

## How Thermal Imaging Works

### Applications of Thermal Imaging For Determining Cross-sectional Functional Wood.

**Evaluation of thermal imaging as a technology.  
Creation of the Tree Thermal Matrix System.**

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### Thermal imaging as a process

***Thermal Imaging allows the classification of wood into optimal and sub-optimal functional wood. This allows identification of risks via a likelihood of failure but also allows a tree's strength to recover to be assessed. This is important in terms of the tree's ability to overcome fungal decay and to overcome work carried out on the canopy. This balance can only be objectively assessed with thermal imaging since only thermal imaging can evaluate functional wood throughout the whole tree.***

### Thermal processes and changes in wood functionality

The surface temperature of trees is a result of the movement of heat energy to the surface. As a result of the first and second law of thermodynamics heat energy tends to move from regions of high energy to regions of low energy in three dimensions (Atkins and de Paula, 2006). The movement of heat through the environment is described by changes in temperature. At steady state, i.e. when there is a persistent supply of heat energy, the rate at which heat flows along a conductive material is seen as a temperature gradient along it; the steeper the gradient, the poorer the conductivity of the material. The heat that reaches an exposed surface reflects the heat energy travelling to it (Atkins and de Paula, 2006; Monteith and Unsworth, 2007). When heat is supplied in a transient form then the movement of heat is reflected in temperature changes (Atkins and de Paula, 2006; Monteith and Unsworth, 2007).

As a whole, trees produce very little heat energy in comparison to other living organisms particularly animals (Monteith and Unsworth, 2007). Internal heat is derived from environmental sources and flows through trees according to the conductive properties of the internal structure. Heat will move through the tree 'system' according to the conductivity of the connected physical parts from hotter regions to cooler regions (Hunt *et al.* 2006).

Heat entering the tree from the environment is conducted through the wood and is eventually emitted from the surface. The conductivity of wood is a function of both its composition (the solid fiber, water and air content) and its three dimensional cell arrangements (Potter and Andresen, 2002). The cell wall elements and the water associated with them have the greatest conductivity in the system around 20 times that of the air and water vapor in the system (Table 1). As a result conductivity is optimal when there is little disturbance to the cell structure and when the relationship between the solid phase and water content is optimal. Once this structure is changed, and particularly if air is introduced into the system, then the conductivity is greatly reduced.

Many early studies of temperatures within and on trees have used thermometers or thermocouples inserted in the tree or attached to the bark (Potter and Andersen, 2002). Both involve physical alteration of the tree studied, and the sensor can alter the temperature by conducting heat into or out of the tree (Derby and Gates 1966). Attempts by Derby and Gates (1966) and Herrington (1969) to develop computer models of the temperature and heat flow in a tree showed the potential of such models as an economical and plausible alternative to installing and monitoring instruments in the field (Potter and Andersen, 2002).

The environmental heat entering the tree is not at steady state and changes throughout the day. Therefore, the conductivity is best described by the efficiency of the system, i.e. the way in which it responds to temperature changes rather than gradients (Monteith and Unsworth, 2007). This manifests itself as areas of the surface that appear warmer (relatively higher surface temperatures) because the heat moves to the surface efficiently or as areas that are cooler because the heat moves inefficiently and the degree of cooling indicates the efficiency of the system behind it.

Table 1 The physical and thermal conductive properties of the components of a tree trunk (from Hunt et al 2006).

TABLE 1. *Physical and thermal properties.*

Symbol	Thermal conductivity (W/m·K)	Density (kg/m <sup>3</sup> )	Specific heat (J/kg·K)
Cell-wall substance (0% MC) <sup>1</sup>	0.410	1540	1260
Air in the lumen (0% MC) <sup>2</sup>	0.026	1.161	1007
Bound water in cell wall <sup>3</sup>	0.680	1115	4658
Saturated cell wall (FSP) <sup>4</sup>	0.489	1415	2256
Water vapor in cell lumen <sup>5</sup>	0.018	0.734	2278
Free water in cell lumen <sup>6</sup>	0.610	1003	4176

Note:

<sup>1</sup>. Property values for cell-wall substance at 0% MC was obtained from Siau (1995).

<sup>2</sup>. Air property values for air were obtained from Incropera and DeWitt (1981).

<sup>3</sup>. Density of bound water was obtained from Siau (1995). Thermal conductivity and specific heat of bound water was obtained based on water properties and assumption of the linear relationship with density.

<sup>4</sup>. Property of saturated cell wall was obtained by rule of mixture. FSP, fiber saturation point.

<sup>5</sup>. Property values of water vapor were obtained from Ierardi (1999).

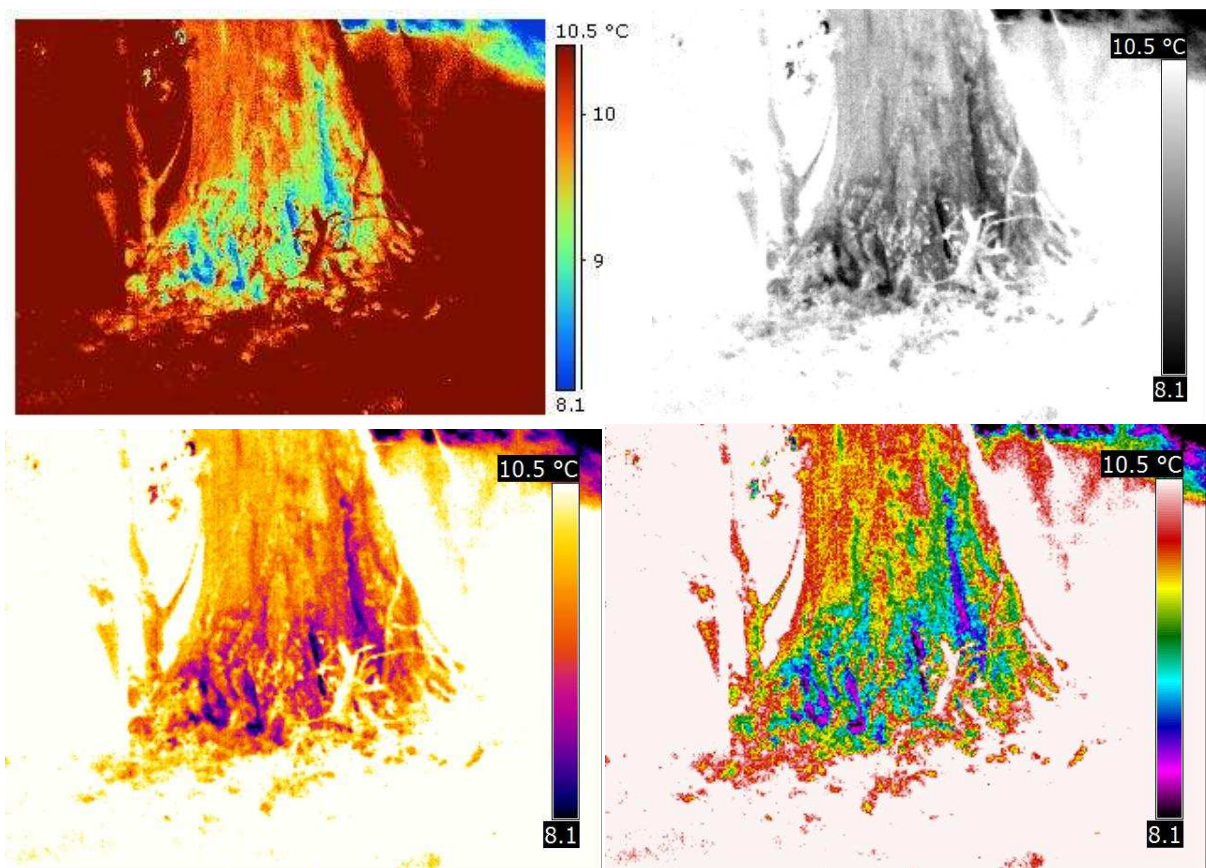
<sup>6</sup>. Property values of free water were obtained from Incropera and DeWitt (1981).

<sup>7</sup>. The *k<sub>f</sub>* is constant when MC is over FSP, but changes with MC below FSP.

The reliance of heat conductivity within trees, on the cell structure and water content of wood, means that there is a strong correlation between the relative physiological performance of the tree and the responsiveness of the tree to changes in heat flux.

Thermal imaging cameras measure the long-wave radiation emitted from solid objects as a result of the heat energy they contain. This can be used to determine their surface temperature (Flir, 2008). The surface temperature is converted into a colour scheme by the camera from warmer to cooler areas, so that areas of a similar temperature can be identified and temperature changes can be identified. The colour scheme can take on any form but the more colours that are used the better the differentiation between temperatures (Figure 1).

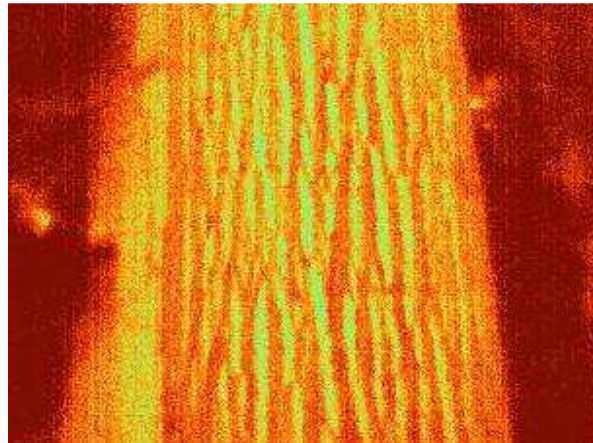
**Figure 1.** Various colour schemes used to describe the surface temperature between 8.1 and 10.5 °C at the base of the same tree.



When trees are healthy, the energy they absorb from the environment is stored and emitted from the surface in an even heat pattern (Catena and Catena, 2007) (Figure 2). If something interrupts the conduction of functional wood, the flow of heat is interrupted and heat must move around them. These lead to a cooling of the surface area in the proximity of the disrupted internal parts due to a reduction in heat flux. The greater the extent of disruption, the greater the effect on the temperature at the surface (Catena and Catena, 2007) (Figure 3).

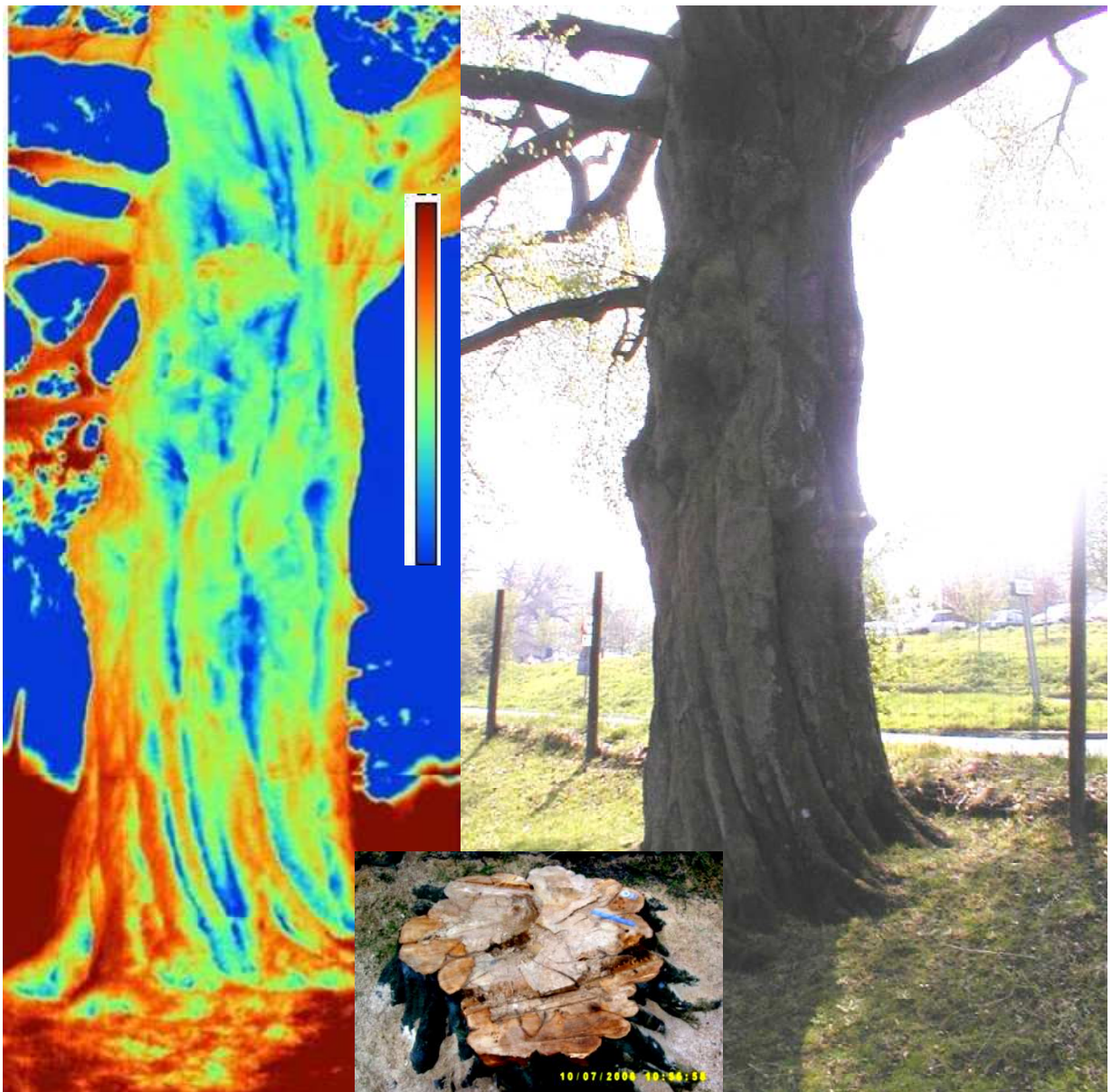
The amount of heat flux changes continuously throughout the day as the environmental heat sources change. Because of these continuous changes Catena and Catena (2007) came to the conclusion that the system could not be quantified. However, the models of Herrington (1969) and others indicated it was possible to quantify the system if detailed quantification of the relationships could be carried out.

**Figure 2.** An even pattern of warm areas of bark ridges (red) and cooler areas bark fissures (green).



Senescence; drying/seasoning of wood; inclusions/wounding/scarring, cavitation; shaking/delamination and infection all obstruct the flow of heat and alter surface temperature but it is the presence of microorganisms and decay that bring about the biggest changes in wood functionality Catena and Catena (2007). The loss of functionality can be detected and quantified but to do this, thermal images must be calibrated against environmental changes.

**Figure 3.** The thermal image (left) shows a temperature range on the surface of the tree from warmer areas show in red through to cooler areas in blue. A central area of decay (pale areas in the cross-sectioned tree inset) is causing cooling of the surface of the tree between buttresses and behind some thinner buttresses where the decayed area is close to the surface. Decayed areas are also much closer to the surface higher up the tree where blue is the predominant colour.

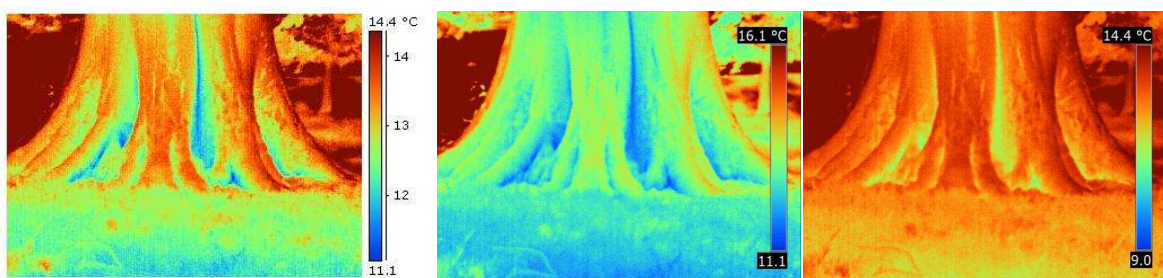


## Development of TTMS

The interpretation of thermal images relies on the understanding of how surface temperature responds to the environment, therefore, it is necessary to calibrate images since the surface temperature will be constantly changing. The calibration will be unique for each set of images, taking into account changes in environmental temperature. Without calibration the thermal images do not reflect the functional tissue below the surface (Figure 4).

Calibration allows two onward processes to be undertaken. The first is the extraction of temperature data that can be analysed to calculate the amount of functional wood in regions behind each distinct point at the surface. The second is the visual analysis of how distinct areas of functional wood are connected together to form elements and conduits within the tree's structure. In these ways, thermal imaging allows the physiological robustness of the tree as a whole to be studied. This allows a prognosis of the tree to be made since the wood within the tree is examined according to its ability to continue to support the tree both structurally and physiologically.

**Figure 4** Correct calibration allows evaluation of the functional wood based on the surface temperature (left), cooler areas, blue, indicate regions where *Kretzschmaria deusta* is close to the surface. The functional wood thickens in the buttresses and the temperature increases, red areas. If the images are not correctly calibrated the buttresses can appear thinner (centre) or the infection can appear much deeper (right).



## How Was TTMS Created

A software system was developed to calibrate images, Tree Thermal Matrix System (TTMS). The TTMS was initially based on a number of algorithms determined from first principles based on the conductivity of the various structures within wood and environmental measurements. These were then tested and modified following data collection over a 2 year period.

The system was validated using a set of key trials that allowed direct comparison between measured surface temperatures and measurements of functional wood. One of these was the Cragmoor Road trial in Nottinghamshire. With the cooperation of Nottinghamshire County Council, thermal images were taken of 20 trees due to be felled. Prior to felling the trees were marked up with marker paint into 25cm sections. After felling the stems of the trees were cut into 25 cm sections and cross-sectional functional wood was evaluated and measured (Figure 5).

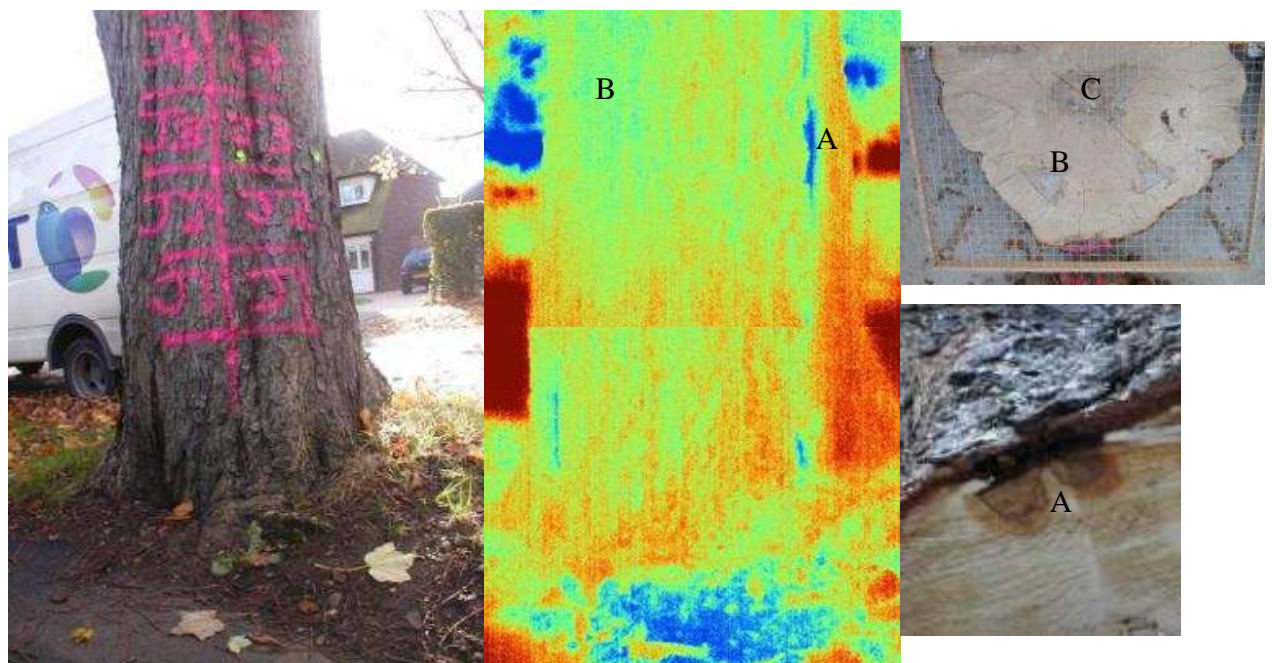
In total 400 trees were studied in this way to determine the relationship between internal functional wood and the apparent surface temperature. The studies also confirmed that the introduction of air into the system such as when there is appreciable drying (Figure 7), and the presence of cankers (Figure 6), were sufficient to alter the surface temperature.

However, the degree and the distribution of the temperature changes were different such that they could be identified as different causal agents from internal decay (Figure 8).

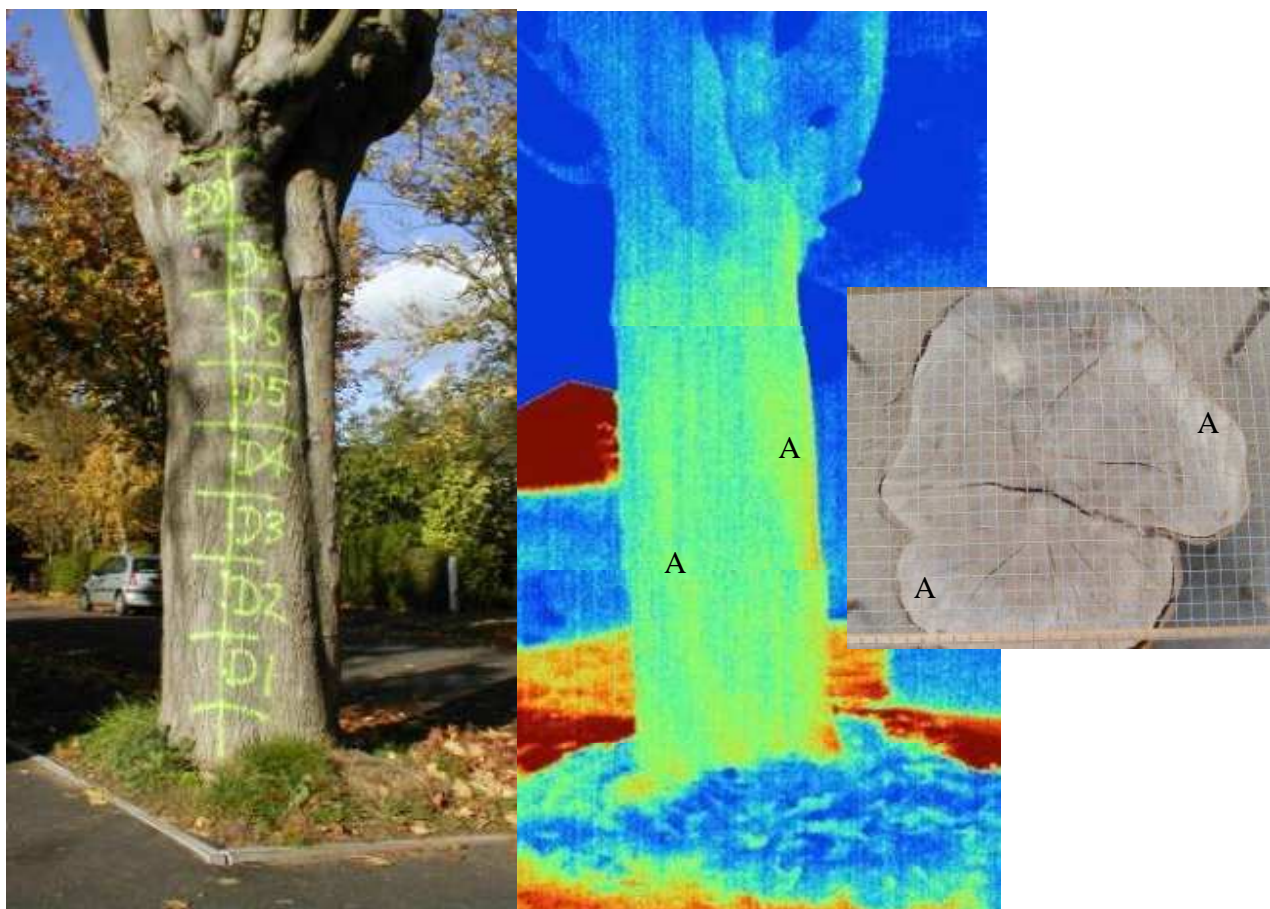
**Figure 5** Photographs for the Cragmoor Road Trial, showing the marked trees the felled stems and sections cut from tree D.



**Figure 6** Thermal images indicating cankers (A) and old pruning wounds (B) in a Horse chestnut in Cragmoor Road, Nottinghamshire with only minor central dysfunction (C).



**Figure 7** Thermal images indicating widespread loss of functional wood, blue-green colour and only localised areas of functional wood, yellow areas in thermal image pale areas on stem cross section (A) in a desiccated Norway Maple in Cragmoor Road, Nottinghamshire.



The TTMS was then validated using a further sample of 12,000 trees using a combination of thermal imaging and increment cores. This process was conducted with the cooperation of Nottinghamshire County Council, Woburn Abbey and others as well as using trees on the Nottingham Trent University estate. This allowed third party confirmation of the results.

The system has been further validated with commercial contracts with Blenheim Palace, Somerset County Council, North Somerset Council, The National Trust for Scotland, The National Trust, Amphill Town Council, Mid Beds Council, Crown Estates and over a hundred other organisations. Again using the technology in the public domain has allowed independent validation of the system.

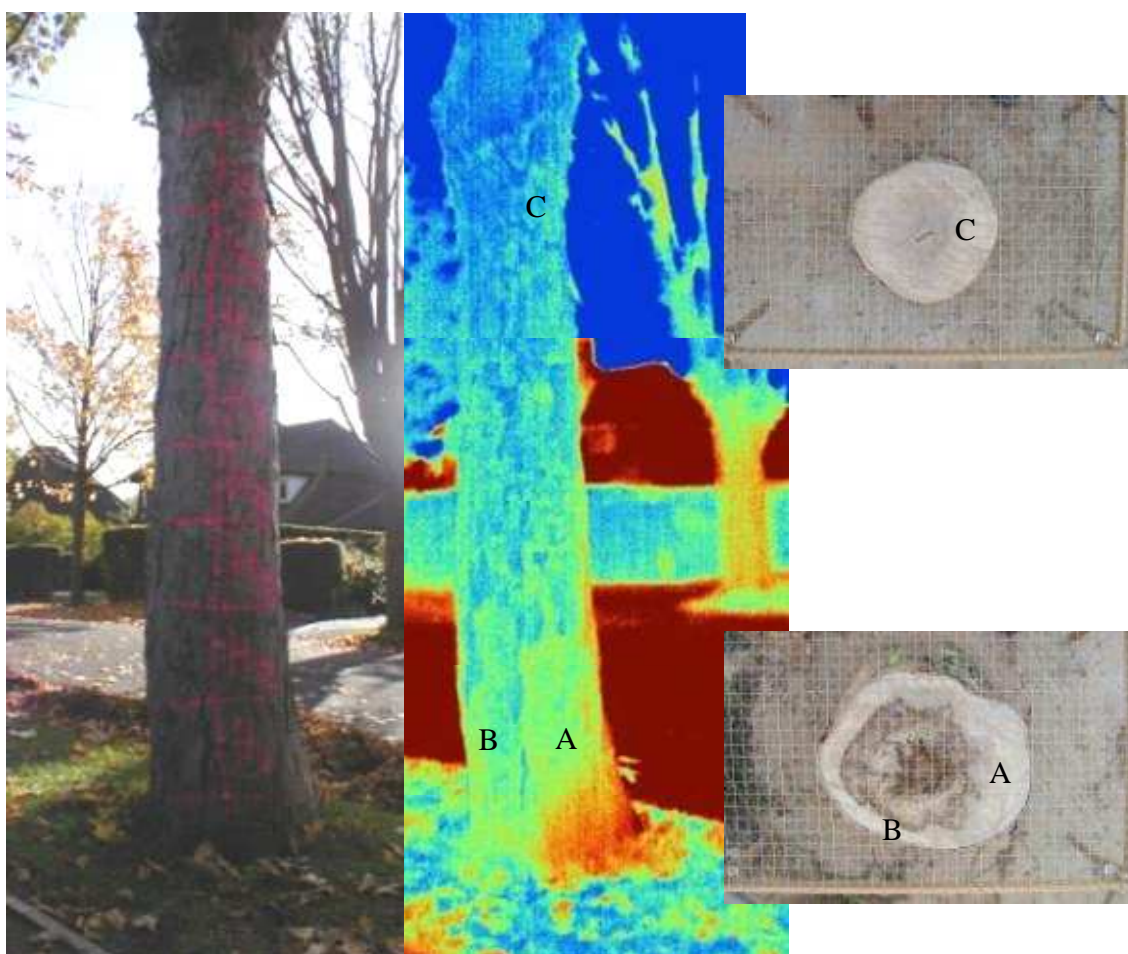
The system is continuously updated through our both the activities of Tree Project Limited and the licensee scheme. The system is now based on over 30,000 trees. Based on estimations of % functional wood. This has led to a precision of  $\pm 2\%$  and an accuracy of  $\pm 0.1\%$  for trees of between 35-150 cm dbh.

### **Third Party Blind Testing**

Three third party blind tests were set up to demonstrate the impartiality of the studies. The most prominent of these was a Horse Chestnut Avenue in North London. The test was arranged by the local authority (London Borough of Barnet) and the trees were visually

assessed by a Registered AA Consultant prior to an additional assessment with thermal imaging. Thermal imaging was able to provide information about the physiological robustness of the trees in addition to the visual information. The visual aspects of the thermal imaging survey were invaluable when communicating the results to other interested parties. More importantly the thermal imaging led to a reduction in both the amount of work carried out on the trees and the number of trees considered for removal.

**Figure 8** Thermal images indicating a central column of dysfunction and decay, the predominant decay at the base causes thinning of the functional wood from (A) to (B) has led to desiccation of the stem higher up at (C).



The system has been used by The National Trust for Scotland for over a year without the direct involvement of Trees Project Limited. Trees Project Limited provide a training and calibration service but the images are captured by the Trust without the involvement of the company.

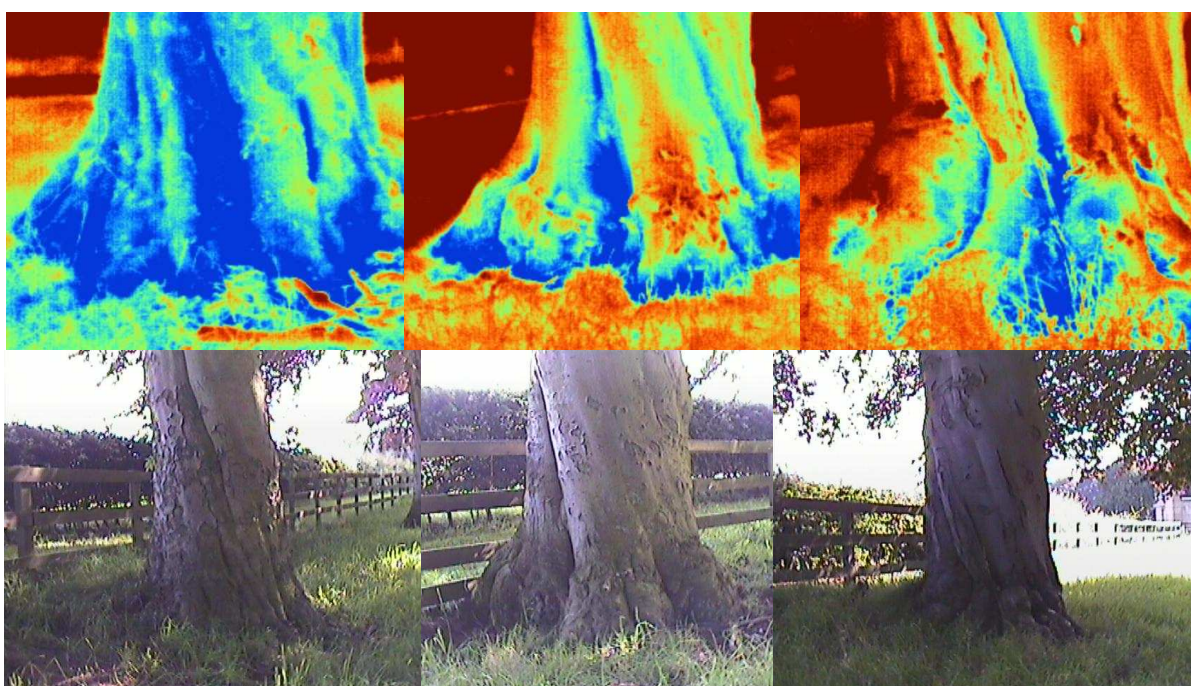
Thermal imaging has now been used successfully for over 3 years in a commercial environment. During this time over 15,000 trees have been surveyed commercially by Trees Project Limited in the UK over a 3 and a half year period. To-date there have been three non-critical failures that were predicted by thermal imaging, in addition around 150 trees with serious defects have been identified that were not identified by visual inspections in some

cases following multiple visual inspections. More importantly over 2000 trees that were condemned are still standing, following the identification of their physiological strength with thermal imaging.

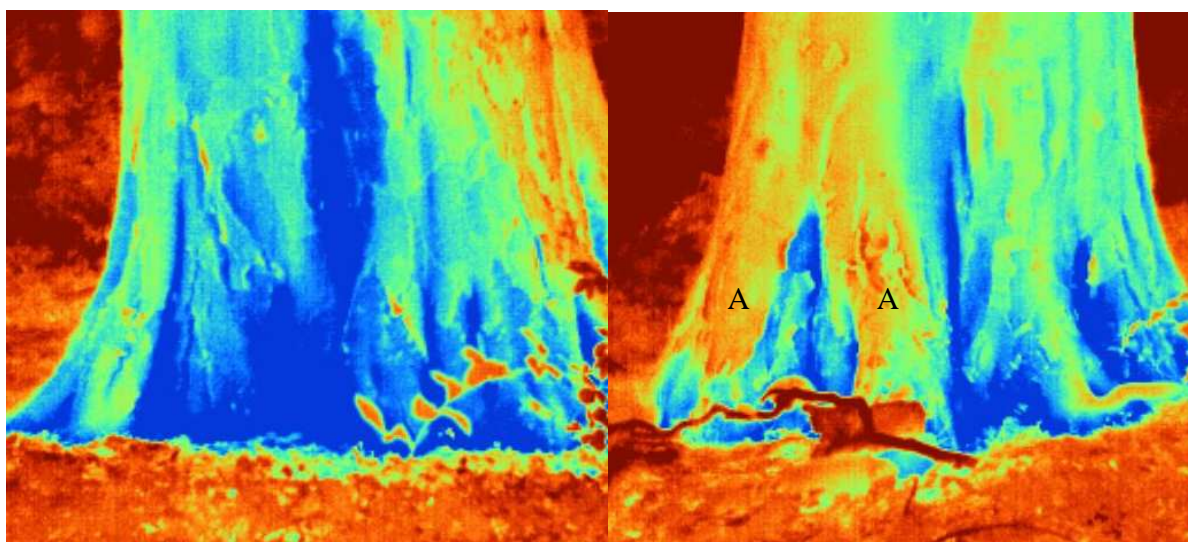
Thermal imaging has been instrumental in the identification of trees infected with *Kretzschmaria deusta* (Figure 12), *Meripilus giganteus* (Figure 11) and many other fungal organisms. It has also greatly increased understanding of the processes that lead to infections and the stages at which structural damage from these elements can become critical.

Thermal imaging has led to a better understanding of how degradation of grafting points can dramatically change the structure of the base of trees (Figure 9) or how construction damage to roots alters physiological function (Figure 10).

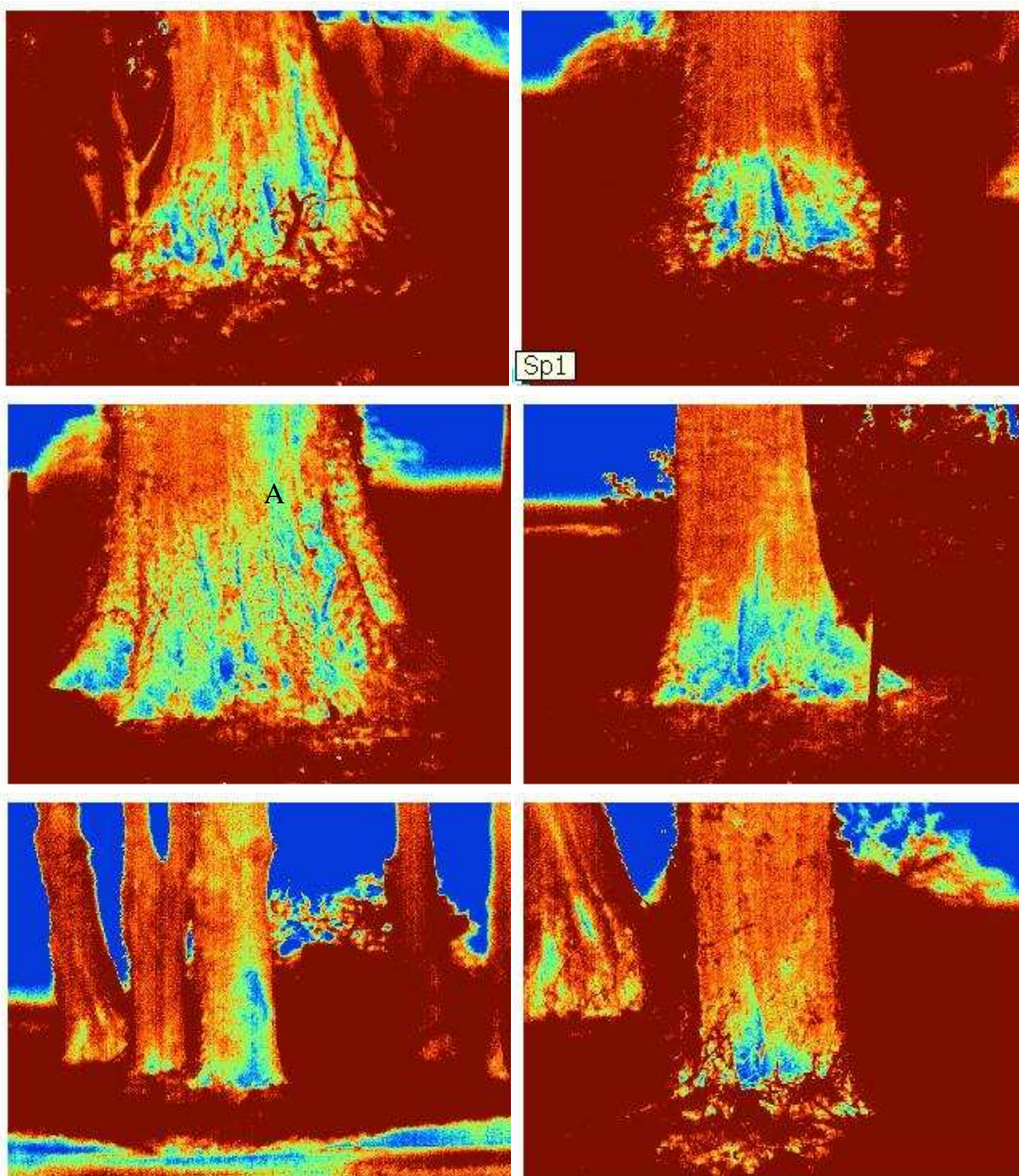
**Figure 9** (Left to right) grafted Beech trees in North Yorkshire showing an increased degree of replacement of a degenerated root stock with a replacement root system from the scion.



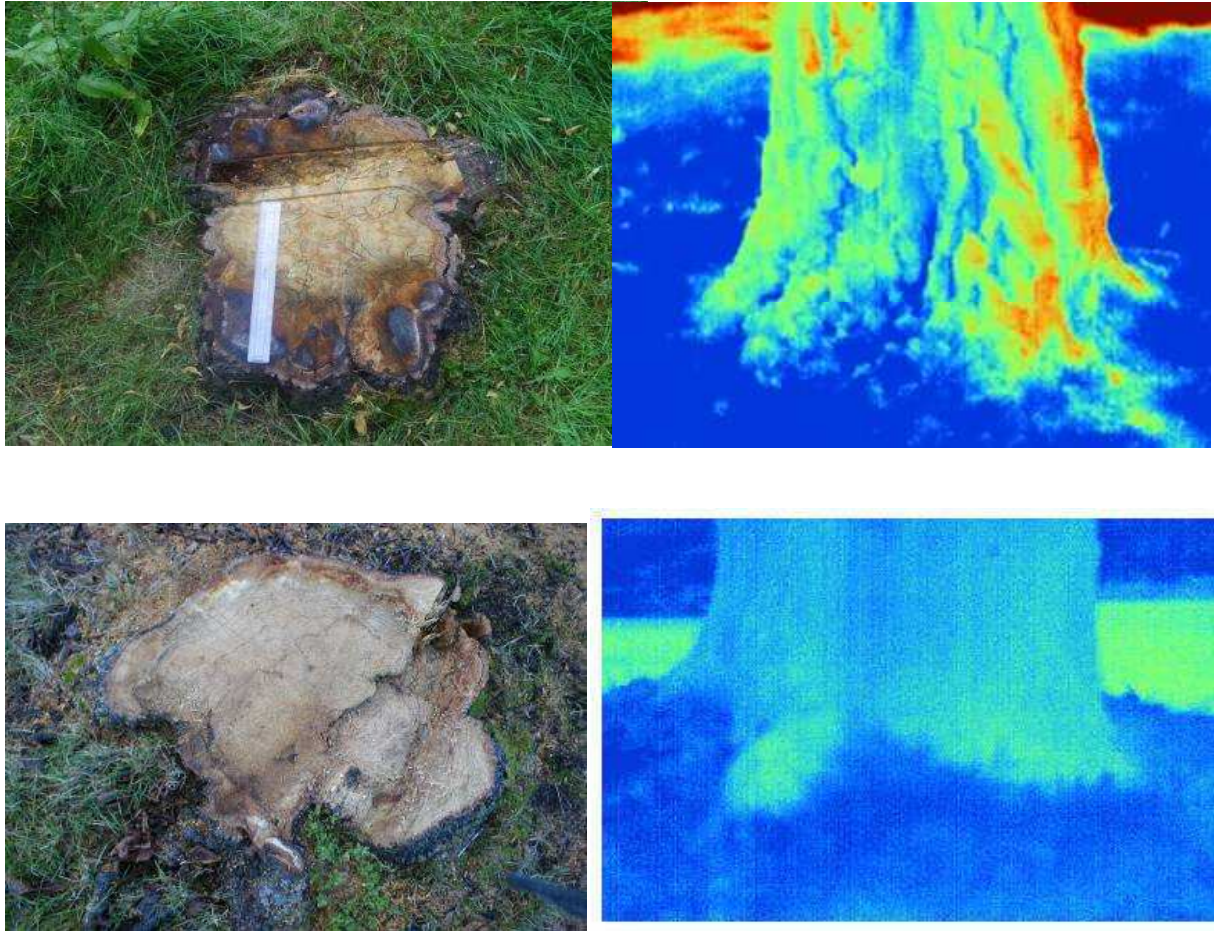
**Figure 10** Construction damage to a beech tree in North Yorkshire 75% of the root system has been severed leading to widespread dysfunction. The warmer areas at 'A' indicate buttresses still attached to a functional root system.



**Figure 11** Varying degrees of basal damage from *Meripilus giganteus* at Windwhistle Ridge, Somerset indicated by the spread and intensity of blue and in combination with mid-stem decay from *Gandoderma* sp. Spreading down to (A).



**Figure 12** Advanced *Kretzschmaria deusta* infections in Silver Birch (top) and Lime (bottom).



## Conclusions

TTMS was developed to allow thermal imaging to be used as a system to assess the amount of functional wood in trees. This can be used as primary data to assess both the structural and physiological robustness of the tree.

The system was developed from one of the largest data sets created in arboriculture and which continues to be added to so that the system will continue to improve. Through the network of more than 30 Licensees this process will be accelerated.

Third party testing and third party blind testing have been used to prove the validity and reliability of the system. In addition the system has been used on over 15,000 trees with over 120 clients in the UK, who have had the opportunity to personally scrutinise the system.

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