (°C)	Daytime
Figure 6	Quercus pyrenaica	20	50	0.95	20	5	Rainbow	10–35	sunlight
Figure 7	Quercus pyrenaica	10	70	0.95	10	5	Rainbow	0–10	night

Table 4. The temperature (°C) of spots on the *Quercus pyrenaica* thermograms (Figures 6 and 7).

Thermogram Image	Sp1	Sp2	Sp3	Sp4	Sp5
Figure 6	32.5	18.0	12.0	15.0	23.5
Figure 7	8.5	8.0	3.0	6.0	4.5

Figure 6 shows areas under direct sun exposure (left zone of the tree) and areas in the shadow (right of the tree). On the left of the trunk is Sp1 under direct sun exposure at 32.5 °C, while Sp2 is in the shadow at 18 °C. The Sp3, on the bottom right, with 12 °C, point out an old cut trunk. Sp4 is in the shadow at 15 °C on a branch of larger diameter than the branch where Sp5 is located. Sp5 is under direct sun exposure at 23.5 °C.

Figure 7 shows the thermogram of the same tree captured 4 h after sunset. It can be seen that Sp1 is on the left trunk at 8.5 °C and Sp2 is on the central trunk at 8 °C. Sp3 is at 3 °C on the stump. Sp4 at 6 °C is located on a branch of larger diameter than the branch of Sp5. Sp5 is at 4.5 °C. The observation conditions and the parameters assumed to capture the thermogram are in Table 3. Table 4 shows the spot temperatures in the thermogram.

Figure 8 shows a photograph (A) and a thermogram (B) of the tree *Quercus pyrenaica* Willd taken at the same time. The capture angle (west) is different from previous images. A red arrow (B) shows a stump that remained from an old cut trunk identified as Sp3 in the thermograms of Figures 6 and 7.

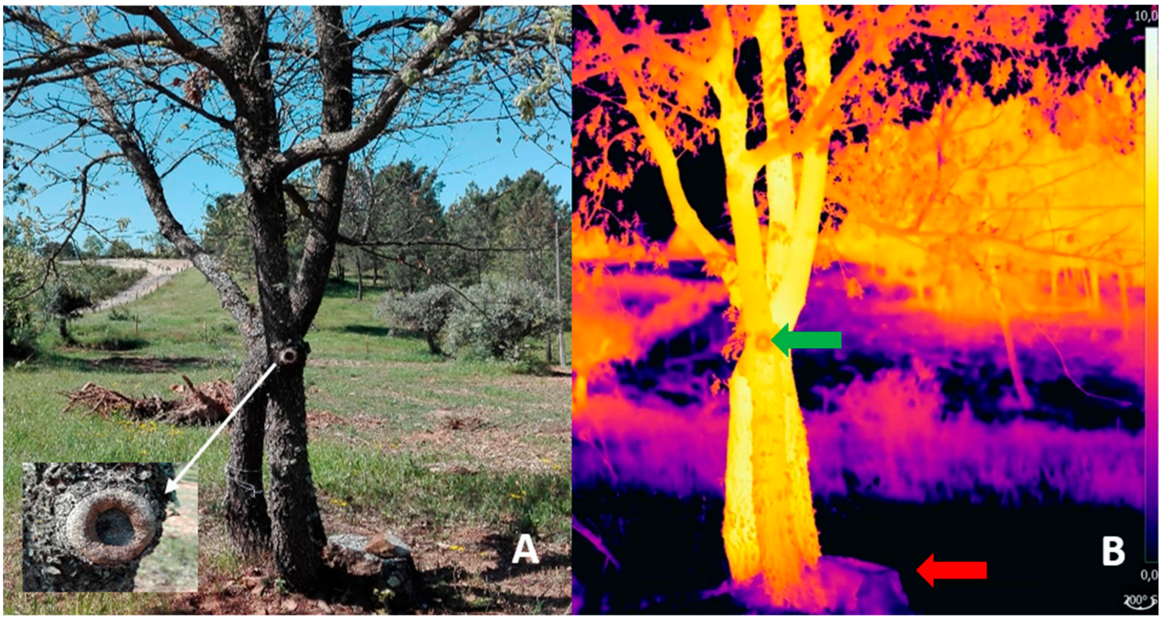


Figure 8. Photo (**A**) and thermogram (**B**) of the *Quercus pyrenaica* Willd tree. The white arrow shows an enlarged image of the CODIT development wall; the green arrow shows the same wall of CODIT on the thermogram; the red arrow indicates a stump. CODIT: compartmentalization of decay in trees.

Figure 9 shows the thermogram of the tree of species *Olea europaea* L. described in Figure 5 and Table 2. Table 5 shows the environmental conditions during the observation, and the parameters assumed. The spot temperatures in Figure 9 are detailed in Table 6. The thermogram was recorded after sunset on a winter day (on 21 January 2018, at 5:50 p.m.; sunset at 5:35 p.m.). The atmospheric temperature was 18.0 °C and the relative humidity was 50%. The atmospheric temperature was 18.0 °C and the relative humidity was 50%. The thermogram was taken a distance of 5 m, using an emissivity of 0.95. A rainbow colour palette and a temperature range of 5.0 °C to 20.0 °C were used.

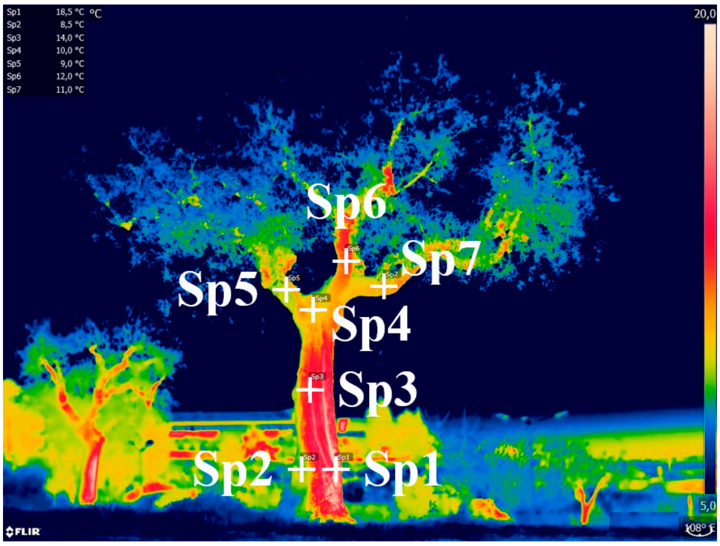


Figure 9. Thermogram of the *Olea europaea* L. tree recorded in passive mode at 5:50 p.m., 15 min after sunset. (Spot's size out of scale for better visualization).

Table 5. The ambient conditions and parameters assumed for recording thermogram of *Olea europaea* L.

Thermogram Image	Tree (Specimen)	Air Temperature (°C)	Relative Humidity (%)	Emissivity	Reflected Temperature (°C)	Observation Distance (m)	Colour Palette	Temperature Range (°C)	Daytime
Figure 9	*Olea europaea* L.	18	50	0.95	18	5	Rainbow	5–20	after sunset

Table 6. The temperature (°C) of the spots on the *Olea europaea* L. thermogram (Figure 9).

Thermogram Image	Sp1	Sp2	Sp3	Sp4	Sp5	Sp6	Sp7
Figure 9	18.5	8.5	14.0	10.0	9.0	12.0	11.0

The *Olea europaea* L. tree shows a large crack identified as Sp1 in the thermogram of Figure 9. Sp1 temperature is slightly higher than the atmospheric temperature. This spot represents a zone of the tree that has been exposed to the sun for a longer time. Sp2 temperature is much lower than Sp1 temperature—the difference between them is 10 °C. The differences in the temperature at the same diameter trunk is an indicator of possible deterioration. Then, it is possible that the Sp2 zone has deteriorated. However, this zone was in the shadow for a longer time. In addition, Sp1 is in a crack area. Thus, the comparison of these two spots is not conclusive, but it reveals a clue of possible deterioration to take into account.

In the same Figure 9, Sp2 is at a much lower temperature than Sp3. These spots are comparable because they are located on trunks of similar calibre. On the other hand, Sp2 was in the shadow for some time. Thus, the comparison is not conclusive, but it reveals a new clue to take into account for possible deterioration. Then, this study analysed the temperature of Sp2 in relation to the atmospheric temperature. The Sp2 temperature of 8.5 °C is much lower than the atmospheric temperature of 18 °C. This condition strengthens the possibility of deterioration at Sp2. Note that Sp3 is in the middle of the main trunk receiving sunlight. Although it already lost temperature, it was at 14 °C.

Sp4 in Figure 9 is at 10 °C, even exposed to direct sunlight, and it is on the same trunk as Sp3, which is at 14 °C. The two of them are located in trunks of the same diameter. The difference of 4 °C between the two points is a strong indicator of deterioration in Sp4. When comparing the temperature of Sp4 with the atmospheric temperature, the difference is 8 °C, which is relevant since Sp4 was exposed to direct solar radiation until just before the thermogram was recorded. This is another reason that indicates deterioration. Sp4 is approximately at the opening of an orifice. Then, it was expected the temperature to be higher than the registered temperature, and still higher than the values of the boundary zones, as is the case at the slot of Sp1. A probable cause for unhealthy conditions in that area is the hole at Sp4 that stores water from precipitation.

Sp5, Sp6 and Sp7 (Figure 9) are on branches of approximately the same diameter. They are at lower temperatures than the main trunk, because they are of smaller calibre. The trunks of smaller calibre heat and cool faster than larger ones. Smaller trunks have a larger surface per volume unit, so they heat and cool faster. The thermal inertia of the trunks of larger diameter is greater because they have more mass. Thus, from the point of view of health, Sp5, Sp6 and Sp7 should be at approximately the same temperature if subjected to the same solar exposure. Sp7 should have a higher temperature since it received directly more sunlight. This did not happen. Sp6 temperature is 1 °C higher than Sp7, which is not significant. The most disturbing is Sp5, because it is at 9 ° C. This value is too low for a healthy area even if exposed to less time in the sun. Sp5 is at a much lower temperature than the atmospheric temperature, which is 18 °C. This is a strong indicator of possible deterioration.

Sp2, Sp4 and Sp5 conditions (Figure 9) strongly indicate possible deterioration. This strong evidence was confirmed with observations of an enormous interior cavity linked to the crack (Figure 10).

Figure 10. Felling the tree has shown the presence and size of the concealed damage (red arrow) detected by the IRT method.

For doubtful cases, more thermography analysis would be recommended, e.g., at night, and if doubt remained, these spots become flags for the application of other diagnostic techniques and methods. Note that, these other diagnostic techniques do not need to be applied to the whole tree, but only in the identified points.

Epiphytic vegetation, such as lichens, is distributed more or less homogeneously throughout the tree and should not be responsible for the differences in the thermal pattern presented.

In IRT, as in all existing techniques, there are several conditions to take into account in order to achieve reliable results on tree analysis. That is: Exposure to sunlight and shadow; thermal contrast between the environment and the object targeted; the absence of water like rainfall; vegetation covers such as mosses and lichens; typical bark patterns of each species; the thermal comparison between the trunks of different calibre within the same tree [2–4,9].

Thermographic observations to trees are often made against the sun, or to tree surfaces when they are under the incidence of solar radiation. Thermographic recordings of trees when the sun is in front of the camera and sunlight directly hitting the tree surface introduces recording noise. In these cases, the temperature differences are more influenced by reading errors (lens, light exposure and reflections) than by material properties and defects. The shaded or less-illuminated areas (lower direct solar exposure) exhibit lower temperature values than expected, suggesting that the tree has deteriorated [2–4]. The IRT application requires a strong thermal contrast between the object to observe the environment and the objects that surround it. There must be a significant difference between the radiative power of the environment and the object analysed [9].

The thermograms and photographs presented are illustrative of relevant aspects to be taken into account in the observation and thermographic analysis of tree salubrity. It can be seen that on the thermogram of Figure 6, Sp1 and Sp5 are exposed to direct sunlight, and they are at a higher temperature than the atmospheric temperature, whereas the spots in the shadow are at a lower temperature than the atmospheric temperature. On the thermogram of Figure 7, all temperatures are lower than the atmospheric temperature. The colour patterns of thermograms of Figures 6 and 7 appear different. The various pattern colours correspond to different temperatures in the thermogram as shown in Table 4. The temperature differences by themselves do not indicate deterioration, as they can result from sunlight exposure and shadows. Figure 7 shows a general homogeneous temperature distribution, in which the different shades of Sp3 in Figure 7 is on a tree stump. Even its diameter is larger than the other trunks and it is at the lowest temperature and considered lifeless, and therefore not functional. It is probably because it does not circulate sap and its water content is much lower than its surroundings. In the upper part of the tree, the branches are of smaller diameter, as in Sp5. The branches heat and cool faster. Therefore, at 2 p.m. (under the action of sun exposure) Sp3 is at a higher temperature than Sp4, and at 9:45 p.m. (night), the opposite is registered.

Under closer inspection, there are subtle differences of the temperature in the thermograms, which result from the bark pattern, pruning wounds, and epiphytic vegetation such as mosses and lichens. They appear as spots of slightly lower temperature than the adjacent ones. In any of these cases, these small thermal contrasts are not deterioration signals. Another case that leads to some doubts is the self-defence process (CODIT) that trees develop.

It is important to point out that thermographic inspection requires photographs because they are visual inspection tools (VTA) that facilitate the interpretation of thermograms. By improving the interpretation of the results, it is often possible to avoid invasive methods [8].

Finally, it is relevant to highlight the main merits and weaknesses of the IRT technique. IRT has an enormous capacity to analyse the trees as a whole and differentiate functional tissue from dysfunctional tissue. This is crucial for the inspection of the vitality and health status, representing a fast, economical, nondestructive and environmentally friendly monitoring tool. However, as in other non-invasive methods, the main limitation is that IRT does not identify specifically the damage detected, i.e., does not identify the pathology, nor its causative agent. Nor can it also give precise indications of the magnitude of the damage. More studies are needed to optimise the technology and training, in order to make the system even more efficient and reliable.

5. Conclusions

In this study, the general principles of the IRT methodology for health status of trees was presented. A qualitative IRT approach of two sample trees, namely species *Quercus pyrenaica* Willd and *Olea europaea* L., was used. Several details were highlighted to describe the IRT analysis applied to trees. The results show the IRT is a non-invasive, sustainable and expedited technique with high potential for tree inspection. It allows for the early diagnosis of damage, even those that are not yet visually noticeable, which is relevant to advanced tree maintenance. As in any other technique, its correct application requires a deep and multidisciplinary knowledge of the phenomena and a high familiarisation with the technique. The study intends, therefore, that thermography and other related methodologies for tree diagnosis result in interventions that privilege sustainability to benefit the economy and nature.

6. Recommendations

IRT is a well-established technique in many fields. However, it is relatively new in agriculture where it remains residually implemented. Most farmers are ready to accept technology if it is profitable, less complex and makes their life easier [26]. For this to happen, more detailed studies to establish a solid application basis, which can guide practitioners needs to be created. In fact, reliable guidelines are not available to describe the acceptable protocol and parameters tailored to adopt for a more straightforward approach for many tree health problems. Several challenges need to be addressed: The complexity of the technique; the new and atypical aspects of the problem; several knowledge gaps related to the technical issues and applicability specificities. Thus, more research is required to ensure its potential and applicability on a large scale. The latest high resolution and sensitivity thermal cameras can also contribute to overcoming these challenges.

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