Concept and methodology of characterising infrared radiative performance of urban trees using tree crown spectroscopy

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Title: Concept and methodology of characterising infrared radiative performance of urban trees using tree crown spectroscopy

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Abstract

Urban trees play an important role in cooling urban microclimates and regulating outdoor thermal comfort. To better understand their contribution to these processes, it is crucial to elucidate urban trees' radiative thermal performance, especially in the infrared (IR) region (approximately 50% of solar radiation). Yet, owing to significant conceptual and methodological challenges, studies on the radiative performance of trees have mainly focused on individual leaves rather than crown-level characteristics. Here we applied a novel conceptual and methodological framework to characterise the crown-level IR radiative performance of 10 lime trees (*Tilia cordata*), a common urban tree in the UK and Europe. Our results show that reflected and transmitted solar energy from leaves is dominated (>70%) by IR radiation. At the leaf level, transmission and reflection spectra are similar between trees (differences typically < 10% in IR region), including those under significantly different urban stress conditions. However, at the crown-level, substantial variations in IR transflectance spectra (maximum difference > 40% in IR region) were found between trees. These variations were largely due to crown structural differences (leaf number, density, angles), rather than leaf solar interaction character (leaf-level transmittance or reflectance, leaf colour). Crown transflectance measured from the four cardinal directions was significantly different in the IR region (maximum differences circa 30%), and changed substantially with solar time. Hence, a tree's surroundings received very different, and time dependent, levels of solar IR radiation. These findings have significant implications for species selection and control of environmental stress factors in urban microclimates.

Keywords: Infrared radiative performance; Transflectance spectra; Tree crown spectroscopy; Urban cooling; Urban microclimate; Urban trees

1 Introduction

Urban green spaces and trees have substantial benefits for people's health, thermal comfort, pollution and noise reduction, sustainable urban drainage, and carbon sequestration [1]. In particular, trees and green spaces offer significant cooling benefits through canopy absorption, reflection, and transpiration, thereby helping to mitigate microclimatic environment in cities and towns and regulate outdoor thermal comfort [2–7]. Surface temperatures of trees and green spaces are typically 10-20 °C lower than those of full sun exposed ground and built surfaces [2, 7–10], leading to a significant reduction of radiant temperatures. Areas shaded by trees can be cooler than tree surfaces [11]. Air temperature reductions are smaller, typically up to 3.5 °C below the tree canopy [2, 7, 12, 13]. Trees are also effective, though to a lesser extent, in ameliorating urban heat island (UHI) [14,15]. In the sense of regulating the outdoor environment, urban trees will help to mitigate extreme heat stress through cooling, and anthropogenic global warming through carbon sequestration [16] as well as reduced cooling energy demand [17]. Among the many climate change projections of the UKCP09 [18], the ones that have the greatest impact on design of the built environment are increasing temperatures and increasing aridity, resulting in hotter and drier summers. The global average temperature rise will be accompanied by more frequent and intense extreme weather events, e.g. heatwaves, such as that of 2003, which resulted in over 2000 extra deaths in the UK and circa 35,000 across Europe [19]. By the end of the century a heatwave could be 10 °C hotter than it is today in the UK [18]. This is intensified by the UHI effect, which could lead to exceptional heatwave periods [20, 21].

To maximize the effect of trees on cooling microclimates in hot and arid summer conditions, research has focused on exploring thermal performance differences among various tree species, and providing tree planting guidelines for policy makers and urban planners, with the aim of developing resilient and resourceful cities [2–7, 12, 22, 23]. Tree species differ significantly in their ability to i) reduce air and surface temperature, and ii) increase relative humidity [7]. Zheng et al. [2] assumed that different tree morphology and characteristics among various tree species led to large differences in trees' cooling performance. They investigated three physiological indices (leaf transpiration rate, leaf surface temperature, and leaf reflectance) as well as seven microclimatic parameters (solar radiation, long wave radiation, mean radiant temperature, ground surface temperature, air temperature, relative humidity, wind speed) characterising four common tree species in Guangzhou, China (a subtropical region). Irmak et al. [4] concluded that surface temperatures of different tree species varied considerably and that the "sky-view factor" had a significant effect on tree surface temperatures, by assessing thermal effects of 15 different tree species (4 coniferous and 11 deciduous) located in the northeastern part of Turkey. The sky-view factor measures the visibility of the sky from a given point, with a value between 0 and 1, where a value of 1 means that the sky is completely visible from that point. A study of 10 common urban tree species in Basel, Switzerland, indicated that tree species differed by up to 9 °C in their canopy surface temperatures [10]. In view of this, choosing the right tree species for urban planting schemes is critical for maximizing their cooling potential. Morakinyo et al. [22] indicated that leaf-area index (LAI) was the main driver of the observed benefits, followed by trunk height, tree height, and crown diameter via a simulation study, taking into account the 8 most common tree species in Hong Kong. Tree species with higher LAI provided significantly more cooling than the other species, and surface temperature reduction was positively correlated with LAI [24]. Faster growing species showed higher LAI and higher stomatal conductivity and so provided more cooling benefits [25]. Lindén et al. [26] showed that transpiration-induced cooling from trees was an important driver of intra-urban differences in Mainz, Germany. It is reckoned by Shahidan et al. [27] that shading from trees and evapotranspiration are the prime factors that contribute to decreased air temperature. A similar viewpoint was presented by Gillner et al. [7], who argued that trees showing both a high leaf-area density and a high rate of transpiration were more effective in cooling air temperatures. The shading effect of trees is closely related to LAI and some work has already focused on modelling or measuring the shading effect [6, 28–33]. However, within this body of work, it seems that the mechanism of the shading effect has not yet been elucidated (e.g. from the perspective of radiative performance of trees) in terms of reflectance and transmittance.

To a large extent, urban tree planting guidelines are proposed according to trees' thermal performance. Some research has proposed useful guidelines based on a simplification of trees' physical characteristics or using a statistical method. Zhao et al. [3] explored optimal tree arrangement for both individual households and residential neighborhoods in a hot arid desert environment by microclimate numerical simulation. Kong et al. [5] declared that trees planted in high density settings were more effective in improving pedestrians' thermal comfort than those in open spaces, and trees with a large crown, short trunk, and dense canopy were the most efficient in reducing mean radiant temperature. They recommended some specific ways to facilitate the integration of tree planting into urban design. For instance, trees with larger crowns are preferable and a closer spacing offers continuous shading in the street environment; parallel rows of trees should be used in wider streets.

Morakinyo et al. [22] developed the approach of sky-view factor mapping to aid tree selection for multiple ecosystem services of trees. They suggested that dense foliage trees of an average height, such as *Bauhinia blakeana* (~7 m, LAI 3.55), *Macaranga tanarius* (~4 m, LAI 3.02), and *Aleurites moluccana* (~9 m, LAI 2.77), should be planted in high sky-view factor areas or locations e.g. shallow street canyons and other open spaces, while tall trees with sparse foliage should be planted in low sky-view factor areas such as deep canyons. The sky-view factor oriented planning approach was tested in Tan et al. [34] in designing outdoor comfort and climate resilience in subtropical high-density cities. Morakinyo and Lam [35] conducted a simulation study on the impact of tree-configuration, planting pattern and wind condition on street-canyon microclimate under hot-humid climate conditions. Additionally, Kjelgren and Montague [36] showed that trees grown over asphalt had up to 6°C higher leaf surface temperatures than those over turf; it also demonstrated up to 3°C variation in leaf surface temperature between the species tested. Nevertheless, trees' thermal performance has not yet been taken into account, from the perspective of their physical characteristics, in the establishment of urban planting guidelines, mainly due to limited information or understanding.

Scrutinising existing literature on urban trees reveals a lack of information on their radiative thermal performance, especially in the infrared (IR) region. This gap is an important one to address because IR radiation accounts for 52.4% of the terrestrial solar radiation reaching on the earth on south facing surface tilted 37° from horizontal [37]. Urban green spaces and trees are known to interact with solar IR radiation in a way that is dramatically different to the way they deal with visible (VIS) solar radiation via photosynthesis. Bridging the gap is thus crucial for fully understanding the role and potential of tree cooling effects. Previous studies on trees' radiative performance can be broken down into two main areas. The first area is studies that were mainly concerned with measuring individual leaves in the laboratory and field [38–42]. An interesting study in this area was done in the context of a different engineering discipline, aimed at cooling photovoltaic cells for maximising their electrical output in the light of tree leaves and tree bark spectroscopy [43]. The second is those studies that have focused on the radiative performance of tree canopies at a regional scale [44–46], which present a significantly different challenge to the tree leaf level. This is mainly because characterising the infrared radiative performance of trees at the tree crown level is complicated by the diverse morphologies and complex crown architecture of trees, as well as the temporal variation in solar radiation received throughout a day and over the course of a year. Importantly, there is no easily applied standard characterisation method available to investigate the radiative performance of trees.

This paper presents a novel study on both leaf level and crown level interactions between lime trees (*Tilia cordata*) and solar radiation. The study was aimed at providing information on the variation between individual trees in IR radiative performance of both individual leaves and tree crown surfaces to lay a foundation for a better understanding of the cooling potential of tree species. The work entailed significant reassessment of previous methodologies and concepts, in order to establish appropriate techniques for characterising urban tree interaction with solar IR radiation. The new conceptual and methodological framework was then applied to study trees in urbanised settings, generating valuable insights into intraspecific variation in the radiative performance of lime trees at the leaf and crown levels.

2 Concepts for tree crown spectroscopy

2.1 Transflection and transflectance

The radiative properties of individual tree leaves are characterised by absorbance, reflectance and transmittance of leaves, which can be measured separately. Yet, the radiative performance of the whole tree cannot be determined in terms of the radiative properties of tree leaves. The radiative performance of trees is rather complex compared to single leaves due to tree morphology, tree architecture and temporal variation of solar radiation. It is impractical to separate solar radiation transmitted through or reflected off various tree leaves, even if a fraction of the 'crown surface' is studied. Figure 1 schematically illustrates the tree crown interaction with solar radiation. When an optical sensor (i.e. fibre spectrometer) is positioned at one side of the tree to measure the radiative performance of 'a patch of tree crown surfaces' (abbreviated as 'a patch' hereafter), the received light of the spectrometer might comprise single-reflected, multi-reflected, multi-transmitted and transmitted-reflected rays through leaves. In this sense, it is necessary to introduce the term, transflectance (transflection) to describe the integrated radiative performance of trees at the crown level. This is not to be confused with the technique of spectral measurement used in near-infrared spectroscopy.

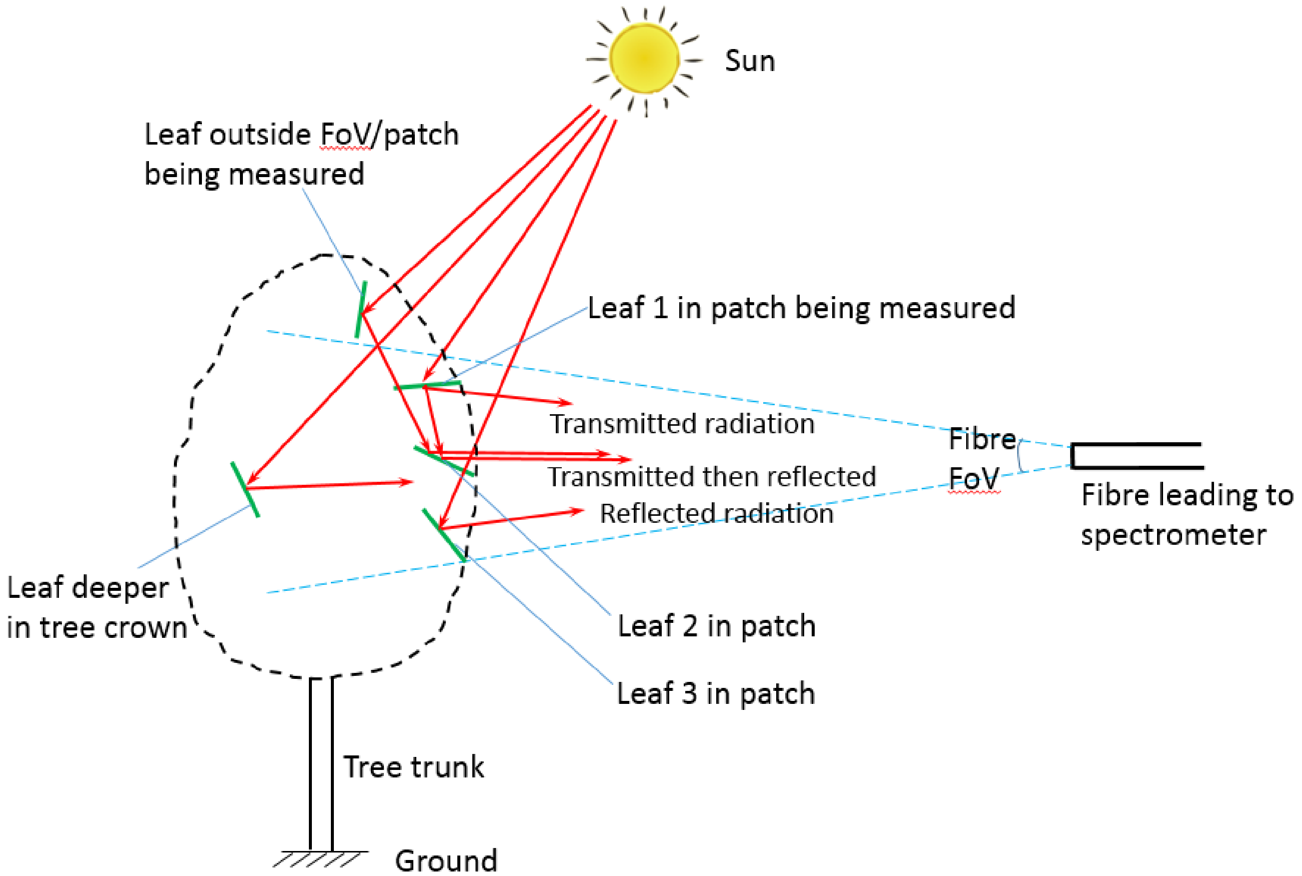

Figure 1. Tree crown-level interactions with solar radiation, illustrating the concepts of transflectance (transflection) for a patch being measured; FOV=Field of View

To establish the measurement method of the transflectance of tree crowns, it is useful to first scrutinise the definitions of radiative properties of individual leaves and then devise methods. At the leaf level, leaf reflectance is measured by the ratio of the reflected radiation from a given leaf to the reflected radiation from a reference plane with a reflectance standard that replaces the leaf at the same position, as shown in Equation (1). Both of the reflected types of radiation are measured by a spectrometer. Similarly, a leaf-level transmittance is obtained by the transmitted radiations from a given leaf and the reflectance standard that replaces the position of the leaf, as given by Equation (2).

$$r = \frac{I_{reflected}}{I_{ref}} \quad (1)$$

where r is reflectance, $I_{reflected}$ is the reflected radiation from a given leaf and I_{ref} is the reflected radiation from a reference plane with a reflectance standard.

$$\tau = \frac{I_{transmitted}}{I_{ref}} \quad (2)$$

where τ is transmittance, $I_{transmitted}$ is the transmitted radiation from a given leaf.

For the tree crown level, the term transflectance of a patch of the crown surface should be used to define the ratio of the total reflected and transmitted radiation from the patch (and received by the spectrometer fibre) to the reflected radiation from a reference plane with a reflectance standard that replaces the patch. For each patch of the crown surface, the reference plane for transflectance spectra measurement is the average plane of this patch of the crown surface as indicated in Figure 2. Definition of the average plane is not quite specific here, which is deliberate, because this concept will evolve further (see section 2.4).

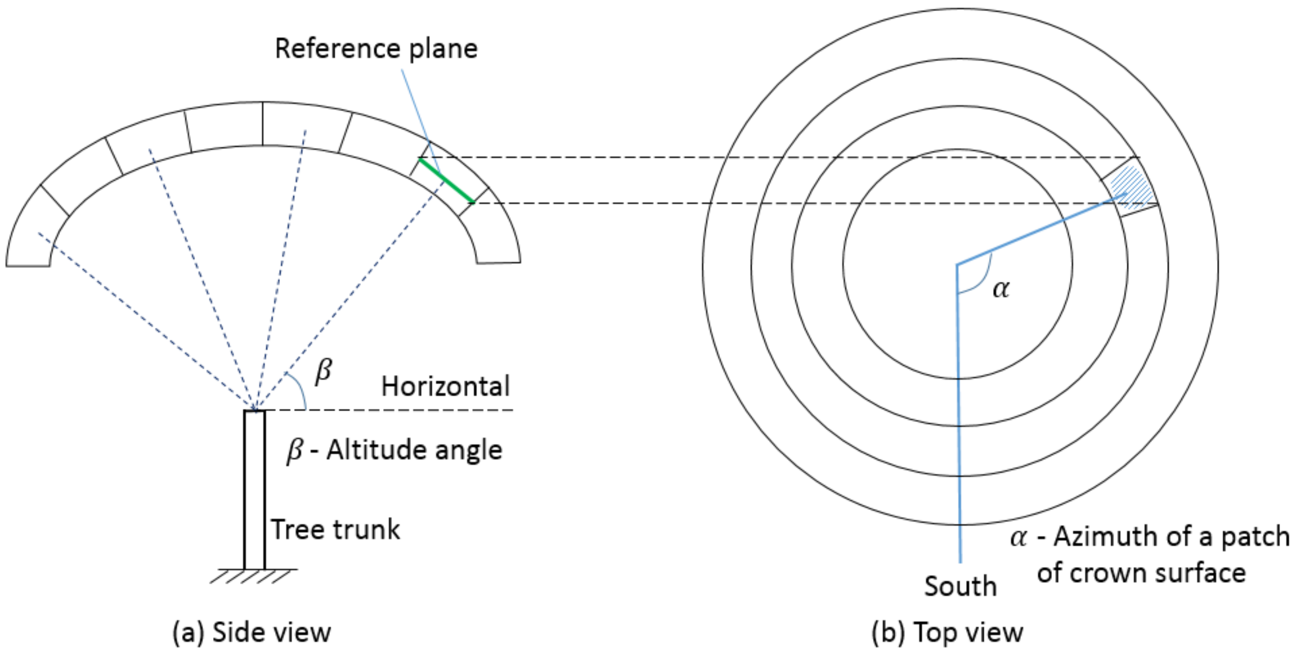

Figure 2. An illustration of a tree model (model 1) showing azimuth and altitude angles and reference plane location for a specific patch of crown surface

2.2 Six angles for characterising tree interaction with solar radiation

Figure 2 illustrates a tree model similar to an umbrella. Each small patch of crown surface locations can be described by the two angles, azimuth (α) and altitude (β). To fully characterise the tree interaction with solar radiation, two more pairs of angles are required. One pair of angles is azimuth and altitude of the sun, shown in Figure 3, allowing a description of the effect of different solar positions, seasons and time of day. Another pair of angles is azimuth and altitude of the viewing direction of the spectrometer optical fibre in relation to the patch of crown surface, shown in Figure 4, which helps to characterise the 3-dimensional variation of the transflected solar radiation from the tree crown surfaces. Thus, in total, 6 angles (Figures 2–4) are needed to map a tree's interaction with solar radiation. Even if each angle is discretised into 10 values in space, which is still rather coarse to characterise the whole tree crown, a total of one million transflectance spectra would need to be obtained. When finer resolutions are required, even greater numbers of spectra would be needed, which would be impractical to achieve. In this sense, rather than a full mapping for each tree, a first step would be to identify a small number of important factors affecting the tree-solar radiation interactions and focus on understanding the nature and magnitude of their effects.

Urban tree research often deals with the effect of trees on buildings and people. In this context, the spectra of solar radiation received by a building or a person can be obtained through the integration of those from each of the small patches with different angles to the building or the person.

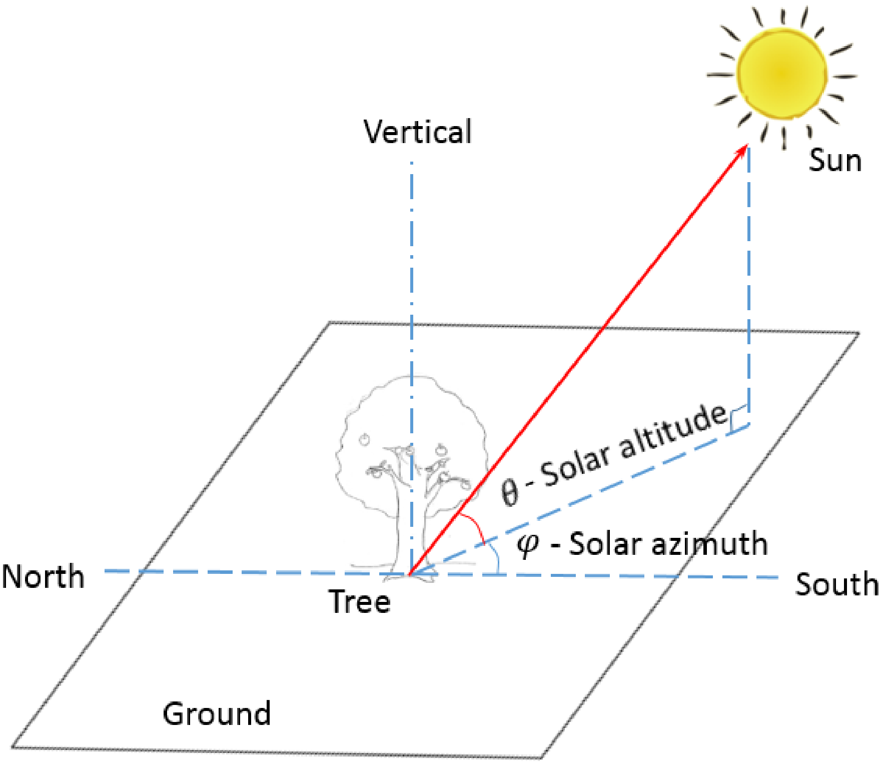

Figure 3. An illustration of solar azimuth and altitude angles in relation to a tree being studied

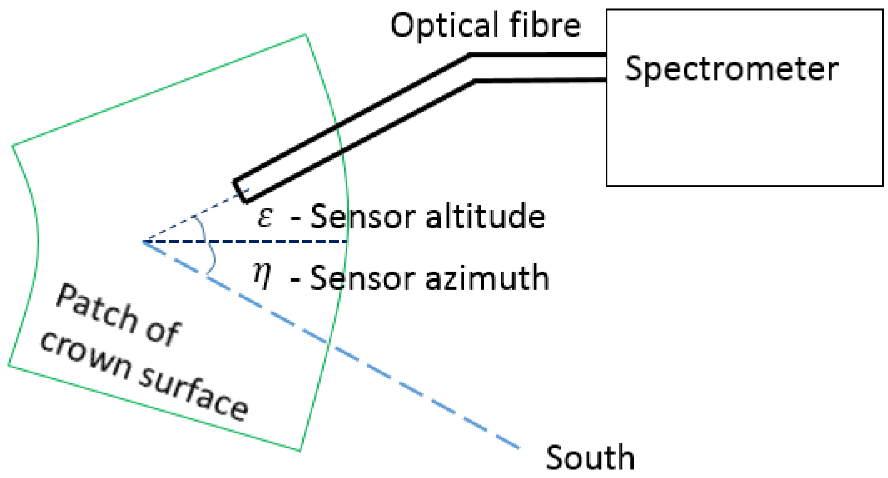

Figure 4. An illustration of a patch of crown surface showing azimuth and altitude angles for the spectrometer optical fibre

2.3 Reference plane and contributing volume

In a leaf-level measurement scenario, the light falling on the leaf is all that is available for reflection off or transmission through the leaf. In contrast, in the situation of crown-level measurement, for any patch of crown surface being measured, light falling on other parts of crown beyond the measured patch of crown surface can contribute to the transflected solar radiation received by the spectrometer /fibre directed on this patch. As shown in Figure 1, solar radiation transflected by foliage located deeper into the crown beyond the patch of crown surface, and by foliage located outside the field of view (FoV) of the spectrometer optical fibre, can contribute to the measured solar radiation spectra. Namely, light from a volume of the crown rather than from just the reference surface for the patch being tested is influencing the spectra measurements, as illustrated in Figure 5, which presents a common tree crown form. Thus at the crown level, the concept of contributing volume, in conjunction with the reference plane, is important for understanding and interpreting transflectance results.

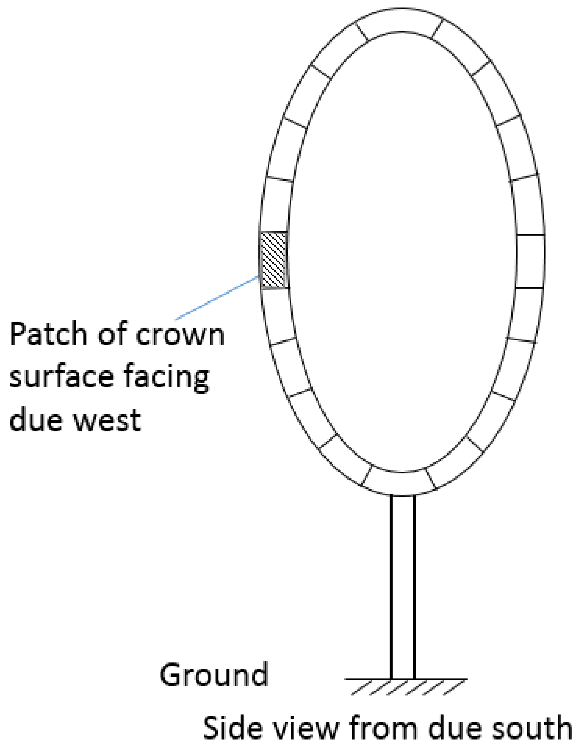

Figure 5. An illustration of tree model 2 and contributing volume

2.4. Single versus multiple reference planes

In the tree model 1 discussed, the concept of a reference plane for each patch of the crown surface is introduced (Figure 2). However, there is a degree of arbitrariness to the selection of this reference plane position. This is due to the variation of leaf surface orientation, density, position, etc. Furthermore, the reference planes for different patches of the crown surfaces have diverse orientations so their reference spectra are different, making comparisons of solar IR performance among different patches (e.g. those facing four cardinal directions revolving around E, S, W, N) of the crown surface rather difficult. Finally, more importantly for the tree model 2 presented in Figure 5, the method of selecting the reference planes for each patch will break down in some cases. For example, at midday, a patch of crown surface facing north has a reference plane which receives no direct sunlight, while the contributing volumes beyond this patch ensure that the patch will still project outwards a significant amount of solar radiation. The resulting spectra will have infinite values throughout the wavelength range of the spectrometer, thus a measurement might not be useful at all. Likewise, patches of the crown surface in the shadow sides of the tree will experience a similar problem.

It was therefore decided that for a single tree, the measured spectra for various patches of the tree crown surface would be referenced to a single (or fixed) reference plane. It is our recommendation that a flat surface vertical to the horizontal ground facing directly to the sun (i.e. perpendicular to the projection of the sunlight line to the horizontal ground) should be chosen. There is no rigid principle of choosing the single reference plane, but once selected the single reference plane will allow quantitative comparisons of different patches of the tree crown surfaces. Note that in principle, surfaces of any orientation could be chosen. Furthermore, the measured spectra on a specified reference plane can be transformed to corresponding spectra in relation to a different reference plane with a different orientation. A vertical reference plane is chosen in this study because it is more intuitive and urban built surfaces are often vertical. More significantly, at a practical level, during early morning or late afternoon a vertical reference plane would avoid the situation where the sunlight is at a shallow angle to the reference plane, resulting in reference spectra being sensitively affected by minute deviation from the horizontal by the reference plane.

3 Test setup

3.1 Test site and studied trees

One common urban tree species, *Tilia cordata* (or small-leaved lime) was chosen to measure the radiative energy exchange of the trees during August and September, 2018. The test programme included a total of 10 *Tilia cordata* (numbered as '*Tilia* 1–10') growing in a plaza surrounded by four-storey modern Halls of Residences on the campus of the University of Reading, Berkshire, UK, as shown in Figure 6. The height of the *Tilia* trees was between 5.4-6.0 m with a crown height of 1.6–2.0 m and crown diameter of 3.0–3.6 m. *Tilia* 1 was tested more often than the other *Tilia* trees given its convenient location in the test site (see Figure 6 (b)). *Tilia* 7, 8 ,9 formed a cluster. *Tilia* 7 tended to be the visually most healthy (greener, more foliage) tree and *Tilia* 10, the visually least healthy tree in the group.

(a) (b) (c) (d)

Figure 6. Test site and *Tilia* trees (a) 3-9, (b) 1 and a tripod holding a spectrometer, sampling fibre and laptop, (c) 1 in foreground, 2 to the right, (d) 7-9 (right to left)

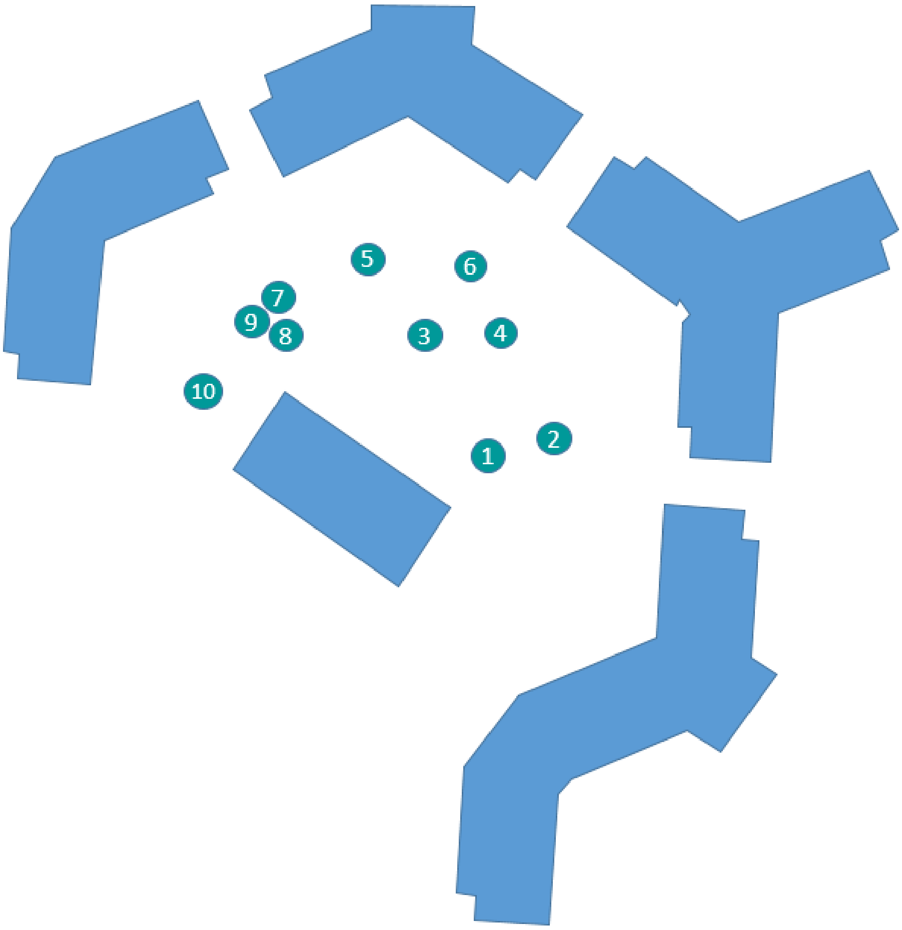

Figure 7. Schematic showing location of the 10 *Tilia cordata* trees

3.2 Test instruments

Measurements of reflection and transmission spectra of individual tree leaves and transflection of tree crowns were carried out in the visible (VIS) and near infrared (NIR) ranges, using a combination of VIS and NIR spectral analysers up to 2500 nm wavelength.

A Spectral Evolution spectrometer (model SM2500, made in USA) with spectral resolution of 3.5–22 nm in the full range of UV (ultraviolet), VIS, NIR (wavelength range: 350–2500 nm and wavelength reproducibility of 0.1 nm at an accuracy of 0.5 bandwidth) was used mainly in the laboratory to measure leaf level reflection and transmission of solar radiation within the range of 350-2500 nm. This was the spectrometer with the broadest spectral range. It was also the most bulky one and not suitable for mounting on a tripod for field canopy measurements.

A StellarNET Black-Comet concave grating miniature spectrometer (model CXR, made in USA) with a wavelength range of 350-900 nm and a spectra resolution of 0.5 nm was used for field canopy tests. This covers the full VIS spectrum of 400-700 nm. It also covers the important spectrum transition from VIS to NIR around 700 nm where the leaf and crown transmission and reflection jump sharply as shown in all measured spectra presented in the following. The spectra also show the peak of reflection or transmission in the IR region, which occur usually immediately following the VIS-IR transition. As can be seen in the reflectance spectra obtained using the Spectral Evolution SM2500 (see Figure 9 in section 4.2) or other published tree leaf spectra to 2500 nm [31–34], the reflectance and transmittance drop monotonically and predictably to levels close to 0 around 2500 nm if two water absorption troughs around 1400 nm and 1900 nm are excluded. Given this largely predictable pattern beyond 900 nm, much information about the NIR behaviour of trees can be obtained by using the miniature spectrometer, which is much lighter and smaller, for field work. It is also much cheaper and can be more quickly replaced as required.

A third spectrometer, a StellarNET Black-Comet-SR concave grating miniature spectrometer (model CXR-SR), has a spectroradiometer mode which allows the irradiance of the radiative energy received by the optical fibre fitted with a cosine receptor of 180° field of view to be displayed for every 0.5 nm wavelength intervals in the 400-1100 nm range (350-1030 nm with acceptable signal-to-noise ratio). It was used for solar irradiance spectra measurements as it was specifically calibrated for such tests.

3.3 Test procedures

A tripod with a full height of 4 m was used to hold and position the optical fibres of spectrometers in the field tests. An optical fibre was mounted onto the top of the tripod at one end and connected to a StellarNET Black Comet miniature spectrometer at the other. The portable spectrometer had a spectral range of 350-900 nm and was powered through an USB cable connected to the data acquisition laptop. The same USB cable also served as the data transmission between the spectrometer and the computer. The battery fully charged usually lasted for about five hours powering both the laptop and the spectrometer. Viewing angle of the optical sensor can be adjusted in all directions. The optical fibre was usually used without any cosine receptor and had a field of view of 25°.

Different scenarios were devised to identify important influence factors on tree’s radiative performances. To begin with, reflected and transmitted radiative energy from individual leaves was measured to quantitatively ascertain the predominant radiative energy of trees in the IR region. Then the reflectance spectra of individual leaves from different lime trees were measured to provide a contrast with the transflectance spectra at the tree crown levels. Measurements of various viewing angles of the optical sensor (fibre spectrometer) and different directions around the crown, representing different azimuth angles of the optical sensor, were performed on a single tree (*Tilia* 1) to distinguish the differences. The transflectance spectra among all 10 lime trees were also explored. To better understand trees' radiative performance at the crown levels, on-site measurements of transmission and reflection spectra of leaves with different fibre viewing angles and different leaf orientations were implemented to supplement the interpretation. The reference plane for the crown transflectance spectra measurements was chosen in a vertical plane towards the sunlight direction. Some other testing details are described alongside the results in the following section.

As to the test conditions, all the tests were performed under cloudless blue sky conditions. This is mainly because a sky with even patchy or thin clouds could result in significantly different solar radiation conditions within a few seconds. Clouds composed of water droplets will dramatically affect the IR solar radiation intensity reaching the trees due to water's characteristic strong solar absorption at specific IR wavelengths. It is hard to obtain the transflectance under such changeable solar radiation conditions, as the transflected radiations of a specified patch and those of the corresponding reference plane would probably not be obtained under the same solar radiation conditions even when they are measured within several minutes. Furthermore, prior planning is needed and a set of tests is completed in quick succession, typically within a few minutes, so that the sunlight conditions remain virtually unchanged, making the comparisons among the set of test results feasible. For this study, weather data were recorded at the University of Reading Meteorology Observatory 100 m away from the test site.

4 Results and discussion

4.1. Reflected and transmitted radiative energy spectra of leaves

An example for an irradiance spectrum of the light reflected from a leaf on *Tilia* 7 (see Figure 6 (d)) is given in Figure 8. The miniature spectrometer with a spectroradiometer mode was used to measure the irradiance. The measurement was made during a period with clear cloudless sky between 1–2 pm BST on 27th September 2018 (Outdoor dry/wet bulb temperatures 20.6–21.1 °C / 13.8–13.9 °C; relative humidity 42–44%; horizontal global solar irradiance 503.2–580.7 W/m^2; horizontal diffuse radiation 52.7–54.4 W/m^2; wind speed 2.8–2.9 m/s). The leaf was fully illuminated by sunlight and reflected light was sampled in a direction vertical to the leaf surface. Although the spectrum was not extended to 2500 nm as in spectra obtained using the Spectral Evolution SM2500 Spectrometer, it was clear from Figure 8 that the reflected energy was dominated by the IR radiation, which accounted for 74.0% of the whole reflected energy measured, assuming 700 nm as the demarcation line of VIS and IR regions. Figure 8 also provides an example of an irradiance spectrum of light transmitted through a leaf on *Tilia* 1 (see Figure 6 (b) or (c)). Likewise, the transmitted radiative energy was dominated by the IR radiation with a high percentage of 70.1%. It can be seen that proportionally, the VIS part of the irradiance spectrum for *Tilia* 1 is larger than that for *Tilia* 7. This larger VIS irradiance was also observed in the reflection spectrum for *Tilia* 1 and was in line with the visual observation that *Tilia* 1 was more stressed than *Tilia* 7 (greater yellowing of leaves).

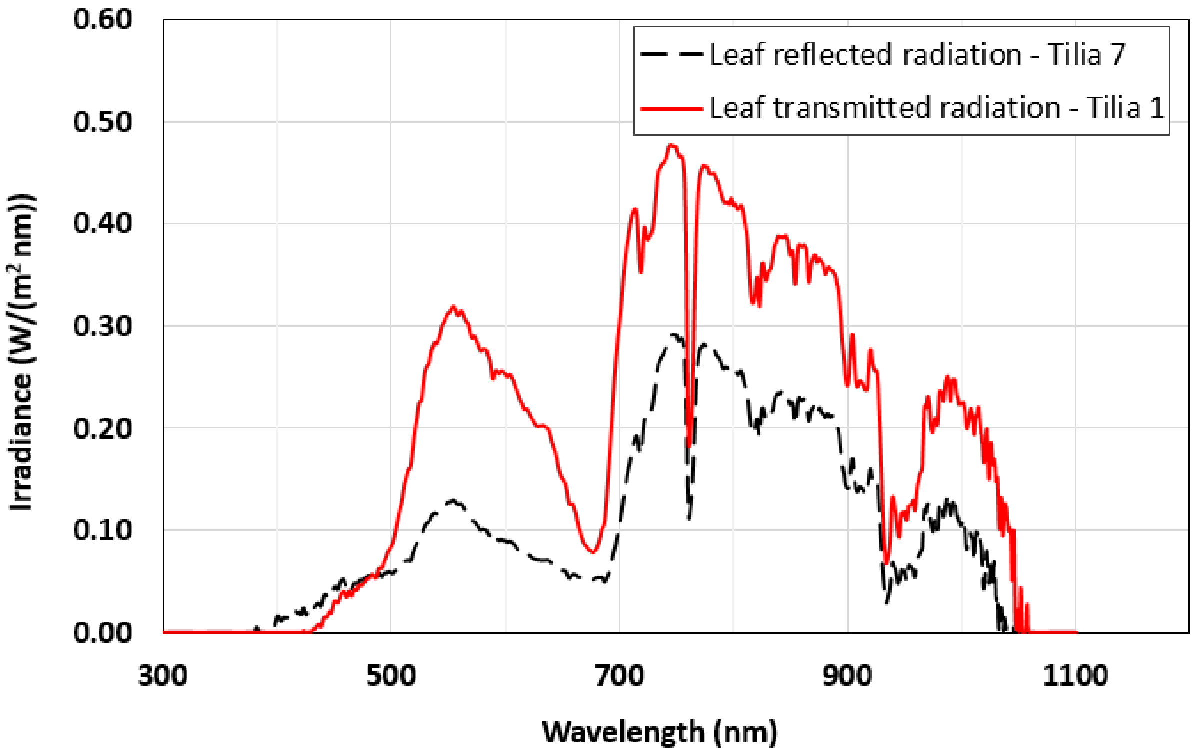

Figure 8. Samples of the reflected irradiance spectrum from a leaf on *Tilia* 7 and the transmitted irradiance spectrum from a leaf on *Tilia* 1

4.2. Reflectance spectra of individual leaves in the laboratory

The individual leaves from all 10 *Tilia* trees were collected then immediately scanned on 11th September 2018 to generate the reflectance spectra of the leaves in the laboratory using the Spectral Evolution SM2500 spectrometer. The spectrometer was deployed together with a leaf clamp, which was purposely built and supplied by the spectrometer manufacturer for measurement of reflectance spectra of leaves. Measurements using the clamp resulted in spectra data which were very repeatable, i.e. multiple scans of leaves in the clamp produced nearly identical spectra.

The leaf reflectance spectra of *Tilia* 1, *Tilia* 7 and *Tilia* 10 (see Figures 6 and 7 for the location and images of the trees) have been given in Figure 9. *Tilia* 7 tended to be the visually most healthy (greener, more foliage) tree and *Tilia* 10, the visually least healthy tree in the group. As seen in Figure 9, the leaf level spectra were broadly similar, despite significantly different (stress) conditions of the trees /leaves. The spectra differences between individual leaves are less than 5% in the IR region. Their similarity at the leaf level is in contrast to the significantly greater differences among crown transflectance spectra of the corresponding trees discussed in the following sections.

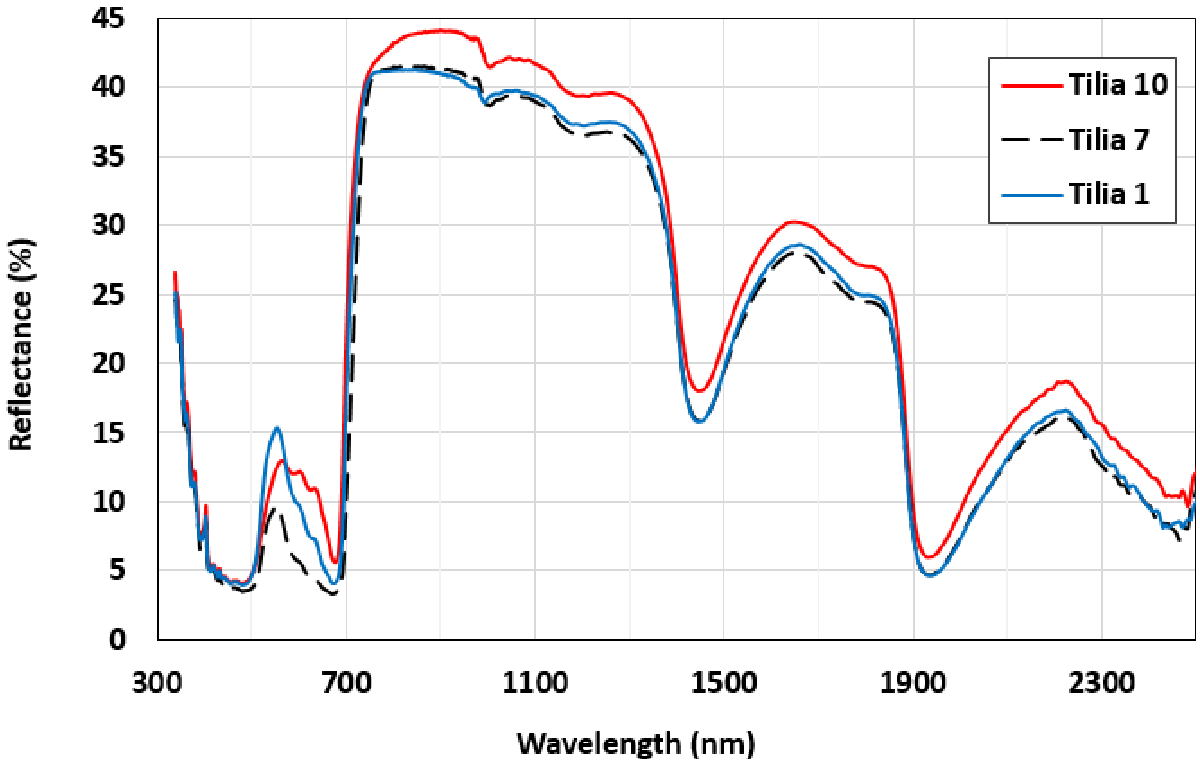

Figure 9. Leaf reflectance spectra of *Tilia* 10, *Tilia* 7 and *Tilia* 1 in question

Also worth noting is the broader VIS reflectance spectrum distribution of the leaf for *Tilia* 10 which was more affected by the summer drought and showing greater yellow/brown colouring in the leaves. This is a repeated feature of drought stress leaves that are yellower/browner.

4.3. Transflectance spectra of single tree crown – effects of viewing angles

The transflectance spectra presented in Figure 10 were measured between 9:45-10:45 am on 1st September 2018 in a clear sky. The transflectance spectra at the viewing angles 0°, 30°, 45° and 60° of the optical fibre were measured - Fibre tip at the top of the tripod setup pointed initially horizontally towards the crown at a distance of about 2.5 m from the tree trunk centre. The fibre tip was then tilted to form an angle of 30° to the horizontal plane looking downwards. This angle was then increased progressively to 60°. The fibre was set in a plane vertical to the ground and parallel to the solar azimuth direction.

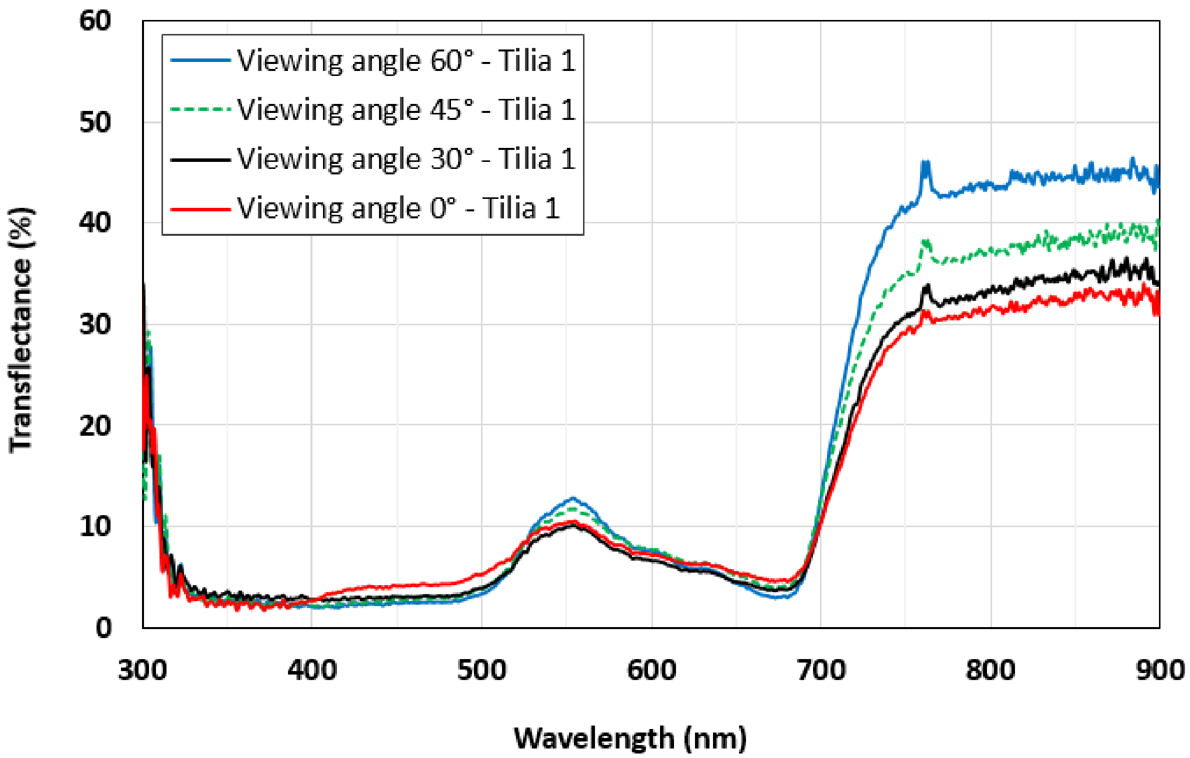

Figure 10. *Tilia* 1 transflectance measurement – effect of viewing angles of the optical fibre in a vertical plane

Figure 10 shows that the transflectance measured on *Tilia* 1 increases with the fibre viewing angle from 0° (horizontal) through to 60° (looking downwards). This monotonic increase with measurement angles is not always so in all tests (due to local foliage characters /non-uniformity of the crown structure in terms of leaf density, number and angular distributions, etc). However, among the tests carried out, the highest IR transflectance were generally found at an angle deviating from the horizontal plane rather than in the horizontal directions.

Figure 11 shows of the transflectance spectra measured from four cardinal directions around the tree crown. All spectra presented were obtained with the horizontal viewing angle (0°) of the optical fibre. The tests were performed in the morning during 9:45–10:45 am BST. Crown transflectance measured horizontally in the sunlight direction (Solar azimuth - southeast) was highest, that measured horizontally in the opposite direction (solar azimuth+200° clockwise) was lowest, while the spectra measured in the two directions perpendicular to Southeast–Northwest, i.e. solar azimuth+90° clockwise and solar azimuth+270° clockwise, fell in between. This ranking of transflectance levels measured in four directions around a tree is frequently observed in our tests and referred to as a ‘Classic Distribution’. Note that two directions of Northwest +/- 20° were used rather than Northwest, ensuring that the optical fibre tip would not include the sun within its field of view.

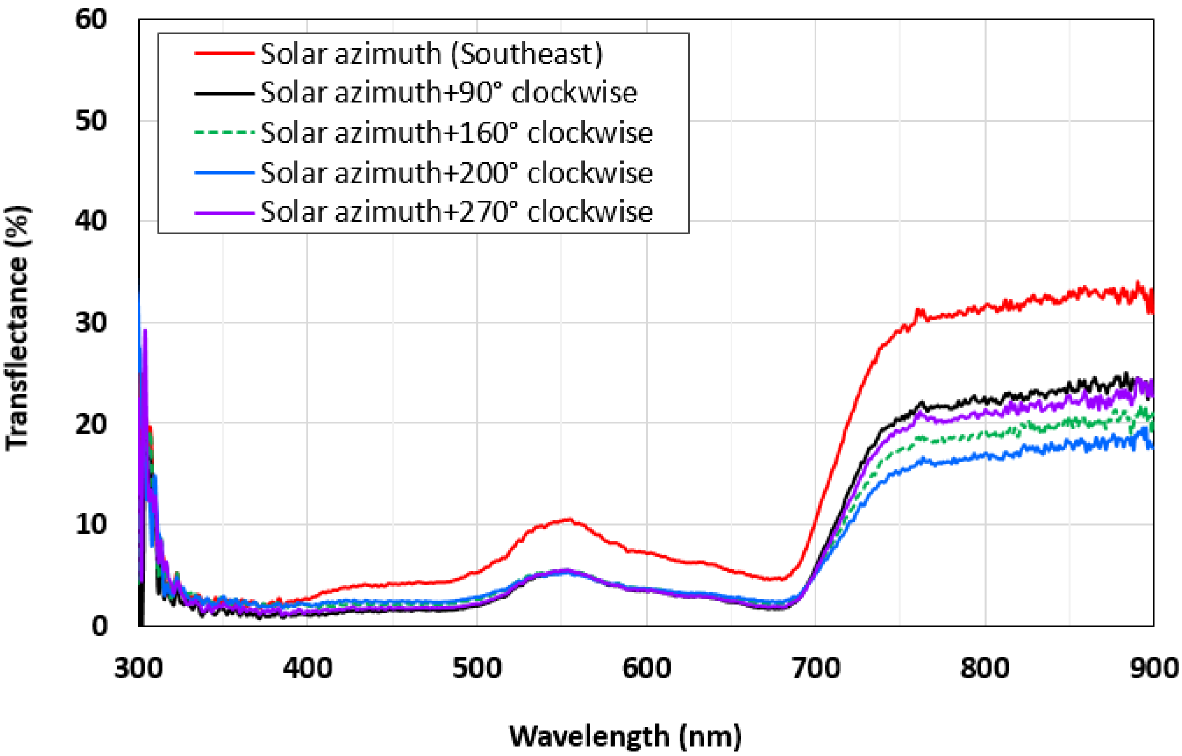

Figure 11. *Tilia* 1 transflectance measurement – spectra measured in four cardinal directions around the tree during 9:45–10:45 am BST

In contrast to the transflectance tests of four cardinal direction distributions in the morning, the results obtained at 2 pm in the afternoon were more spread out vertically, with the transflectance ranging from 20% to 50% as displayed in Figure 12. The significant differences between Figures 11 and 12 indicate that tree canopy transflection distribution is not only a property of the tree crown but also varies with solar time. Moreover, the distributions in Figure 12 also reveal a relatively less common situation where the highest transflection levels were not found in the sunlight direction (Southwest) but at a direction with 90° clockwise + sunlight direction (e.g. the highest transflection appeared in the Northwest when the sunlight was in the Southwest direction). Visual observation showed that the FoV of the spectrometer positioned at 90° + sunlight direction included some high density and bright (suitably aligned with sun direction) leaf clusters. Such local characters or non-uniformity of the tree crown is one of the key features of the crown architecture which was found to affect significantly the tree crown / solar IR interactions. Our initial tests on other species, e.g. oak, showed that the choice of tree species also had a substantial effect on the four-direction transflection distributions, apparently due to crown structure differences as well.

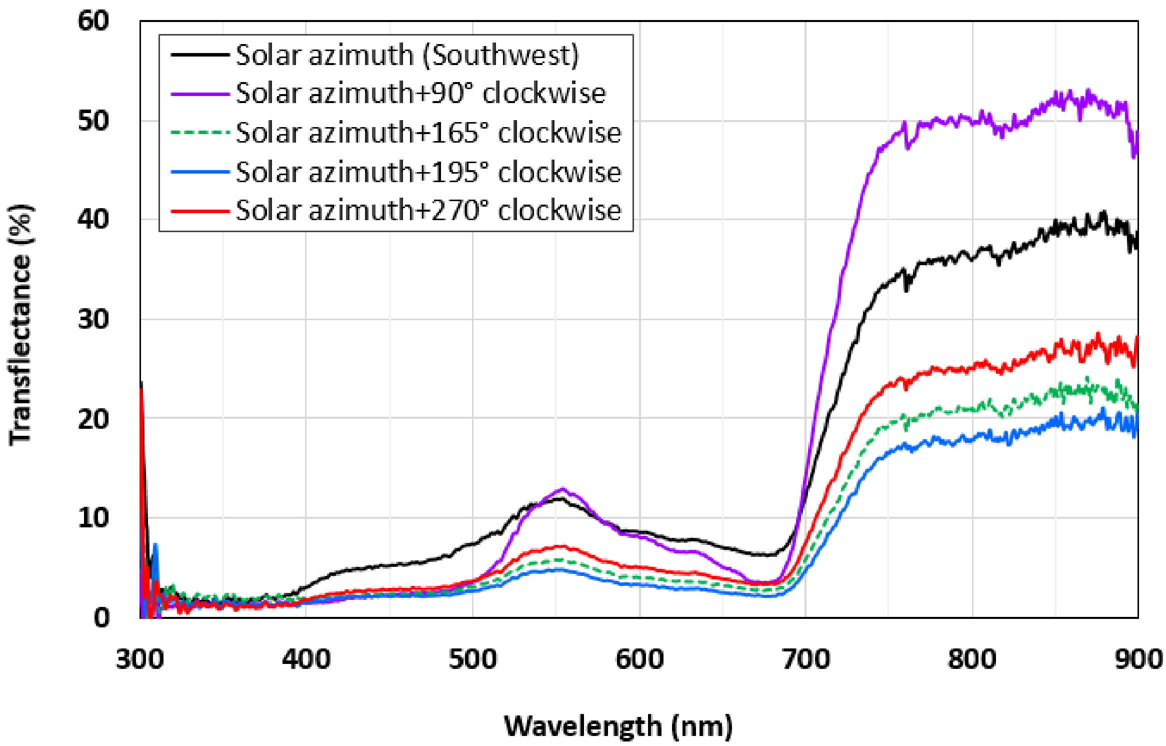

Figure 12. *Tilia* 1 transflectance measurement – spectra measured in four directions around the tree at 2 pm BST

The variations among the transflectance spectra measured in the four cardinal directions reveal that locational relationship of buildings and people to trees could sensitively affect the levels of solar IR radiation they receive. Furthermore, the significant changes of transflectance distributions with time show that buildings and people around a tree would not only receive different levels of solar IR radiation at different time, but the relative intensity of the solar IR radiation they receive will also change. As will be discussed further in the following, a significant factor for the change with time is the change of solar angle. Also important are changes of tree leaf angle and density in response to environment stress, although their effects will take longer to manifest and will also last over a relatively longer time-scale.

4.4. Variation of IR radiative performance among trees in a single species

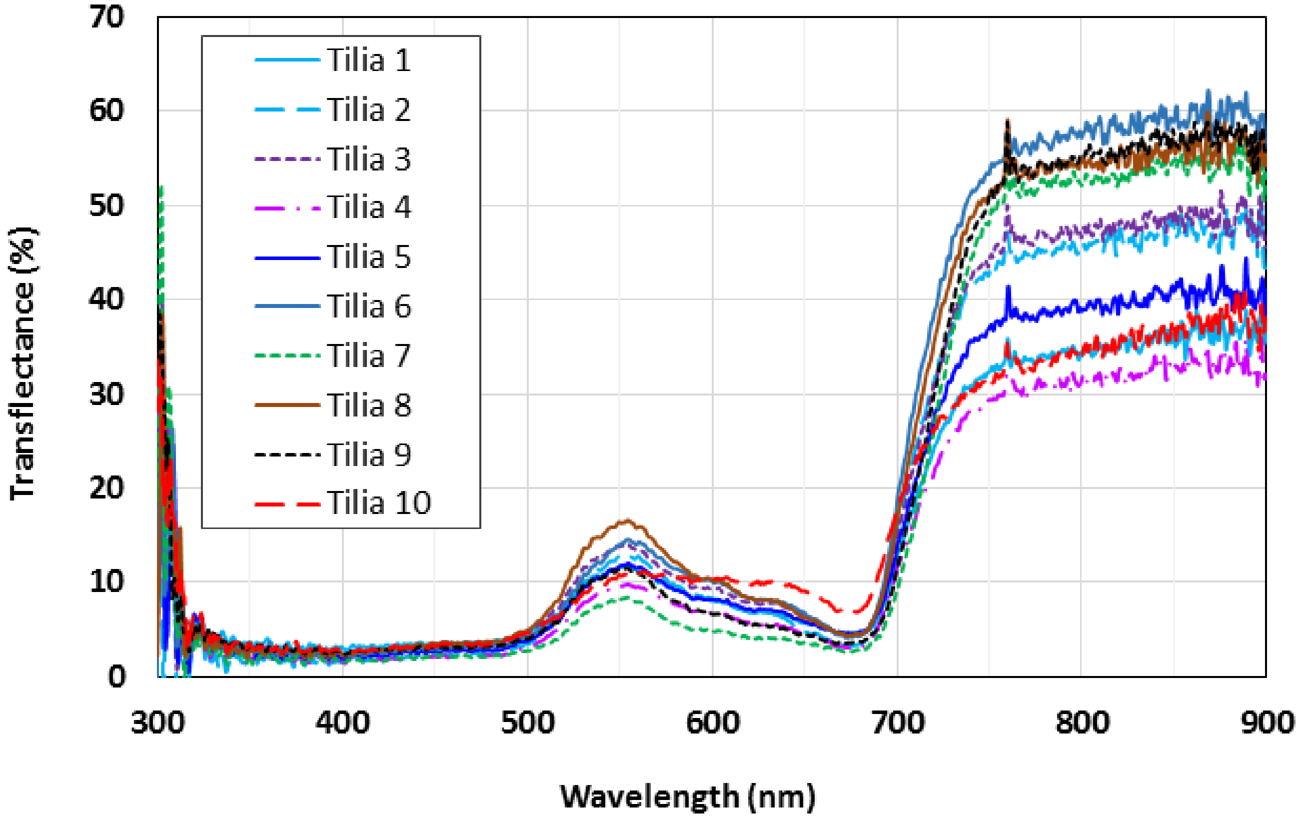

Figure 13. Transflectance spectra of all 10 *Tilia* trees

Figure 13 displays transflectance spectra of all 10 *Tilia* trees included in the study. These were measured during the period of 10:15–11:15 am BST on 6th September 2018 with a clear blue sky. For each of the 10 trees, the spectra were measured with the sampling optical fibre pointing in the sunlight direction horizontally and 30º downwards in a vertical plane.

Tilia 6, 7, 8, 9 exhibited the highest IR transflectance and the latter three formed a cluster. They generally had denser foliage among the tested trees. The clustered trees sheltered and shaded each other so that they were less thermally stressed. *Tilia* 7 was the most sheltered and had the lowest VIS peak in the cluster, while *Tilia* 8 being the least sheltered showed the highest VIS peak among the cluster of 3 trees. These were in line with the visual observation that *Tilia* 7 was greener (greater/healthier chlorophyll content in foliage) and *Tilia* 8 was slightly more affected by the hot dry summer with more yellowish patches.

Tilia 1, 4, 5, 10 exhibited the lowest IR transflectance spectra among the 10 tested trees. *Tilia* 10 was the most seriously affected by the summer drought and heat stress and was visibly damaged. *Tilia* 1, 4, 5 were visibly greener and healthier but they shared with *Tilia* 10 a common feature, i.e., relatively but visibly lower foliage density. *Tilia* 10 had grown larger than *Tilia* 1, 4, 5 prior to the drought year of 2018. The lower crown leaf density of *Tilia* 10 probably resulted from leaf shedding during the drought. *Tilia* 10 also showed broader and higher VIS peak which was in line with the more brownish appearance of its drought stressed leaves.

The above results and discussions, together with the individual leaf spectra scan carried out in the laboratory using leaves from these 10 trees (Figure 9), indicate that the substantial variations among transflectance spectra of tree crowns are much more affected by the structure of the crown (e.g. leaf number, density, etc) than by the character of the leaves (yellower, greener, more or less stress by drought etc).

The same contrasting results also highlighted the fact that despite similarity among reflectance and transmittance spectra at leaf levels, crown level spectra of the trees tested exhibit significant differences, thus confirming the importance of carrying out crown level investigations.

4.5. On-site measurement of leaf transmission and reflection spectra - effect of viewing angles

Figure 14 shows spectra of light transmission through a single leaf on *Tilia* 1. It was close to the bottom of the canopy thus could be easily reached by the spectrometer optical fibre. The leaf was fully sunlit and visually in average condition with slight signs of drought stress (yellowing). The leaf orientation was largely horizontal with a slight slope towards Southeast. The tests were carried out during the period of 10:15–11:15 am BST on 6th September 2018 with a clear blue sky. The transmission spectra were measured with the sampling optical fibre pointing towards the centre of the back of the leaf, forming various viewing angles to the leaf surface (30°–150°) within two measured planes that were perpendicular to each other (W &N) and were both perpendicular to the leaf surface.

A single reference plane was adopted to allow the direct comparison of transmitted and reflected solar radiation measured at various viewing angles. This single reference concept is adopted here for leaves, also because the resulting spectra will later be used to offer insightful explanations of crown level spectra results. The reference plane azimuth was the same as that of the sun and the plane was perpendicular to the ground. This is the reason that some of the spectra contain values greater than 70%.

Figure 14 shows that the spectra are relatively close to each other despite the vast variation of the transmission directions.

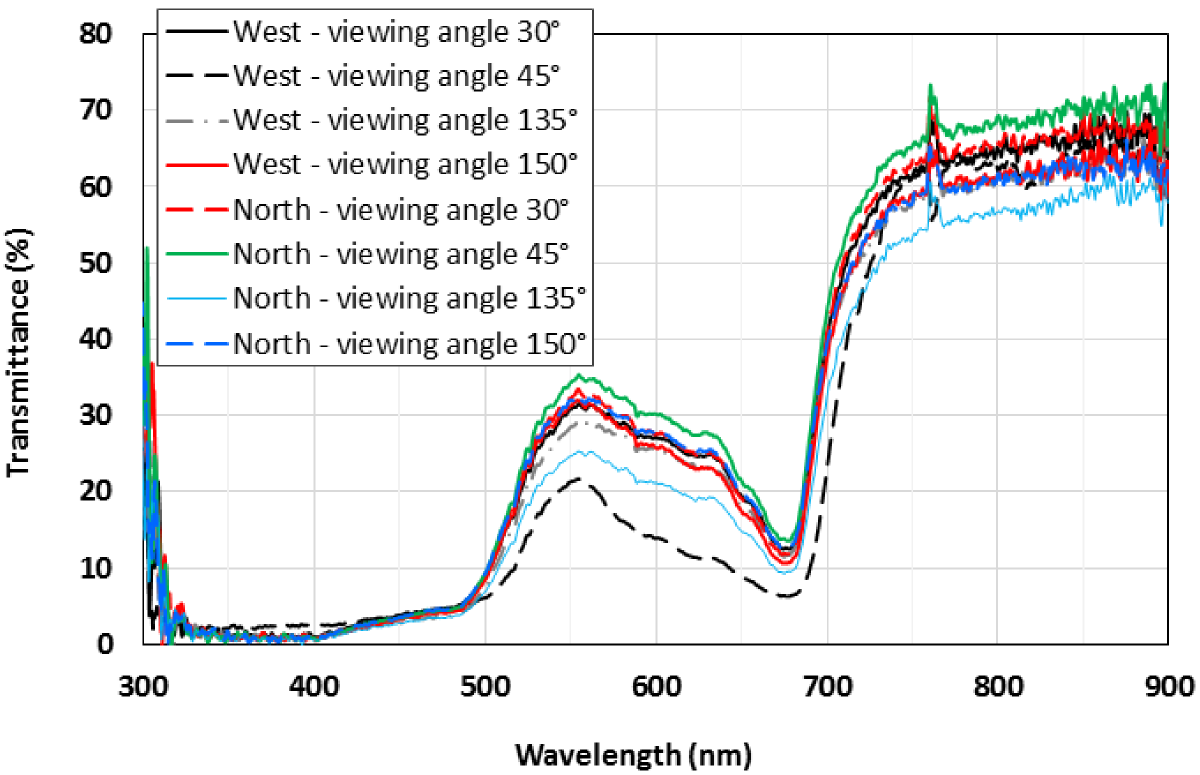

Figure 14. Leaf transmission spectra measured from various viewing angles

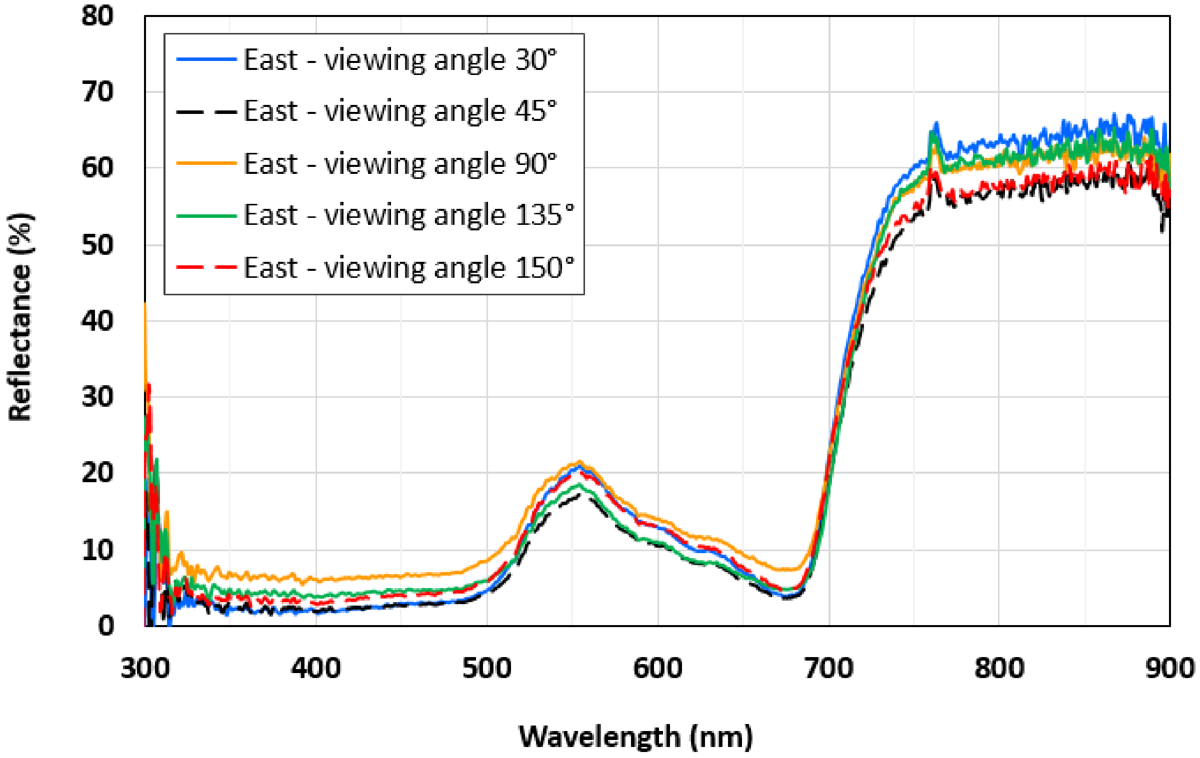

Figure 15. Leaf reflection spectra measured from various viewing angles

Figure 15 similarly shows spectra of light reflection from a single leaf in *Tilia* 9. The leaf location orientation and conditions were very similar to those for the transmission measurements shown in Figure 14. Also similar were the test time and sampling optical fibre arrangement except that in this case, the fibre pointed towards the centre of the top of the leaf. The reflection spectra were obtained in one of the planes vertical to the leaf. As seen in Figure 15, all spectra were again close to each other despite the large variation of the reflection directions.

The spectra in Figures 14 and 15 show a modest effect of the viewing angle which resulted in differences of about 10% among the spectra in the IR region. They are in contrast to the diverging spectra seen Figures 16 and 17 presented in the next section, where the dramatic effect of the leaf angle on reflected and transmitted IR and VIS radiation was revealed.

4.6. On-site measurement of transmission and reflection spectra of leaves - effect of leaf orientations

Figure 16 shows leaf-level reflectance measurement on randomly selected leaves on *Tilia* 1. All the selected leaves were directly and fully illuminated by sunlight, i.e. none of them were shadowed in any way. All were tested *in situ* rather than picked off from the tree then tested in the laboratory. The normal of the leaf surface deviated from the sunlight direction to various extents, and the reflections were measured vertical to the individual leaves. The reference plane was chosen as vertical to the ground with the same azimuth as that of the sun.

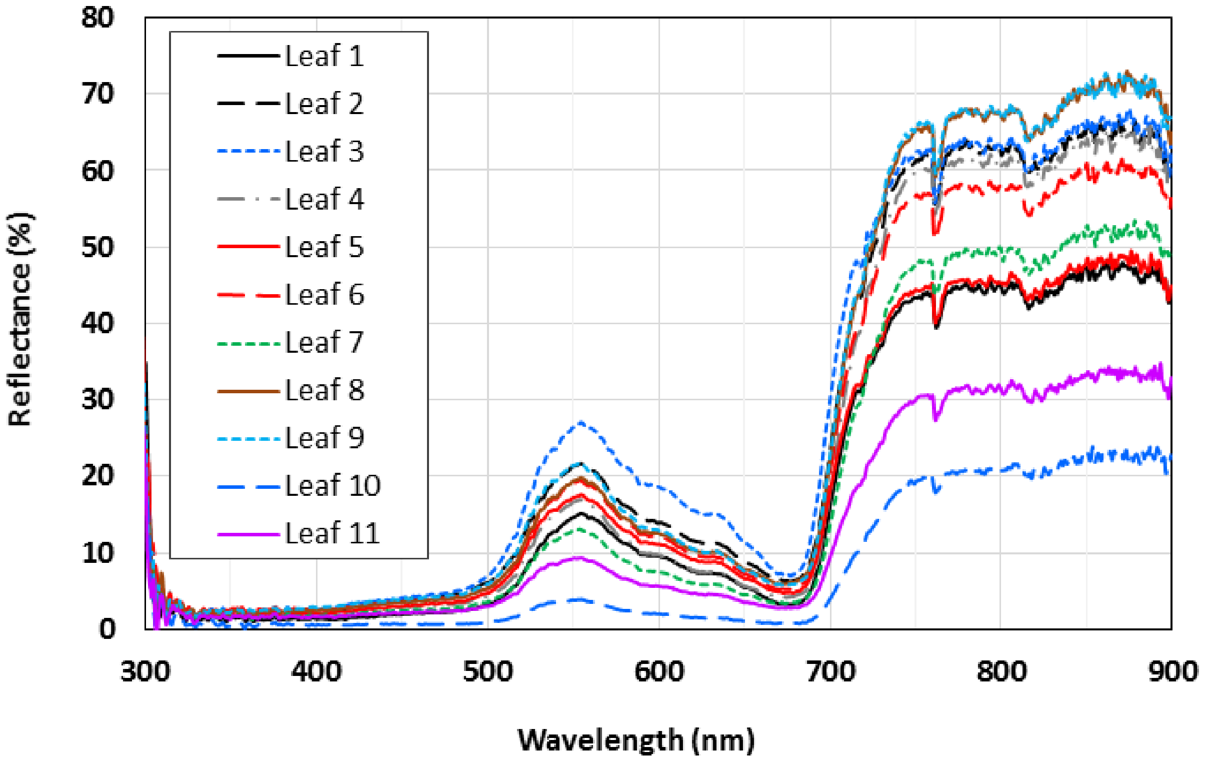

Figure 16. Leaf-level reflectance measurement on randomly selected leaves which were fully exposed to sunlight

Figure 16 shows substantially different reflectance levels of the leaves, from around 20% to over 60% in the IR regions. The maximum IR reflectance difference was over 40%. This dramatic difference contrasts with the relatively much smaller levels of reflectance spectra variation associated with the viewing angles relative to the leaf surface normal in Figure 15. The principal reason for the dramatic differences seen in Figure 16, is apparently the sun's angle to the leaf surface, with sunlight more parallel to the leaf surface creating a relatively less bright leaf surface.

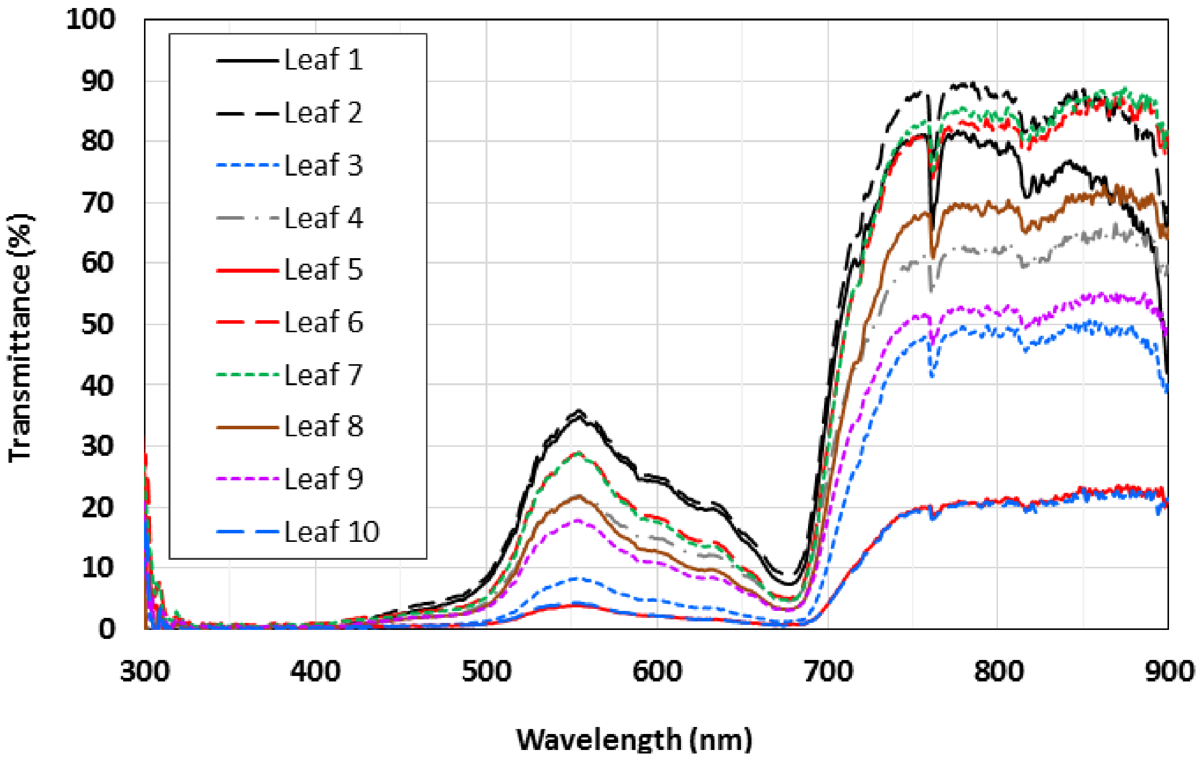

Figure 17. Leaf-level transmittance measurement on randomly selected leaves which were fully exposed to sunlight

Figure 17 shows leaf-level transmittance measurement on randomly selected leaves on *Tilia* 1. All the selected leaves were directly and fully illuminated by sunlight. Dramatic variations similar to those of on-site leaf-level reflectance were observed, with the maximum transmittance difference over 60% in the IR region. This is particularly obvious in contrast to the transmitance spectra which were measured at various viewing angles and much closer to one another, as seen in Figure 14. The main reason for the substantial differences seen in Figure 17, as in the case of Figure 16, is apparently the sun's angle to the leaf surface, with sunlight more parallel to the leaf surface resulting in less solar radiation transmitted through the leaf. Thus solar position/angles strongly affects both transmission and reflection of solar radiation through the leaves. As the solar angle changes through the day, insights presented here reinforce, and offer explanations to, the findings reported in Section 4.3 that the transflectance spectra measured around a tree crown changes significantly with solar time.

The results in Figures 16 and 17 imply that the overall transflectance levels at the crown level, which are a combination of transmission and reflection of individual leaves, are significantly affected by the leaf angle distributions within a crown, which may vary with both tree species and the environmental stress conditions including solar radiation, urban heat and soil water deficit [47]. Crown structure in terms of leaf number, density and angles are known to change with choice of tree species and with environmental conditions and stresses, including solar radiation, urban heat, and soil moisture depletion. It follows that the choice of species and the severity of environmental stress factors will affect crown level IR solar radiation performance more than performance at the leaf level. In this sense, the findings have significant implications for species selection and control of environmental stress factors in urban microclimates.

5 Conclusions

To study IR radiative performance of urban trees at a crown, rather than leaf, level, new concepts are necessary to underpin a new framework or methodology. Associated concepts, including *transflectance* (*transflection*), *contributing volume* and *single reference plane* for multiple *patches* of crown surfaces, were introduced and justified here. In the measurement of tree crown spectroscopy, it was proven that portable miniature spectrometers suitable for *in situ* tests are valuable in characterising crown level IR transflection performance despite their often narrower wavelength range. Based on the methodological framework established here, experimental tests of one type of common tree species in the UK and Europe, namely lime trees (*Tilia cordata*), have been implemented to characterise the IR radiative performance of the trees in different scenarios. The main findings are summarised as follows:

- The reflected and transmitted solar energy from tree leaves is dominated by IR radiation, which accounts for over 70% of the total reflected or transmitted solar radiation, respectively.
- At the leaf level, transmission and reflection spectra are similar (differences typically < 10% in IR regions) for different trees including those under significantly different urban stress conditions. In contrast, at the crown level, substantial variations in the transflectance performance were found between trees. The substantial variations among transflectance spectra of tree crowns are largely due to crown structural variations (leaf number, density and angles), rather than the solar interaction character of the leaves (leaf level transmittance or reflectance, yellower or greener appearance).
- Regarding the important factors affecting tree-solar radiation interactions, it is confirmed that the crown transflectance spectra are affected by viewing angles of the optical sensor, orientations of measured patches on the tree crown surfaces, local

foliage character or non-uniformity of the tree crown structure, as well as the solar time. For various viewing angles of the optical sensor, the highest IR transflectance is typically found at the viewing angles deviating from the horizontal. For the orientation of the measured patches, the transflectance difference between the maximum and the minimum values in the IR region is about 30% in four cardinal directions around the crown. Often, but not always (depending on local foliage characters including leaf density and angles within the FoV of the optical fibre), the highest values are found in the sunlight direction and lowest on the opposite side. Also importantly, the crown transflectance spectra change substantially with solar time in terms of both absolute and relative levels for the various viewing directions. This change with solar time is particularly pronounced for the four cardinal directions around a tree crown with a horizontal viewing angle.

- On-site measurements of transmission and reflection spectra of leaves showed modest effects of the viewing angle, which resulted in differences of about 10% among the spectra in the IR region. In contrast, the leaf angle variation created dramatic spectra differences, with the maximum spectra difference of over 40% (minimum around 20% and maximum over 60%) in the IR region. It is inferred that the crown transflectance would be significantly affected by the leaf angle distributions within the crown.

These findings have significant implications for species selection and for the control of environmental stress factors in urban microclimates. We are planning to set up a database (website) with the infrared radiative performance information of multiple tree species commonly planted in the UK with different canopy structures as a reference of species selection for urban planners. Additionally, the new conceptual framework and methodology presented here will lay a foundation for more comprehensively investigating radiative interactions among trees, buildings and people.

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Declaration of interest: none.

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Figure Captions:

Figure 1. Tree crown-level interactions with solar radiation, illustrating the concepts of transflectance (transflection) for a patch being measured; FOV=Field of View

Figure 2. An illustration of a tree model (model 1) showing azimuth and altitude angles and reference plane location for a specific patch of crown surface

Figure 3. An illustration of solar azimuth and altitude angles in relation to a tree being studied

Figure 4. An illustration of a patch of crown surface showing azimuth and altitude angles for the spectrometer optical fibre

Figure 5. An illustration of tree model 2 and contributing volume

Figure 6. Test site and *Tilia* trees (a) 3-9, (b) 1 and a tripod holding a spectrometer, sampling fibre and laptop, (c) 1 in foreground, 2 to the right, (d) 7-9 (right to left)

Figure 7. Schematic showing location of the 10 *Tilia cordata* trees

Figure 8. Samples of the reflected irradiance spectrum from a leaf on *Tilia* 7 and the transmitted irradiance spectrum from a leaf on *Tilia* 1

Figure 9. Leaf reflectance spectra of *Tilia* 10, *Tilia* 7 and *Tilia* 1 in question

Figure 10. *Tilia* 1 transflectance measurement – effect of viewing angles of the optical fibre in a vertical plane

Figure 11. *Tilia* 1 transflectance measurement – spectra measured in four cardinal directions around the tree during 9:45–10:45 am BST

Figure 12. *Tilia* 1 transflectance measurement – spectra measured in four directions around the tree at 2 pm BST

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Figure 14. Leaf transmission spectra measured from various viewing angles

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