COMPARISON OF THE SPECTRAL BIOLOGICALLY EFFECTIVE
SOLAR ULTRAVIOLET IN ADJACENT TREE SHADE AND SUN

A.V. Parisi1,* and M.G. Kimlin1

1Centre for Astronomy and Atmospheric Research, Faculty of Sciences, University of Southern Queensland, TOOWOOMBA 4350 AUSTRALIA. Fax: 61 74 6312721.

*To whom correspondence should be addressed.

Running Title: Spectral Solar UVR in Tree Shade
ABSTRACT

The solar spectral UVR irradiances in tree shade and sunlight have been measured in a sub-tropical Southern Hemisphere summer. The spectral data allowed the UVB and UVA irradiances and the biologically effective irradiances to be calculated for different harmful biological processes to human skin and eyes. The average of the ratio of the UVA to UVB irradiances was lower by 26% in the shade compared to the same ratio in the sun. The spectral shade ratio calculated as the ratio of the spectral biologically effective irradiances in the shade to those in the adjacent sun decreased with increasing wavelength for all of the trees. The decrease in the shade ratio was approximately 42% at 400 nm compared to the shade ratio at 300 nm. Despite the UVR protection provided by tree shade, the erythemal UVR exposure received in one hour in the tree shade exceeded the occupational limit for UVR exposure.
1. INTRODUCTION

Ultraviolet radiation (UVR) is a factor in the formation of eye disorders (Young, 1994) and sun related skin damage (Longstreth et al., 1995). The all-year round high ambient ultraviolet irradiances in Australia and particularly, Queensland (Sabburg et al., 1998, Roy et al., 1995) and the associated high personal UVR exposures (Kimlin et al., 1998), requires all-year monitoring of the human UVR exposure. Although, trends in NMSC (non melanoma skin cancer) are reported to be continuing to rise in Australia, (a total increase of 35% between 1985 and 1995) (Staples et al., 1998) there have been reductions in one type of NMSC, namely basal cell carcinomas (BCC), in younger age groups even though the overall incidence of BCC continues to rise by a 20% increase between 1985 and 1995 (Staples et al., 1998). This may be evidence that public health campaigns to reduce sun exposure may be having a beneficial effect. Although Australians are adopting sun prevention strategies, more needs to be done so that Australians may continue enjoying an outdoor lifestyle. In Australia, due to its high ambient UVR irradiances, it is necessary to minimise UVR exposure in all climatic conditions throughout the year. This requires scientific measurements in order to increase the knowledge about the UVR environment to allow strategies to be developed and implemented to adapt our environment in order to reduce exposure to UVR.

One of the strategies recommended by Australian Health authorities for reduction of the exposure to solar erythemal UVR is the making use of shade (Department of Architecture, 1995, 1996, 1997). The UVR under shadecloth has been investigated (Wong, 1994, Wong et al., 1994). The protection provided by hats has also been reported
(Wong et al., 1996, Diffey and Cheeseman, 1992). During outdoor sporting and recreational activities, protection may be provided to spectators and competitors by the shade of trees. Despite the intuitive understanding that the shade of a tree will reduce the exposure to solar UVR, there is very little quantitative data on the protection from and reduction of personal exposure to solar UVR provided by sheltering from the sun in the shade of a tree. Two recent studies have investigated the UVR protection provided by tree shade (Parsons et al., 1998, Parisi et al., 1999). The first study measured the UVR exposure predominantly on a horizontal plane at approximately noon under 65 different trees. Parsons et al. (1998) found that tree shade that is unobstructed on the sides does not provide adequate protection from solar UVR. The research by Parisi et al. (1999) measured the erythemal UVR under two trees in the morning, noon and in the afternoon over spring and summer. Additionally, this research measured the distribution of UVR exposure to humans with UVR dosimeters. This previous research measured the erythemal irradiances with broadband meters and the personal UVR exposures with dosimeters. No previous research has measured the spectral UVR irradiances in tree shade and no quantitative data exists. One of the advantages of spectral irradiance measurements compared to broadband data is that they can be accurately weighted with the biological action spectrum for any biological process. This paper determines the spectral biologically effective irradiances for different harmful biological processes to humans on a horizontal plane in tree shade.
2. MATERIALS AND METHODS

2.1 Spectral Irradiances

The spectroradiometer used in this research is based on a dual holographic grating (1200 lines/mm) monochromator (Jobin Yvon, model DH10, Jobin Yvon Co., France) and a UVR sensitive photomultiplier tube detector (model R212, Hamamatsu Co., Japan), temperature stabilised to 15.0 ± 0.5 °C, to measure the spectral irradiances in nanometre increments. The input optics of the spectroradiometer are provided by a 15 cm diameter integrating sphere (model OL IS 640, Optronics Laboratories, Orlando, USA). Careful procedures must be followed to ensure the calibration of spectroradiometers so that they remain radiometrically stable over a wide dynamic range and accurately aligned in wavelength (McKenzie et al., 1993). For this project, the spectroradiometer was wavelength calibrated against the mercury 365 nm spectral line and before each set of measurements for each tree, irradiance calibrated to a UVR standard lamp. The standard lamp was a 250 W quartz tungsten halogen lamp (SYL 235, Sylvania Lighting, Japan) at a distance of 10 cm from the optics entrance aperture and powered by 9.500 ± 0.005 A from a constant current power supply (Kenwood PD35-20D, Kenwood Co., Tokyo, Japan). This UVR lamp has calibration traceable to the UVR standard housed at the CSIRO National Measurements Laboratory.

Consequently, each set of shade and adjacent full sun spectral scans for each tree, had an associated absolute irradiance calibration. The time between the shade and sun measurements was of the order of 5 minutes and the sun spectral data was measured
immediately after the equipment was moved into the sunlight. As a result any
temperature effects on the calibration of the spectroradiometer were minimised.

2.2 Trees

The trees employed in this research were five typical Australian trees in the grounds of
the University of Southern Queensland campus, Toowoomba (27.5° S latitude). The trees
are referred to as 1 to 5 consecutively in the following. The solar zenith angle (SZA) for
each tree at the time of measurement along with the canopy width, tree height and height
to first branches for each tree are provided in Table 1. The density of the leaves in each
tree canopy was characterised by measuring the visible irradiances on a horizontal plane
at ground level in the shade of each tree with a LUX meter (model EMTEK LX-102,
supplier, Walsh’s Co., Brisbane, Australia). These irradiances were measured at each
point of a 1 m grid within each shade, averaged for each tree and the visible shade ratios
provided in the final column of Table 1 calculated by dividing each of the averages of the
visible irradiances in the shade by the adjacent visible irradiances in full sun.

The spectral UVR irradiance data were collected on a horizontal plane in the Southern
Hemisphere summer between 10:07 Eastern Standard Time (EST) with an SZA of 25°
and 12:10 EST with an SZA of 6°. For the spectral measurements for trees 1 and 2, there
was 1 out of a possible 8 okta (okta meaning one-eighth of the sky dome as seen by an
observer) of cloud cover, with 8 okta representing complete coverage of the sky dome
with cloud. There was 4 okta cloud for the spectral measurements for trees 3 to 5. During
the data collection period for all the trees, the solar disc was clear of any cloud. Each tree
was 5 to 10 metres from other trees or structures, so the effect of any other trees or
structures was negligible. The UVR albedo of the ground cover under the trees was measured as less than 5%.

For each tree, the spectroradiometer was levelled on a horizontal plane, wavelength calibrated and irradiance calibrated to the UVR standard and three scans of the UVR spectrum in the shade recorded at one location in the tree shade. This location was in the shadow side of the trunk, in the approximate centre of the canopy shadow and at least 2 m from the visible shadow edge. The UVR spectrum scan was repeated by moving the spectroradiometer to a second location in the tree shade and three scans of the shade UVR spectrum recorded. The intention of the second location was to provide a second set of data in the shade and the location was approximately within 0.3 m of the first location. Each UVR scan was completed within 40 seconds. Within five minutes of each two series of UVR shade spectra, the spectroradiometer was moved to full sunlight, at least three metres from the tree shade and three scans of the solar UVR spectrum recorded. The change of the solar zenith angle in the period between recording the shade and sun spectra was minimal.

The series of three scans were averaged at each wavelength to provide the spectral irradiance in the sun and two sets of spectral irradiances in the shade for the individual trees. The two sets of spectral irradiances in the shade were averaged at each wavelength to provide the average spectral irradiance in each tree shade.

2.3 Biologically Effective Irradiances

The biologically effective irradiances, UVBE, were calculated as follows (CIE, 1992):
\[ UVBE = \int_{UV} S(\lambda)A(\lambda)d\lambda \]  

where \( S(\lambda) \) is the spectral irradiance measured with the spectroradiometer, \( A(\lambda) \) is the action spectrum for the particular biological process and the wavelength range is over the solar terrestrial UVR waveband. A series of action spectra specific to harmful UVR effects on human skin and eyes were employed, namely, erythema (CIE, 1987), actinic hazard (IRPA, 1989), fish melanoma (Setlow, 1993), photoconjunctivitis (CIE, 1986a), photokeratitis (CIE, 1986b) and DNA damage (Setlow, 1974). The reason the action spectrum for fish melanoma has been employed is that no action spectrum exists for melanoma in humans and this action spectrum may possibly provide an indication of the wavelengths effective in human melanoma (Gasparro et al., 1998).

The shade ratio was calculated for each tree for all the action spectra, as follows (Parisi et al., 1999):

\[ T = \frac{\sum_{UV} S_s(\lambda)A(\lambda)\Delta\lambda}{\sum_{UV} S(\lambda)A(\lambda)\Delta\lambda} \]  

where \( S_s(\lambda) \) and \( S(\lambda) \) are the spectral UVR irradiances in the tree shade and full sun respectively, \( A(\lambda) \) is the relevant action spectrum, \( \Delta\lambda \) is the wavelength increment, 1 nm in this case and the summation is over the UVR waveband.
3. RESULTS

3.1 Tree Shade Spectral Irradiances

The solar spectral irradiances in the shade and adjacent full sun for trees 1 and 5 are provided in Figure 1. As expected, the spectral irradiances in the shade were lower than in the sun with a shade to sun ratio of 0.26 and 0.11 at 300 nm and 400 nm respectively for tree 1 and 0.36 and 0.27 for tree 5 at 300 and 400 nm respectively. The shade spectral irradiance in tree 5 relative to that in the sun was higher for this tree compared to tree 1. This may be due to the extra cloud cover at the time of measuring the spectral irradiances for tree 5. The spectral irradiances have been summed over the UVB (280 – 320 nm) and UVA (320 – 400 nm) wavebands to produce the irradiances in tree shade and sun in Table 2. For each tree, the ratios of the UVA to UVB irradiances have been calculated for both the shade and sun. This ratio is lower in the tree shade compared to the sun with an average ratio of 11.0 in shade and 14.8 in sun.

3.2 Tree Shade Biologically Effective Irradiances

The spectral biologically effective irradiances in the shade of tree 1 compared to that in full sun are provided in Figure 2 and Figure 3 for each individual action spectrum. The differences between the spectral biologically effective irradiances in the sun and the shade are higher in the UVA wavelengths for the action spectra with relative sensitivity at these wavelengths, namely, erythema, actinic, DNA and fish melanoma. The action spectra for photoconjunctivitis and photokeratitis do not have a sensitivity in the UVA wavelengths. Specifically, the relative protection provided by the tree shade is less at the
UVB wavelengths compared to the UVA wavelengths. This coincides with the higher relative effectiveness of the erythema, actinic and DNA action spectra.

The spectral biologically effective irradiances in the tree shade have been summed to provide the irradiances in Table 3 for the erythema, actinic, DNA, photoconjunctivitis, photokeratitis and fish melanoma action spectra. The erythemal irradiance is provided in units of MED hr\(^{-1}\) with one MED (minimum erythemal dose) defined as 200 J m\(^{-2}\) (Diffey, 1992) and is the amount of biologically effective UVR required to produce barely perceptible erythema in people with skin type I (Gies et al., 1995) after an interval of 8 to 24 hours following UVR exposure. High erythemal irradiances ranging from 0.80 to 1.56 MED hr\(^{-1}\) were measured in the tree shade. Dependent on the tree type and time of day, an exposure of one MED would be received for a surface on a horizontal plane in a period of between 38 to 75 minutes.

### 3.3 Shade Ratio

The shade ratios for the UVA and UVB wavebands and for the biologically effective irradiances are provided in Table 4. The shade ratio is highest for the UVB waveband with a range of 0.144 to 0.356 compared to the UVA with a range of 0.111 to 0.274. This is due to the larger degree of Rayleigh scattering at the shorter wavelengths increasing the relative proportion of diffuse radiation at these shorter wavelengths. For the biologically effective irradiances, the range of the shade ratios was 0.117 to 0.361. The mean and standard deviation averaged across the five trees for each of the shade ratios are shown in the final two rows of Table 4. The relatively large standard deviation is due to the variation between the different trees due to the different properties of the trees. The
erythema, actinic, DNA, photoconjunctivitis and photokeratitis action spectra have a mean the same as that for the UVB shade ratio due to the relatively high response of these action spectra in the UVB. Nevertheless, the individual values show the variation for each tree and action spectrum. The spectral shade ratio for the UVR waveband is shown in Figure 4. The data are the average for all of the trees. The noise in the data is due to leaf flicker, however, the trend is an increasing shade ratio for decreasing wavelength.

4. DISCUSSION

The solar spectral UVR irradiances in tree shade and sunlight have been measured in a sub-tropical Southern Hemisphere summer. The spectral data allowed the UVB and UVA irradiances and the biologically effective irradiances to be calculated for a number of action spectra, namely, erythema, actinic hazard, DNA damage, photoconjunctivitis, photokeratitis and fish melanoma. The relative proportion of UVA to UVB irradiances changed in the tree shade compared to that in sun. Specifically, the average of the ratio of the UVA to UVB irradiances was lower by 26% in the shade compared to the same ratio in the sun. The consequence of this is that there is a higher proportion of the UVB wavelengths in the tree shade compared to the proportion of UVB wavelengths in sun. As a result, the tree shade is not as effective at providing protection at the shorter wavelengths where the erythema, actinic, DNA and fish melanoma action spectra have a higher relative effectiveness.

The spectral shade ratio of the biologically effective irradiances decreased with increasing wavelength for all of the trees and all of the action spectra. The shade ratio at
400 nm at the start of the visible waveband is lower than the shade ratio at 300 nm. The decrease in the shade ratio was approximately 42% at 400 nm compared to the shade ratio at 300 nm. The higher shade ratio is expected from the large degree of Rayleigh scattering at the shorter wavelengths contributing to a larger proportion of diffuse radiation at the UVB wavelengths. However, this is the first research to undertake spectral UVR measurements in tree shade to quantify the spectral irradiances and spectral biologically effective irradiances in tree shade.

Despite the UVR protection provided by tree shade, the erythemal UVR exposure received in one hour in the tree shade exceeded the occupational limit for UVR exposure (NHMRC, 1989). Previous research on home workers (Kimlin et al., 1998) found that in the cooler temperatures, the population did not use as many UVR protective strategies. As a result of the cooler temperatures in the shade, the population may not be employing additional UVR protective measures. The UVR protection provided by tree shade is a valuable component of a UVR protection strategy, however, additional UVR protective measures must be employed in the tree shade as a significant exposure to skin and eyes may be received.

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FIGURE CAPTIONS

Figure 1 – The UVR spectral irradiance in the (1) shade of tree 1 and (2) adjacent full sun and in the (3) shade of tree 5 and (4) adjacent full sun.

Figure 2 – The (a) spectral erythemal irradiance in (1) tree shade and (2) sun, (b) spectral actinic irradiance in (1) tree shade and (2) sun and (c) spectral DNA damage irradiance in (1) tree shade and (2) sun.

Figure 3 – The (a) spectral photoconjunctivitis irradiance in (1) tree shade and (2) sun, (b) spectral photokeratitis irradiance in (1) tree shade and (2) sun and (c) spectral fish melanoma irradiance in (1) tree shade and (2) sun.

Figure 4 – The spectral shade ratio for UVR averaged over the five trees.
Table 1 – The solar zenith angle for each tree at the time of measurement along with the canopy width, tree height, height to first branches and the shade ratio in the visible waveband for each tree.

<table>
<thead>
<tr>
<th>Tree</th>
<th>SZA (degrees)</th>
<th>Canopy Width (m)</th>
<th>Tree Height (m)</th>
<th>Height to first branches (m)</th>
<th>Visible shade ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>10.1</td>
<td>10.2</td>
<td>2.9</td>
<td>0.49</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>8.0</td>
<td>9.9</td>
<td>1.5</td>
<td>0.28</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>6.4</td>
<td>9.6</td>
<td>1.9</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>4.2</td>
<td>6.4</td>
<td>0.4</td>
<td>0.11</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>7.8</td>
<td>17.0</td>
<td>1.8</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Table 2 – The UVB and UVA irradiances in adjacent tree shade and sun and the ratios of UVA to UVB irradiances.

<table>
<thead>
<tr>
<th>Tree</th>
<th>Tree shade</th>
<th>Sun</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UVB (W m⁻²)</td>
<td>UVA (W m⁻²)</td>
</tr>
<tr>
<td>1</td>
<td>0.61</td>
<td>6.1</td>
</tr>
<tr>
<td>2</td>
<td>0.98</td>
<td>11.7</td>
</tr>
<tr>
<td>3</td>
<td>0.80</td>
<td>8.6</td>
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<tr>
<td>4</td>
<td>0.66</td>
<td>7.2</td>
</tr>
<tr>
<td>5</td>
<td>1.17</td>
<td>13.6</td>
</tr>
</tbody>
</table>
Table 3 – The biologically effective irradiances in the tree shade for the erythemal, actinic, DNA, photoconjunctivitis, photokeratitis and fish melanoma action spectra.

| Tree | Biologically Effective Irradiances |  
|------|-----------------------------------|---|
|      | Erythemal (MED hr\(^{-1}\)) | Actinic (W m\(^{-2}\)) | DNA (W m\(^{-2}\)) | Photoconjunctivitis (W m\(^{-2}\)) | Photokeratitis (W m\(^{-2}\)) | Fish Melanoma (W m\(^{-2}\)) |
| 1    | 0.80 | 0.013 | 0.0011 | 0.00024 | 0.028 | 1.57 |
| 2    | 1.36 | 0.023 | 0.0018 | 0.00043 | 0.047 | 2.88 |
| 3    | 1.07 | 0.018 | 0.0015 | 0.00034 | 0.037 | 2.14 |
| 4    | 0.89 | 0.015 | 0.0012 | 0.00028 | 0.031 | 1.79 |
| 5    | 1.56 | 0.026 | 0.0021 | 0.00048 | 0.054 | 3.35 |
Table 4 – Shade ratios for each of the trees for the UVA and UVB wavebands and the biologically effective irradiances.

<table>
<thead>
<tr>
<th>Tree</th>
<th>Shade Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UVB</td>
</tr>
<tr>
<td>1</td>
<td>0.245</td>
</tr>
<tr>
<td>2</td>
<td>0.290</td>
</tr>
<tr>
<td>3</td>
<td>0.144</td>
</tr>
<tr>
<td>4</td>
<td>0.201</td>
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<tr>
<td>5</td>
<td>0.356</td>
</tr>
<tr>
<td>Av</td>
<td>0.25</td>
</tr>
<tr>
<td>SD</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Figure 1 - The UVR spectral irradiance in the (1) shade of tree 1 and (2) adjacent full sun and in the (3) shade of tree 5 and (4) adjacent full sun.
Figure 2 - The (a) spectral erythemal irradiance in (1) tree shade and (2) sun, (b) spectral actinic irradiance in (1) tree shade and (2) sun and (c) spectral DNA damage irradiance in (1) tree shade and (2) sun.
Figure 3 - The (a) spectral photoconjunctivitis irradiance in (1) tree shade and (2) sun, (b) spectral photokeratitis irradiance in (1) tree shade and (2) sun and (c) spectral fish melanoma irradiance in (1) tree shade and (2) sun.
Figure 4 - The spectral shade ratio for UVR averaged over the five trees.