SPECTRAL SHADE RATIOS ON HORIZONTAL AND SUN NORMAL SURFACES FOR SINGLE TREES AND RELATIVELY CLOUD FREE SKY

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Abstract

The spectral shade ratios defined as the ratios of the spectral irradiances on horizontal and sun normal planes in the tree shade to those on a horizontal plane in sunlight were calculated. These planes were in the shade of an isolated medium canopy density tree and a sparse canopy density tree at the tree shade sites of the centre, edge and trunk. The sun normal plane was employed as there are some activities that have exposures to parts of the body that are orientated in a sun normal plane. The horizontal plane shade ratios for the medium density canopy dropped by 47% - 56% from the ratios in the range 301 to 310 nm to the ratios in the range 391 to 400 nm. In absolute terms, the largest change in the shade ratio of 0.28 was for the centre and edge sites compared to 0.07 for the trunk. Similarly, for the sun normal plane, the ratio dropped by 40% - 49% with an absolute reduction of 0.19 for the edge and 0.04 for the trunk. For the sparse density canopy, the decrease in the shade ratios over the same wavelength range were a drop by 37% - 42% on a horizontal plane, or in absolute terms, a reduction by 0.22 for the edge and 0.13 for the trunk. Similarly, the decrease was 34 - 39% on the sun normal plane, or in absolute terms, a reduction by 0.19 for the edge and 0.12 for the trunk.

Keywords: UV; tree shade; spectrum; erythema.

1. INTRODUCTION

Broadband UVA (320-400 nm) and UVB (280-320 nm) irradiances have been measured in tree shade (for example, [1-6]). The primary factors influencing the UV irradiances in tree shade are cloud cover, tree canopy density, solar zenith angle and the amount of sky view [5-7]. Cloud increases the ratio of the UV in tree shade compared to the UV in full sun [2] due to an increase in the diffuse component of the solar UV. This diffuse component is a major component of the solar ultraviolet radiation in tree shade [8].

This previous research has considered the broadband UVA and UVB irradiances in the tree shade. Additionally, the human anatomical UV exposure distribution of solar erythemal UV radiation in tree shade has been quantified with polysulphone dosimeters for Australian trees [9,10]. A model has been developed for prediction of the UVB exposures to people in open tree canopies relative to the above canopy irradiances [11]. However, spectral measurements in the UV waveband in the shade of trees are not common [12] and more are required.

Spectral and broadband UV measurements in full sun have been reported for vertical surfaces [13] and surfaces on planes that are normal to the sun direction (sun normal) [14,15], along with research on the angular distribution of UV in full sun [16-18]. To the authors' knowledge, the only other set of spectral measurements in tree shade was in the approximate centre of the tree canopy shadow of five different trees on a horizontal plane [12].

Spectral information for sun normal planes in tree shade is just as important as measurements on a horizontal plane. Although it is not possible to model the complex topography of the human body, there are some activities, for example watching sports that may have exposures to parts of the body that are orientated in a sun normal plane rather than a horizontal plane [14]. Consequently, spectral measurements on a sun normal plane provide a closer approximation of the biologically damaging exposures for parts of the human body that are at angles between the vertical and the horizontal and are orientated towards the sun. To the authors’ knowledge no research has measured the UV spectrum on a sun normal plane in tree shade.

This paper presents the variation in the shade ratio for both a horizontal plane and a sun normal plane. The variation in shade ratio is investigated for different wavelengths and locations in the tree canopy shade of two isolated trees and for relatively cloud free skies.

2. MATERIALS AND METHODS

2.1 UV Spectrum

A UV spectroradiometer was employed for the measurement of the UV spectrum in 1 nm increments. The spectroradiometer and the calibration are described in Parisi et al. [19]. Briefly, the instrument is based on a dual holographic grating (1200 lines/mm) monochromator (model DH10, Jobin Yvon Co., France) and a UV sensitive photomultiplier tube detector (model R212, Hamamatsu Co., Japan), temperature stabilised to $15.0 \pm 0.5\ ^{o}C$. The input optics of the spectroradiometer are provided by a 15 cm diameter integrating sphere (model OL IS 640, Optronics Laboratories, Orlando, USA) that can be manually rotated through 180^{o}. Prior to each set of field measurements, the spectroradiometer was both wavelength calibrated to the spectral lines in the UV waveband from a mercury discharge lamp and irradiance calibrated to a standard lamp.

Measurement of the UV spectrum, $S(\lambda)$ and weighting with the action spectrum for a certain process, $A(\lambda)$ allows the calculation of the biologically effective spectral UV irradiance, UVBE. Summing over the UV waveband as follows:

$$\int_{280}^{400} S(\lambda)A(\lambda)d\lambda \qquad (1)$$

provides the biologically effective UV for a certain process. In this research, the action spectrum for erythema [20] was employed.

2.2 UV Spectral Shade Ratio

The UV spectral shade ratio, $T(\lambda)$ at each wavelength, λ, is defined as:

$$T(\lambda) = \frac{S_S(\lambda)}{S(\lambda)} \qquad (2)$$

where $S(\lambda)$ is the UV spectrum in full sunlight on a horizontal plane and $S_S(\lambda)$ is the UV spectrum in the tree shade. Ideally, the two sets of UV spectra need to be measured simultaneously as has been done by researchers in the measurement of the UV albedo of ground cover [21]. This requires the usage of two spectroradiometers and was not logistically feasible in this research with only one spectroradiometer available. Consequently, the UV spectrum in tree shade was measured and the spectroradiometer shifted into the sunlight and at least 5 m clear of any tree shade, and the respective UV spectrum in sunlight in 1 nm increments was measured as previously employed [12]. The two sets of measurements were taken within ten minutes of each other to minimize any changes in the solar UV irradiances due to changes in solar zenith angle. Each scan from 280 to 400 nm took approximately 45 seconds.

For each scan, the electronic noise or dark signal was calculated by averaging the recorded output between 280 and 295 nm for that scan, as there were negligible solar irradiances in this range. This dark signal was subtracted from the respective $S_S(\lambda)$ and $S(\lambda)$ prior to the calculation of the spectral shade ratio.

2.3 Measurements

The spectral shade ratio was measured for a tree with a medium density canopy (*Cinnamomum camphora*) and a tree with a sparse density canopy (*Eucalyptus* sp.). These trees will be referred to as tree M and tree S respectively. The density of each tree canopy was estimated by measuring the reduction by the tree shade of the irradiances in the visible waveband at approximately ground level on a horizontal plane with a LUX meter (model EMTEK LX-102, supplier, Walsh's Co., Brisbane, Australia) as compared to that in full sun. The LUX in the shade were 15% and 24% of those in full sunlight for trees M and S respectively. The dimensions of the trees were: canopy widths of 4.2 m and 4.5 m respectively; tree heights of 6.4 m and 12.2 m respectively; average tree trunk diameters of 27 cm and 22 cm and heights to the first branches of 0.4 m and 1.6 m respectively. Both of the trees were isolated trees in the grounds of the University of Southern Queensland, Toowoomba (27.5 ^{o}S), Australia. The distance to the nearest tree was over 10 metres and the distance to the nearest single storey building was over 30 metres. The ground cover was short mown grass with an erythemal UV albedo as measured with a hand held detector of less than 5%.

The spectral UV measurements were made between 10:19 Australian Eastern Standard Time (EST) and 11:15 EST and between 8:35 EST and 12:30 EST on 15 and 22 August respectively for tree M. For tree S, the measurements were between 9:53 EST and 12:20 EST and between 11:30 EST and 14:36 EST on 15 August and 29 September respectively. The ranges of solar zenith angles were 40^o to 62^o for tree M and 25^o to 51^o for tree S. During the measurement periods, the sky was relatively cloud free with less than 25% of the sky covered in cloud.

The UV spectrum was measured on the side of the trunk furthest from the sun at: the centre of the tree shade; the edge of the tree shade; and in the shade of the trunk. The site at the edge of the shade was approximately 50 cm in from the visible edge of the shade/sun boundary as visually determined by the researcher. The site at the trunk was in the shade of the trunk at the point where the shade of the leaf canopy started. All spectral measurements were on the major axis of the tree shadow formed by the extension of a line between the sun and the tree trunk. The opening of the integrating sphere was 93 cm above ground level. For each of the tree shade measurement sites and the site in full sun, the UV spectrum was measured on a horizontal plane and in a sun normal plane. For the sun normal measurements in the sunlight, the spectroradiometer position was adjusted in azimuth and the integrating sphere adjusted in elevation angle until a tube, approximately 10 cm long and 1 cm diameter cast a shadow of zero length [12]. At the tree shade sites, this technique was not possible due to insufficient visible irradiances and the alignments were made by eye with an estimated uncertainty of $\pm 5^o$.

3. RESULTS

3.1 Horizontal and Sun Normal Plane Spectra

An example of the UV spectra and respective spectral erythemal UVBE for a horizontal plane and a sun normal plane; both in the shade of tree M are provided in Figure 1 for the centre, edge and trunk sites. The spectra presented were obtained on 22 August. The troughs that are at the same wavelengths in each spectrum are due to the Fraunhoher absorption lines and the peaks at random wavelengths are due to the sun flecks in the tree shade. The spectral irradiances on the sun normal plane are less than the spectral irradiances on the horizontal plane with the exception of the centre site between 360 and 370 nm. The likely reason for this exception is the wind generated movement of the leaves due to the wind, causing sun flecks to reach the sensor during the sun normal scan. Apart from this exception, the spectral irradiances on the sun normal plane are lower due to the reduced amount of sky view on the sun normal plane. The differences between the spectral irradiances on the sun normal and horizontal planes generally decrease with increasing UVA wavelengths. This is due to the reducing proportion of scattered UV at the longer wavelengths. Consequently, the reduced amount of sky view on the sun normal plane has less of an influence. In general, the spectral irradiances for both planes are less at the trunk site compared to the other two sites.

3.2 Horizontal Plane Shade Ratios

The spectral shade ratios for trees M and S on a horizontal plane are provided in Figure 2 and Figure 3 respectively for the three measurement sites of the trunk, centre and edge. For each scan in the shade and the corresponding scan in the sun, the calculated shade ratios at each nanometre have been averaged over each successive 10 nm range starting from the first range of 301 to 310 nm. For each site and 10 nm range, the shade ratios have been averaged over the scans at the different times. The averages are plotted at the mid point of the respective 10 nm range and the error bars represent the standard error of the scans at the different times. For both trees, the shade ratios have a general downward trend with increasing wavelength. The only exceptions to the downward trend were for the ranges 361 to 370 nm and 381 to 390 nm for the edge and centre respectively for tree S. This results from the intermittent sun flecks due to the gusty breeze, causing the higher shade ratio.

For tree M, the shade ratios are marginally less at the centre of the shade than the edge, however, the differences are less than the standard error in the mean of each of the shade ratios. Tree S provides no differences between the centre and edge sites due to the higher degree of sun flecks. The spectral shade ratios on a horizontal plane range from 0.52 to 0.24 for the edge site compared to the range of 0.15 to 0.08 for the trunk site for tree M. The trunk site for tree S has a higher shade ratio with a range of 0.35 to 0.22. This is due to the larger amount of sky view at this site for this tree due to the greater height above the ground of the tree S canopy and the sparser canopy.

3.3 Sun Normal Plane Shade Ratios

The spectral shade ratios on a sun normal plane relative to full sun on a horizontal plane are shown in Figure 4 and Figure 5 for trees M and S respectively. These spectral ratios decrease with an increase in wavelength. This is most likely due to the decreasing proportion of diffuse radiation with wavelength. For tree M, the shade ratios are lower for the respective sites of the sun normal plane compared to the horizontal plane. The ranges are 0.50-0.22, 0.52-0.24 and 0.15-0.08 (horizontal plane) compared to 0.28-0.15, 0.39-0.20 and 0.10-0.06 (sun normal plane) for the centre, edge and trunk respectively. The lower shade ratio for the sun normal plane at all three sites is due to the reduced sky view in this direction with the largest reduction for the centre site. For tree S, the ranges are 0.51-0.30, 0.52-0.30 and 0.35-0.22 (horizontal plane) compared to 0.48-0.33, 0.49-0.30 and 0.35-0.23 (sun normal plane) for the centre, edge and trunk respectively. The shade ratios are marginally lower for the centre and edge sites for the sun normal plane. The differences between the horizontal and sun normal plane shade ratios are not as large as for tree M due to sun flecks being a larger contributor to the UV in the shade of tree S.

The spectral ratios of the irradiances on a sun normal plane to a horizontal plane in full sunlight and at each of the three sites in the tree shade are shown in Figure 6. The results shown in sunlight are the averages of the ratios for solar zenith angles of 46^o and 50^o. In full sunlight, the spectral ratios of these irradiances are larger than 1 and the ratio increases with wavelength due to the decrease in scattered radiation. In comparison, the spectral ratios of these irradiances in the tree shade are less than one, with the lowest ratio for the trunk and the highest for the edge.

4. DISCUSSION

The spectral shade ratios on horizontal and sun normal planes have been measured for an isolated medium canopy density tree and an isolated sparse canopy density tree at the tree shade sites of the centre, edge and trunk. This was for relatively cloud free skies at a sub-tropical location. In Australia, much use is made of isolated trees like these by people undertaking a wide range of everyday outdoor activities. Consequently, there is a need for the quantitative data provided by this research.

The shade ratios decreased with increasing wavelength for the two trees and both orientations. This is due to the higher proportion of diffuse radiation at the shorter wavelength UV due to the greater degree of Rayleigh scattering that is inversely proportional to the fourth power of wavelength. The horizontal plane shade ratios for tree M dropped by

47% - 56% from the ratios in the range 301 to 310 nm to the ratios in the range 391 to 400 nm. In absolute terms, the largest change in the shade ratio of 0.28 was for the centre and edge sites, compared to 0.07 for the trunk. Similarly, for the sun normal plane, the ratio dropped by 40% - 49% with an absolute reduction of 0.19 for the edge and 0.04 for the trunk The lower shade ratios for the sun normal plane are due to the combination of the reduced amount of sky view for this plane due to the tree and the lower proportion of diffuse radiation for this plane compared to the horizontal plane [15]. Consequently, the change in the proportion of diffuse radiation with wavelength has less of an influence. For tree S, the decrease in the shade ratios over the same wavelength range were a drop by 37% - 42% on a horizontal plane, or in absolute terms, a reduction by 0.22 for the edge and 0.13 for the trunk. Similarly, the decrease was 34% - 39% on the sun normal plane, or in absolute terms, a reduction by 0.19 for the edge and 0.12 for the trunk. In all cases, the smallest decrease in absolute terms was at the trunk.

For tree M with the height of the canopy lower to the ground, the amount of protection provided by the tree shade for a horizontal plane is improved by a factor of 3 to 3.5 by sheltering at the trunk site. This is due to the combined effect of the non-existence of sun flecks in the solid shade of the trunk and the reduced amount of sky view. Although the amount of sky view is less at the centre of the shade compared to the edge, the shade ratios on a horizontal plane are not significantly different for both trees at the two sites. The explanation is that there is a reasonable amount of sun flecks at both sites. For a tree variety with a dense canopy, it is expected that the shade ratio will be lower at the centre [1]. Additionally, it is expected that the spectral shade ratios will change for different solar zenith angles as the proportion of diffuse radiation changes [8]. However, in this paper, the spectral shade ratios were considered as an average for solar zenith angles between 40^{o} and 62^{o} for tree M and 25^{o} to 51^{o} for tree S. Although, the results may vary quantitatively for other types of trees at different latitudes, the qualitative variation of the shade ratios with wavelength and for the different sites in the tree shade can be applied in other cases of sparse and medium canopy density trees for relatively cloud free skies.

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FIGURE CAPTIONS

Figure 1 – The UV spectra for a horizontal plane and a sun normal plane for tree M at (a) the edge, E and trunk, T sites, (b) the center, C site and the corresponding spectral erythemal irradiances for tree M at (c) the edge, E and trunk, T sites, (d) the center, C site.

Figure 2 – Spectral shade ratios for tree M on a horizontal plane for the centre, edge and trunk sites of the shade canopy.

Figure 3 - Spectral shade ratios for tree S on a horizontal plane for the centre, edge and trunk sites of the shade canopy.

Figure 4 – Spectral shade ratios for tree M in the sun normal direction for the centre, edge and trunk sites of the shade canopy.

Figure 5 - Spectral shade ratios for tree S in the sun normal direction for the centre, edge and trunk sites of the shade canopy.

Figure 6 – Ratios of the spectral irradiances on a sun normal plane to a horizontal plane in (a) the shade of tree M and (b) sunlight.

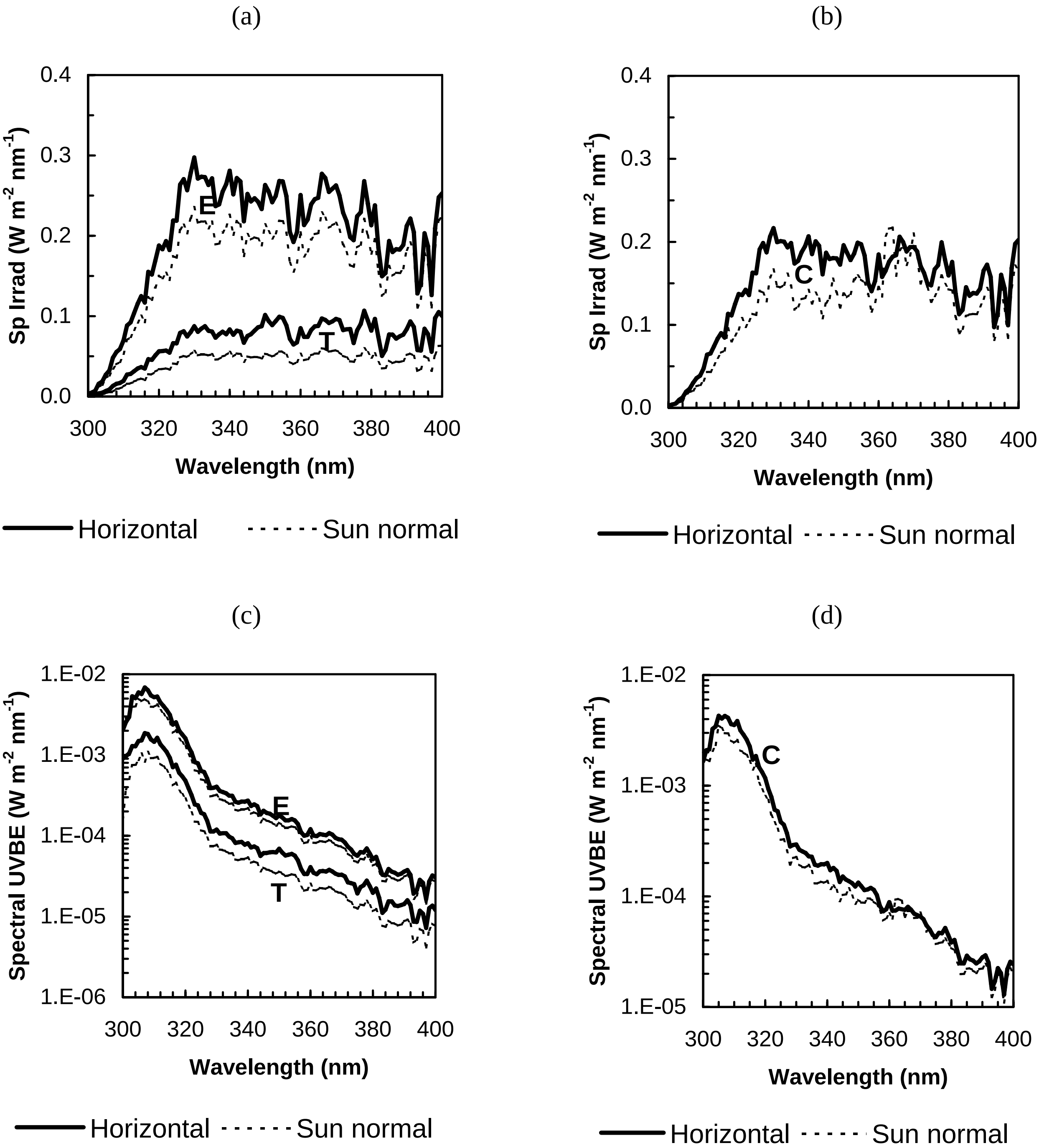


Figure 1 – The UV spectra for a horizontal plane and a sun normal plane for tree M at (a) the edge, E and trunk, T sites, (b) the center, C site and the corresponding spectral erythemal irradiances for tree M at (c) the edge, E and trunk, T sites, (d) the center, C site.

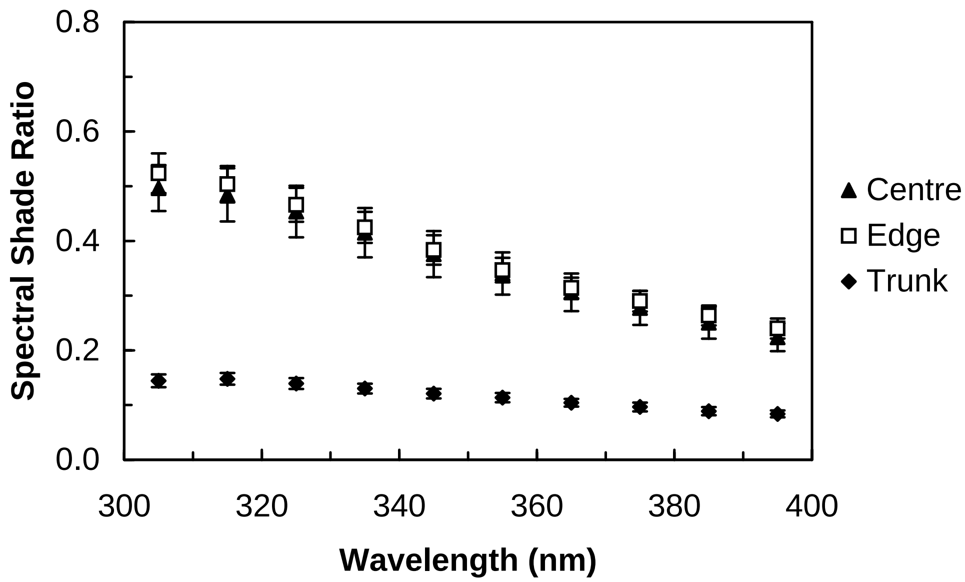


Figure 2 – Spectral shade ratios for tree M on a horizontal plane for the centre, edge and trunk sites of the shade canopy.

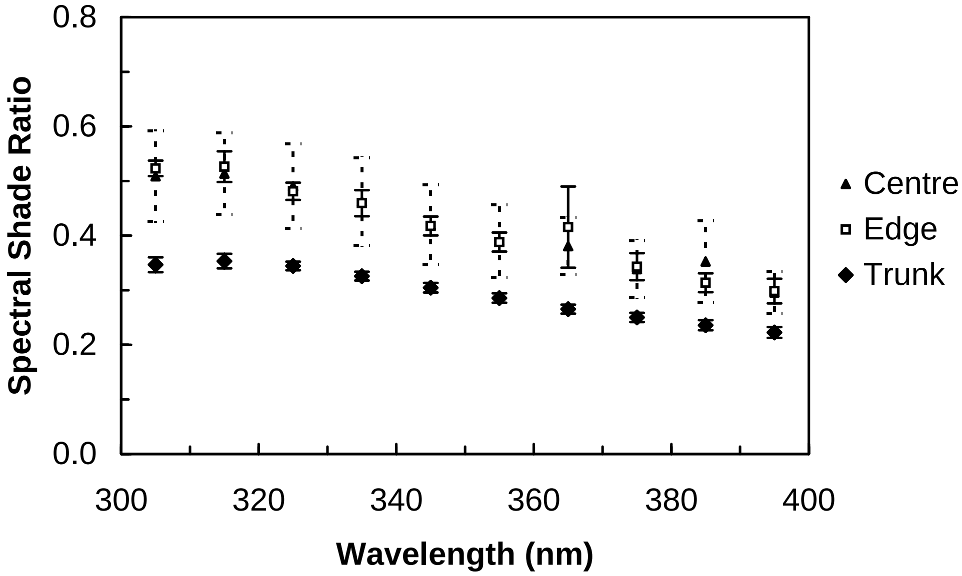


Figure 3 - Spectral shade ratios for tree S on a horizontal plane for the centre, edge and trunk sites of the shade canopy.

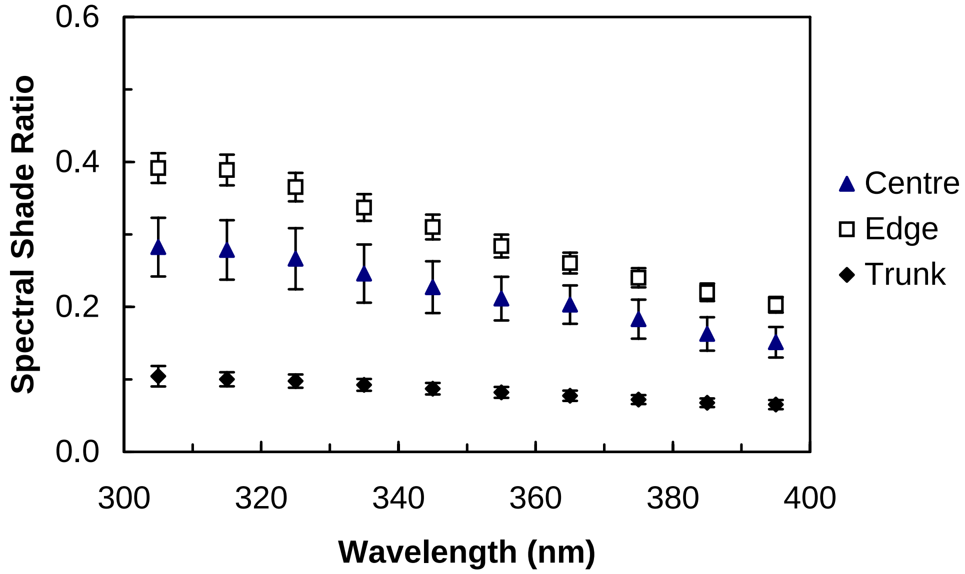


Figure 4 – Spectral shade ratios for tree M in the sun normal direction for the centre, edge and trunk sites of the shade canopy.

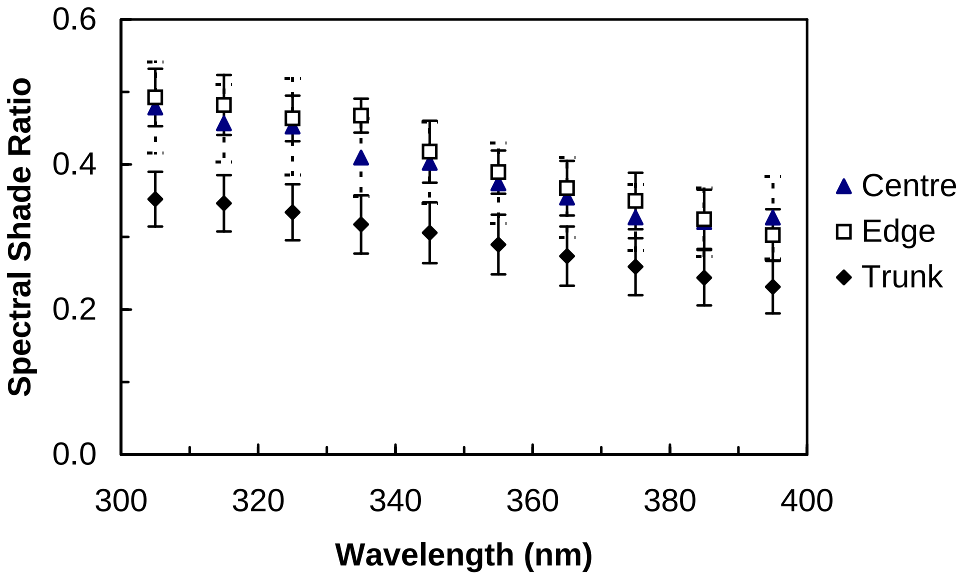
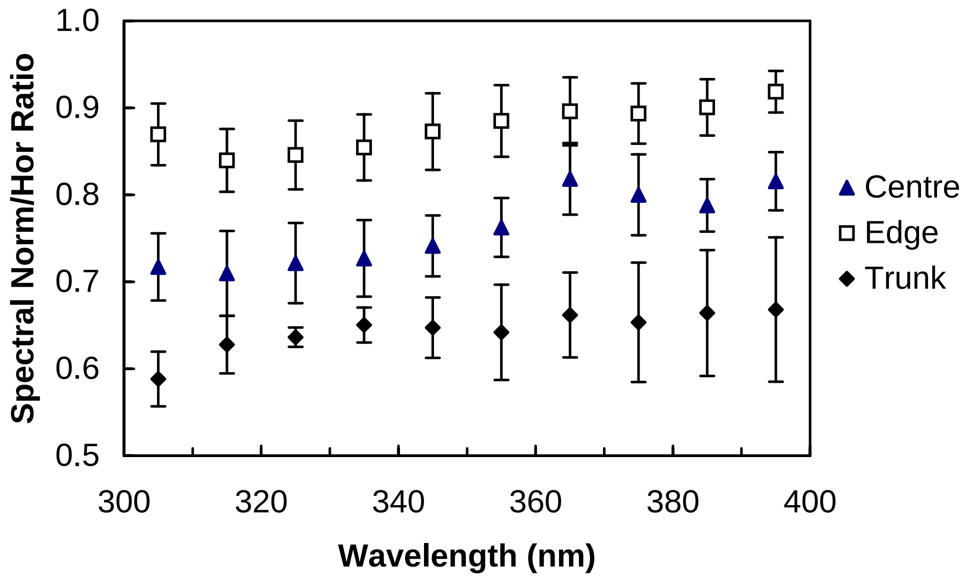


Figure 5 - Spectral shade ratios for tree S in the sun normal direction for the centre, edge and trunk sites of the shade canopy.

(a)



(b)

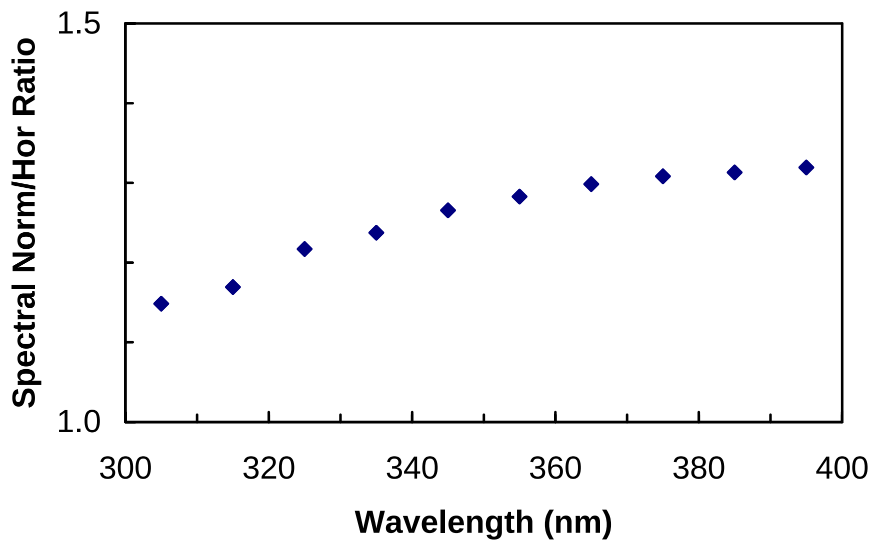


Figure 6 – Ratios of the spectral irradiances on a sun normal plane to a horizontal plane in (a) the shade of tree M and (b) sunlight.