Solar ultraviolet exposures at ground level in tree shade during summer in south east Queensland

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Running Title: Solar UV at Ground Level in Tree Shade in Summer

Abstract

Data is presented on the effect of the tree canopy transmittance in the visible waveband (V_T), canopy width, height and height of the start of the tree canopy (C_H) on the solar UV in tree shade on a horizontal plane at ground level during a Southern Hemisphere summer. Of these factors, the V_T and C_H have an influence on the UV irradiances in the tree shade. The shade ratios (UV in tree shade to that in full sun) for erythemal UV ranged from 0.71 to 0.42, 0.54 to 0.29 and 0.63 to 0.41 for morning, noon and afternoon respectively for the V_T range of 0.4 to 1.0. Over the same V_T range, the shade ratios for UVA ranged from 0.61 to 0.28, 0.50 to 0.22 and 0.49 to 0.29 for morning, noon and afternoon respectively. The UV exposures in the tree shade decreased with the V_T with a marginally higher decrease in the irradiances for the UVA compared to the erythemal UV. Despite the protection by the tree shade, significant UV in the tree shade of approximately 4 MED (minimum erythemal dose) were received for the latitude in this research on a cloud free summer day on a horizontal plane over a two hour period centred about solar noon.

Key words: Ultraviolet; Erythema; Tree shade; Summer; UVA

Introduction

A majority of the UV exposure people actually receive is due to their behaviour (Stick et al., 1997). Outdoor activities are an essential component to provide a sense of physical well being and contribute to quality of life. Environmental protection from solar UV radiation through the usage of tree shade during outdoor sporting and recreational pursuits is an important supplementary solar UV protection measure. In Queensland, Australia, recommendations for planning sun safe outdoor environments have been produced (Department of Architecture, 1995, 1996, 1997). These consider shade for sports fields, young children and public pools, but do not quantify the UV protection provided by tree shade.

The UV irradiances, predominantly on a horizontal plane under 65 different trees predominantly at noon have been measured (Parsons et al., 1998). Grant (1997) has considered the photosynthetically active radiation, along with UVB (280–320 nm) and UVA (320–400 nm) in tree shade. Researchers have measured UVB and photosynthetically active radiation (PAR) under forest canopies and in forest gaps (Flint and Caldwell, 1998, Brown et al., 1994, Killik and Warden, 1991) along with the research by Grant (1991) on the UV and PAR irradiances at the base of a corn canopy. Parisi et al. (1999) have measured the erythemal UV on a horizontal plane and the personal erythemal exposure to various human anatomical sites while in the shade of two Australian trees. In addition to this research, further research is required to quantitatively assess the factors of tree shade that influence UV exposure. This paper addresses that and considers the effect of the tree canopy transmittance in the visible waveband (V_T), tree canopy width, tree height and height of the start of the tree canopy above the ground (C_H) on the protection from solar UV provided in tree shade.

Methods

Tree Parameters

The trees employed in this research are in the grounds of the University of Southern Queensland (USQ) campus, Toowoomba, (27.5^{o} S latitude), Australia. Small trees with a canopy width of less than approximately 2 metres were excluded as being too small. Approximately forty-seven isolated trees that were sufficiently distant from other trees and structures were selected for this research in the three months of December to February in the Southern Hemisphere summer. This number of trees was selected in order to provide sufficient data to be statistically significant and also to be manageable within the timeframe of the project. Each of the trees was an evergreen tree and characterised by measurement of the parameters of tree canopy width, tree height, height of the start of the tree canopy above the ground and the tree canopy transmittance in the visible waveband.

The denseness of the canopy is a function of the leaf size and angle and number of leaves per unit volume. This 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 cosine response of the meter was measured in the laboratory using a goniometer arm to rotate a quartz tungsten halogen lamp, powered by a current stabilised supply, around the detector. For angles up to 50^{o}, the agreement was within 11% of the ideal cosine response. For each tree, the visible irradiances were measured in the morning between 8:30 Australian Eastern Standard Time (EST) and 9:30 EST, at noon between 11:30 EST and 12:30 EST and in the afternoon between 14:30 EST and 15:30 EST both in the full sun and in the tree shade. In the remainder of this paper, these measurement periods will be referred to as 9:00 EST, noon and 15:00 EST.

In the tree shade, the visible irradiances were measured on a horizontal plane at each point of a 1 m grid within the visible shade boundary and averaged over all grid points. The measurements were at least 5 cm inside the visible shade boundary. The visible irradiances were measured at the same time as the erythemal UV (UV_{ery}) (CIE, 1987), and UVA irradiances and the set of three irradiances took approximately 10 to 15 minutes per tree to measure. The cloud cover during the measurement periods over the summer ranged from 1 to 7 out of a possible 8 okta (okta meaning one-eighth of the sky dome as seen by an observer) with 8 okta representing complete coverage of the sky dome with cloud. No measurements were made if the visible shade boundary was not well defined due to cloud. The full sun visible irradiances were measured once before the measurements in the tree shade and once after the tree shade measurements and the full sun irradiance taken as the average of the two. The tree canopy transmittance in the visible waveband, V_T, is defined in this research as:

$$V_T = 1 - \frac{V_S}{V} \qquad (1)$$

where V is the average of the visible irradiances before and after in full sun and V_S is the average of the visible irradiances in the tree shade.

Erythemal UV and UVA Irradiances

The ambient UV irradiances on a horizontal plane at ground level in the erythemal UV and UVA wavebands were measured with a hand-held detector (model 3D V2.0, Solar Light Co., Philadelphia, USA) fitted with an erythemal sensor and a UVA sensor. The response of the erythemal sensor approximates the human erythemal response. The cosine response of the two detectors was measured as described in the previous section. For the UV_{ery} detector, the measured cosine response was 18% or better of the ideal for angles up to 40^o. For the UVA detector, the agreement was 9% or better for angles up to 40^o. The UV_{ery} and UVA irradiances in the tree shade were measured at each point on a 1 metre grid in the tree shade at locations similar to those for the measurement of the visible irradiances. The erythemal UV was measured in units of MED/h where a MED is defined as a minimum erythemal dose and is the amount of biologically effective UV required to produce barely perceptible erythema after an interval of 8 to 24 hours following UV exposure (Diffey, 1992). The UVA irradiances were recorded as research has shown that the UVA waveband can also induce skin damage (Anders et al., 1995). These measurements were taken in the shade of each tree at the same time as the visible irradiances. The erythemal UV and UVA sensors in the hand-held detector were calibrated against a spectroradiometer (Wong et al., 1995) based on a dual holographic grating (1200 lines/mm) monochromator (Jobin Yvon, 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 with calibration traceable to the UV standard lamp at the CSIRO National Measurement Laboratory. The calibration provided a conversion for the erythemal UV of 210 J m^{-2} for one MED. The calibrations were undertaken for a range of solar zenith angles between the times of 8:00 EST to noon in order to minimise the effect of the cosine response of the detectors at the larger solar zenith angles.

Shade Ratio

In order to take into account, the variations of the ambient UV irradiances in full sun due to changes in atmospheric conditions, the irradiances in the two wavebands were measured in full sun on a horizontal plane for each tree at the time of measuring the irradiances in tree shade. The ambient unshaded irradiances were calculated as the averages of the respective irradiances measured before and after the irradiances in the tree shade. These averages were calculated to take into account variations in the unshaded irradiances during the measurement of the shaded irradiances. The shade ratio, T_s (Wong, 1994) defined as:

$$T_S = \frac{UV_S}{UV} \qquad (2)$$

was calculated for both the UV_{ery} and UVA wavebands for each tree, where UV_s is the average of the UV_{ery} or UVA irradiances in the tree shade and UV is the respective ambient UV_{ery} or UVA irradiance to an unshaded horizontal plane in full sun. The UV_{ery} and UVA irradiances in the tree shade were calculated as the average of the respective irradiances at each of the individual grid points. The average over the whole shade was calculated to take into account variations in the shade UV_{ery} and UVA due to leaf flicker and variations in the V_T (Grant, 1997).

The effect of the V_T, tree canopy width, tree height and C_H on the shade ratios for erythemal UV and UVA have been analysed with the SPSS 8.0 for Windows software. The shade ratios at each of the three times in Table 1 have been averaged over the three times for each tree and a multiple regression analysis was employed. Principal component analysis was considered, however, it was not required as the independent variables are not sufficiently correlated.

UV Exposure

The usage of shade will reduce the cumulative erythemal UV exposure over a day. In order to quantify the amount of reduction, the reduction in the cumulative erythemal UV exposure between 9:00 EST and 15:00 EST on a horizontal plane has been considered for a typical mainly cloud free day in summer. The ambient erythemal UV exposure on a horizontal plane was measured with a Biometer (model 501, Solar Light Co., Philadelphia, USA) permanently mounted on a horizontal unshaded plane on the roof of a building at the USQ and calibrated against the calibrated spectroradiometer. The data was recorded in units of MED/15 minutes.

The values of V_T for the trees have been grouped into 0.4 to 0.59, 0.6 to 0.79 and 0.8 to 1.0 respectively. This division of V_T was selected to cover the full range. A smaller division in the V_T groupings was not used as the number of trees in each group would have been too small (three in some groups) to provide statistically significant averages. The shade ratios at each time in Table 1 within each V_T range were averaged to provide the average for that V_T range and time. The respective shade ratios for each V_T group were interpolated with a second order polynomial fitted to the three data points to provide the values of the shade ratio at the intermediate times.

Results

Erythemal UV and UVA Irradiances

The calibrated erythemal UV irradiances at each point of a 1 m grid in the shadow of a typical larger tree (canopy diameter of 7.7 m) at 9:00 EST and a typical smaller tree (canopy diameter of 4.4 m) at noon are provided in Figure 1. The X represents the location of the tree trunk. The standard error of each set of erythemal UV irradiances is less than 5% for these two trees. For the remaining trees, the consistency of the measurements was studied and the variation of the erythemal UV and UVA irradiances are predominantly less than 10%.

The calibrated erythemal UV and UVA irradiances in the tree shade averaged over each tree are plotted in Figure 2 for the three times. For each time there is a range of UV_{ery} and UVA irradiances. The erythemal irradiances in the tree shade range from 0.52 to 1.5 MED/h, 0.53 to 2.2 MED/h and 0.57 to 1.3 MED/h for each time respectively. The UVA irradiances in the tree shade range from 0.57 to 1.8 mW cm^{-2}, 0.48 to 2.6 mW cm^{-2} and 0.6 to 1.7 mW cm^{-2} for each time respectively. The maximum irradiances at noon for both the UV_{ery} and UVA irradiances in the tree shade are higher than the respective maxima in the morning and afternoon. This is due to the higher UV irradiances at noon in full sunlight causing the higher

UV irradiances in the tree shade. The days with the large differences between the irradiances at noon and the irradiances in the morning or noon are generally due to the days with lower cloud cover or the cloud clear of the solar disc. On other days, the differences between the irradiances at noon and the irradiances in the morning or afternoon are small or negligible. This is due to the higher amount of cloud cover, up to seven okta, at noon on those days. For some days, the irradiances at noon are less than the irradiances in the morning or afternoon on other days. This may be due to the combined influence of higher cloud cover at noon and the effect of a tree with a higher V_T reducing the UV irradiances in the tree shade. The differences between the erythemal UV and the UVA irradiances may be due to the higher proportion of Rayleigh scattering at the shorter wavelengths.

Shade Ratio

The multiple regression established that the UV_{ery} and UVA shade ratios are dependent on V_T and C_H ($P \leq 0.1$) and not dependent on canopy width, and tree height ($P > 0.1$). For the UV_{ery} shade ratio, $T_s(UV_{ery})$:

$$T_s(UV_{ery}) = 0.854 - (0.579 * V_T) + (0.02378 * C_H) \quad (3)$$

with an R squared of 0.72. Similarly, for the UVA shade ratio, $T_s(UVA)$:

$$T_s(UVA) = 0.792 - (0.649 * V_T) + (0.0220 * C_H) \quad (4)$$

with an R squared of 0.89. A higher V_T produces a lower shade ratio for both wavebands or improved UV protection and a higher C_H produces a higher shade ratio.

The shade ratios for 9:00 EST, noon and 15:00 EST are shown in Table 1 for each of the V_T groups. Each of the ratios is the average for the range of V_T. For the UV_{ery} irradiances, the shade ratios are lower at noon compared to 9:00 EST and 15:00 EST. For each V_T, the shade ratios are higher for the erythemal UV compared to the UVA for the same time period.

UV Exposure

The UV_{ery} irradiances for the typical mainly cloud free summer's day of 8 January, 1999 are shown in Figure 3 in units of MED for every 15 minute interval. For the same day, the UV_{ery} irradiances for each of the V_T ranges in Table 1 employing the measured erythemal UV shade ratios in Table 1 and interpolated to provide the shade ratios at the intermediate times are also plotted in Figure 3. This Figure shows the protection from solar erythemal UV provided for each category of V_T.

The erythemal UV exposures on a horizontal plane for the two scenarios of full sun and tree shade for each category of V_T are provided in Table 2 for the two scenarios of:

- The cumulative erythemal UV exposure between 9:00 and 15:00 EST provided in the shade of trees with the different V_T. This scenario was employed to consider the case of any persons that are outdoors for the majority of the day and seek shelter from the sun in tree shade;
- The cumulative erythemal UV exposure between 11:00 and 13:00 EST provided in the shade of trees with V_T the same as the previous scenario. These times were selected in order to consider the effect of shade during the high UV irradiances times.

For the exposure between 9:00 EST and 15:00 EST, the trees with V_T of 0.8 to 1 reduce the erythemal UV to about a third of the 33.4 MED exposure in full sun. Similarly, for exposures between 11:00 EST and 13:00 EST, the V_T of 0.8 to 1 reduce the erythemal UV to 4.0 MED compared to 13.3 MED in full sun.

Discussion

While outdoors, protection from solar UV may be provided by tree shade. It is easy to underestimate the UV exposure in tree shade due to the lower temperatures of the skin due to the reduced radiation load in the shade (Kimlin et al., 1998). This paper has presented scientific data to establish the effect of the tree V_T, canopy width, tree height and height of the start of the canopy above the ground on the UV irradiances on a horizontal plane in tree shade during a Southern Hemisphere summer. The measurement of V_T was used instead of 'leaf area index' as the latter is a more difficult parameter to measure. In comparison, the V_T is easier to measure by a lay person. Consequently, the parameter V_T was used in the analysis in order to be more applicable to the general public. The shade ratios measured may not apply to other seasons of the year, however, the research has provided regression models to estimate the shade ratios for the summer at a sub-tropical site. The measurements were at ground level. Consequently, the irradiances measured in this research are not measurements of the UV exposures to humans, however, the research provides information on the factors influencing the UV irradiances in the visible shade area of a tree. Of the factors investigated, the tree V_T and C_H are the factors that have an influence on the UV in the tree shade with the other factors not having any significant effect. The UV irradiances in the tree shade are influenced by the atmospheric conditions. This has been addressed by taking the measurements through the summer for the range of atmospheric conditions encountered.

The shade ratios for erythemal UV ranged from 0.71 to 0.42, 0.54 to 0.29 and 0.63 to 0.41 for 9:00 EST, noon and 15:00 EST respectively for the V_T range of 0.4 to 1.0. Over the same V_T range, the shade ratios for UVA ranged from 0.61 to 0.28, 0.50 to 0.22 and 0.49 to 0.29 for the three times respectively. The erythemal UV in the tree shade decreased with the increase in the V_T with a marginally higher decrease in the UVA irradiances compared to the UV_{ery}. For a crop canopy, Grant (1991) found that the UV irradiances at the base of the canopy were reduced by a larger proportion compared to the reduction at the longer wavelengths of the PAR due to the higher canopy reflectance of the PAR. This is opposite for the single tree canopy employed in this research. For the single tree canopy, the influence of the larger proportion of Rayleigh scattering at the shorter wavelengths (Parsons et al., 1998) contributes to the higher relative reduction of the longer visible wavelengths compared to the UV wavelengths.

For the UV_{ery}, there was a drop of 35 to 46% in the mean shade ratio for the 0.8 to 1.0 V_T category compared to the mean shade ratio for the 0.4 to 0.59 V_T category. For the UVA waveband, there was a 41 to 56% drop for the same categories. For a given V_T category and time, the standard error in the mean of the shade ratios is less than 10% for UV_{ery} and less than 16% for the UVA. These standard errors and the standard errors in the respective irradiances for each tree shade are less than the change in the shade ratios with V_T. For each time and V_T category, all of the shade ratios for the UVA waveband are smaller. This is most likely due to the larger amount of scattering in the UVB (280 to 320 nm) waveband compared to the UVA waveband (Parsons et al., 1998). Additionally, the shade ratios at noon are less than the shade ratios in the morning and afternoon. The lower relative protection by the shade in the morning and afternoon may be due to the larger relative proportion of diffuse UV at the larger solar zenith angles (Blumthaler et al., 1994).

Conclusion

As a general guide for the public, trees with a heavier shade in the visible waveband and the canopy closer to the ground provide the better protection from UV exposure. Despite the protection provided by the tree shade, it is necessary to note that there was still significant UV irradiances in the tree shade with a maximum of 2.2 MED/h in the tree shade. Even for the trees from the highest V_T category an exposure of approximately 4 MED would be received for the latitude in this research on a cloud free summer day on a horizontal plane over a two hour period centred about solar noon.

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Table 1. Shade ratios at 9.00 EST, noon and 15.00 EST for each of the V_T ranges. The error is represented as the standard error of the mean. The angles in parentheses are the range of solar zenith angles over the summer for the respective times.

V_T	UV_{ery} shade ratios			UVA shade ratios		
	9.00 EST (30^o-54^o)	noon (4^o-21^o)	15.00 EST (36^o-52^o)	9.00 EST (30^o-54^o)	noon (4^o-21^o)	15.00 EST (36^o-52^o)
0.4-0.59	0.71 (SEM 0.05)	0.54 (SEM 0.04)	0.63 (SEM 0.06)	0.61 (SEM 0.06)	0.50 (SEM 0.06)	0.49 (SEM 0.08)
0.6-0.79	0.56 (SEM 0.03)	0.43 (SEM 0.02)	0.55 (SEM 0.03)	0.41 (SEM 0.03)	0.33 (SEM 0.02)	0.41 (SEM 0.03)
0.8–1.0	0.42 (SEM 0.02)	0.29 (SEM 0.02)	0.41 (SEM 0.01)	0.28 (SEM 0.02)	0.22 (SEM 0.01)	0.29 (SEM 0.01)

Table 2. The erythemal UV exposures for the two scenarios of full sun and tree shade for each category of V_T.

V_T	Erythemal UV (MED)	
	Scenario 1	Scenario 2
Full sun	33.4	13.3
0.4-0.59	19.3	7.3
0.6-0.79	15.3	5.7
0.8–1.0	11.1	4.0

Legends to Figures

Figure 1. The erythemal UV irradiances in units of MED/h at each point of a 1 m grid in the shadow of (a) a typical larger tree at 9:00 EST and (b) a typical smaller tree at noon. The X represents the location of the tree trunk and the lines are the approximate shadow outline.

Figure 2. The irradiances in the tree shade throughout the summer at the times of 9:00 EST, noon and 15:00 EST for (a) UV_{ery} and (b) UVA.

Figure 3. The erythemal UV on a horizontal plane for a mainly cloud free summer's day in (1) full sun and in tree shade for V_T of (2) 0.4 to 0.59, (3) 0.6 to 0.79 and (4) 0.8 to 1.

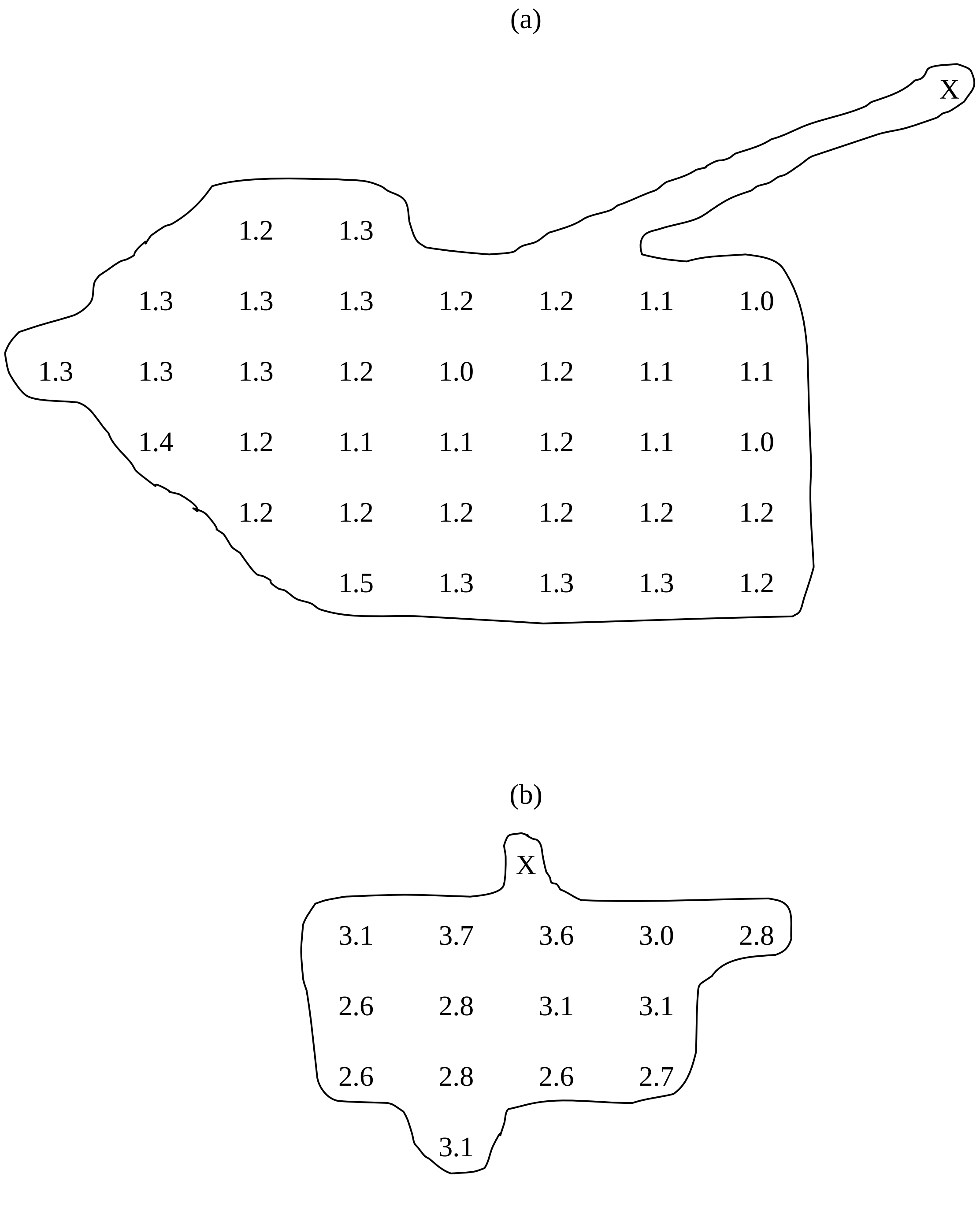
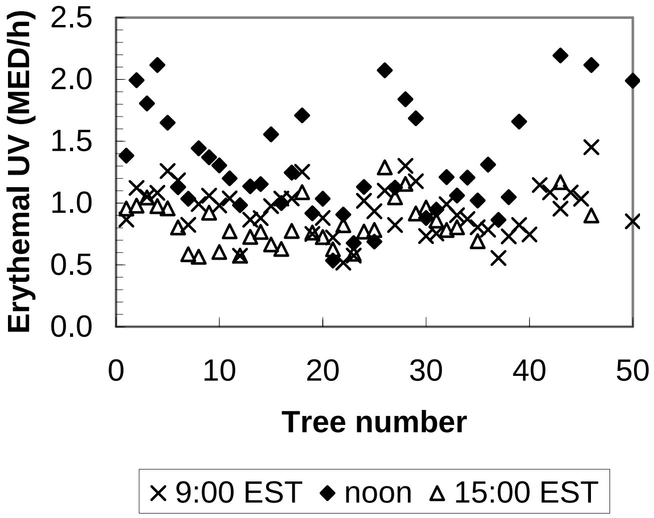

(a)
X
1.2 1.3
1.3 1.3 1.3 1.2 1.2 1.1 1.0
1.3 1.3 1.3 1.2 1.0 1.2 1.1 1.1
1.4 1.2 1.1 1.1 1.2 1.1 1.0
1.2 1.2 1.2 1.2 1.2 1.2
1.5 1.3 1.3 1.3 1.2
(b)
X
3.1 3.7 3.6 3.0 2.8
2.6 2.8 3.1 3.1
2.6 2.8 2.6 2.7
3.1

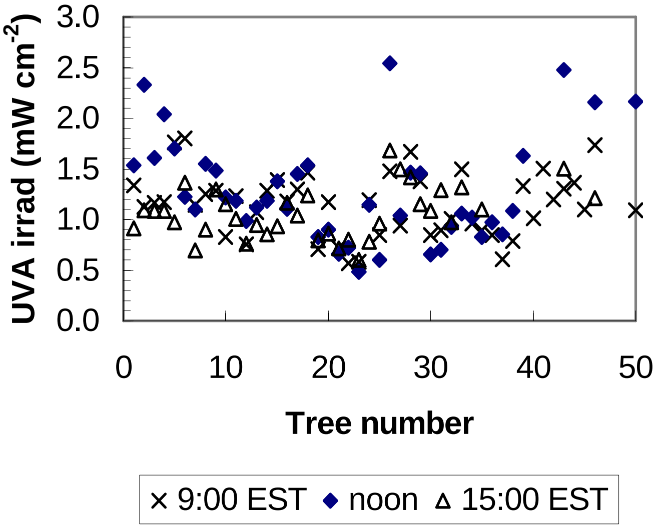
Figure 1.

(a)



Erythemal UV (MED/h)
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
Tree number
9:00 EST
noon
15:00 EST

(b)



UVA irrad (mW cm-2)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
Tree number
9:00 EST
noon
15:00 EST

Figure 2.

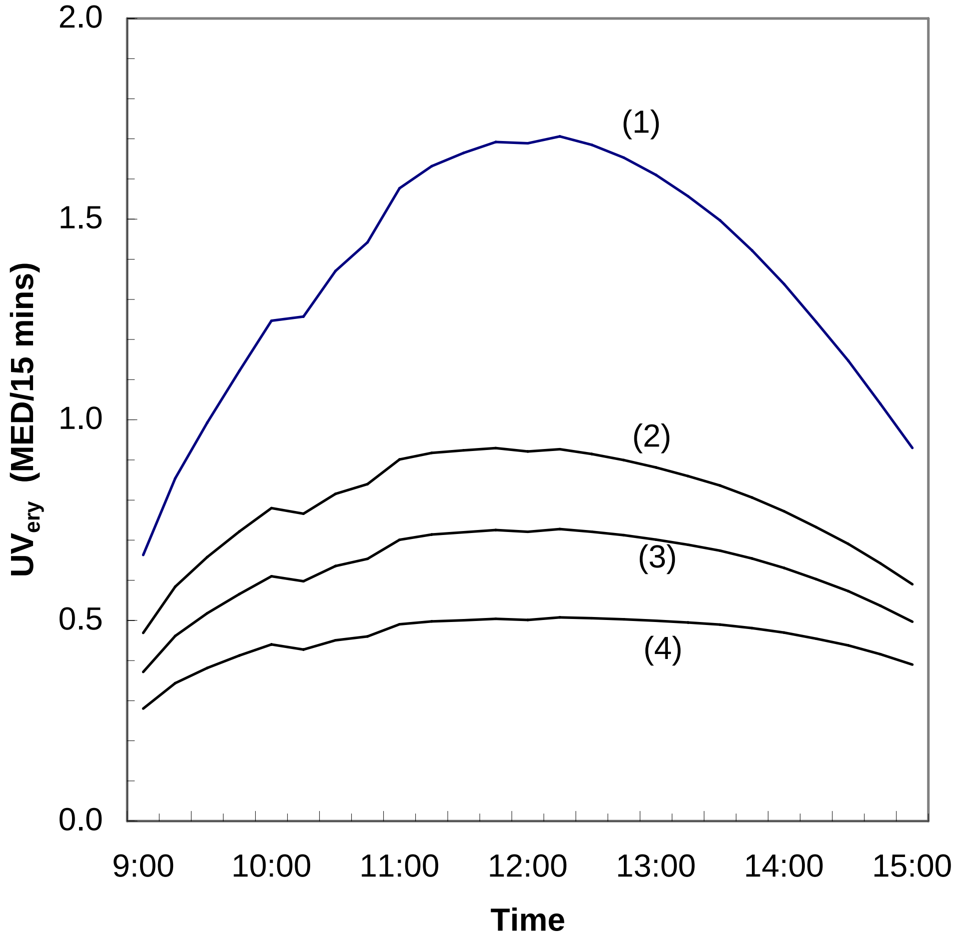

2.0
1.5
1.0
0.5
0.0
UV_{ery} (MED/15 mins)
(1)
(2)
(3)
(4)
9:00
10:00
11:00
12:00
13:00
14:00
15:00
Time

Figure 3.