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VITAMIN D EFFECTIVE ULTRAVIOLET WAVELENGTHS DUE TO SCATTERING IN SHADE

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Abstract
Solar UVB radiation (280-320nm) is an initiator of vitamin D_3 production in the human skin. While numerous studies have been conducted in relation to the biological impact of UV exposure in full sun, less research has investigated the irradiances in shade. The purpose of this study was to determine the levels of UV radiation in relation to vitamin D_3 induction with six commonly encountered shade environments for the larger solar zenith angles observed during autumn and winter. Spectral UV irradiance measurements were made under relatively clear sky conditions at a sub-tropical Southern Hemisphere site for six specific shade environments and solar zenith angle between 35^o to 60^o to investigate the biologically effective UV irradiances for pre-vitamin D_3 production. Data from this research indicates that pre-vitamin D_3 effective UV wavelengths in the shade were most significant for tree shade and a shade umbrella. Compared to that in full sun, pre-vitamin D_3 effective UV wavelengths were at levels of approximately 52 and 55% respectively, beneath the shade umbrella and in tree shade. UVB irradiance levels in the shade of a northern facing covered veranda and in a car with windows closed were significantly less than those beneath the shade umbrella, with levels of approximately 11 and 0% respectively of those in full sun. Shade is important as a UV minimisation strategy; however, it may also play an important role in providing the human body with adequate levels of UVB radiation for pre-vitamin D_3 production without experiencing the relatively higher levels of UVA irradiances present in full sun.

Keywords: Shade; Scattered UV; Vitamin D; UVB; UVA; action spectra

1. Introduction

Research has shown that exposures to solar UV radiation are beneficial for the human body and important in the production of pre-vitamin D_3, whereas excessive exposure to sunlight is known to cause erythema, skin aging, skin cancer and sun-related eye disorders [1,2].

Solar UV radiation is acknowledged as an initiator of the synthesis of vitamin D_3 for humans. UV radiation in the UVB (280 to 320 nm) portion of the solar spectrum photolyses 7-dehydrocholesterol in the human skin, to pre-vitamin D_3, which is then converted to vitamin D_3 by a heat induced process. After two separate hydroxylation's (first in the liver, then in the kidney) the active form of the vitamin (i.e. $1\alpha,25(OH)_2$-vitamin D_3) is produced [1,3,4]. One function of the active metabolite of vitamin D_3 in humans is to maintain extracellular fluid concentrations of calcium and phosphorous [5,6]; hence, it is important for the prevention of rickets in children and osteoporosis, osteomalacia, and fractures in the elderly [7].

The longer wavelength UVA (320 to 400 nm) radiation plays no part in the synthesis of pre-vitamin D_3 in humans, as is shown by its appropriate action spectrum shown in Figure 1 [4]. In this paper, this action spectrum will be referred to as the pre-vitamin D_3 action spectrum. Although, over exposure to these UVB wavelengths is known to cause skin damage, pre-vitamin D_3 synthesis occurs at sub-erythemal irradiances [4]. Research has shown that the UVB exposure provided to the full body that produces a significant increase in serum vitamin D_3 is 18 mJ/cm^2 [8]. Recommendations have been provided for the elderly to receive sub-erythemal exposures to the face, hands

and possibly the arms and legs at a frequency of 2-3 times/week [6]. A UV radiation model to predict the biologically effective exposure on a horizontal plane and a technique to calculate the subsequent exposure received by the human face has been previously described [9]. If there is over exposure to solar UV, Holick [6] states that over exposure to sunlight can regulate the total output of vitamin D_3 in the skin by causing the photodegradation of pre-vitamin D_3 through a thermal reaction.

There is a proportion of the solar UV present in shade due to scattered radiation [10,11]. Studies on the levels of UV observed in the shade of different shade environments (e.g. [12-16]) have shown that the relative proportions of UVA and UVB in the shade are significantly different to those in full sun. The relative proportions are generally decreased for UVA and increased for UVB. These differences are due to the phenomena of Rayleigh scattering ($\propto \frac{1}{\lambda^4}$) and Mie scattering ($\propto \frac{1}{\lambda}$) in the atmosphere, which causes greater scattering at the shorter UVB wavelengths compared to the longer wavelength UVA. Therefore, in the shade there is a higher relative proportion of the biologically effective wavelengths needed for pre-vitamin D_3 production in the body and less of the UVA irradiances compared to full sun.

The purpose of this study is to examine the levels of UV radiation in different shade environments and how these environments may affect the synthesis of pre-vitamin D_3. No research has measured the biologically effective UV for human pre-vitamin D_3 synthesis in the shade provided by public shade structures, the inside of cars and trees. This research compares the biologically effective UV for this process beneath four common shade structures, inside a car and in the shade of a tree with that of the global solar UV for relatively cloud free sky conditions and changing solar zenith angle. The months of March to August (southern hemisphere autumn and winter) were chosen, because, it is expected that there is a higher proportion of diffuse UV in the shade caused by the higher solar zenith angle. This study reports on spectral UV measurements only and not actual biological pre-vitamin D_3 formation.

2. Materials and Methods

2.1. Environments

The different environments employed in this research were located at the University of Southern Queensland (USQ), Toowoomba (27.5^{o}S), Australia. These particular environments were selected because of the regular use by the public and previous research [12,14,15] has shown that there were relatively high erythemal irradiances in these environments. The environments were as follows: a shade umbrella; a covered veranda; a covered sand pit; a covered walkway; a car; and tree shade. Details of the environments have been stated elsewhere by Turnbull and Parisi [12], Kimlin et al [14] and Parisi et al [17]. Brief details of the environments are:

1. The diameter of the shade umbrella was 1.8 m and a height at the apex of 2.1 m. The ground cover was dry grass with an albedo (albedo is defined as the ratio of reflected radiation to incident radiation) of approximately 0.04 and the UV transmission of the umbrella material was less than 1%;

2. The northern facing veranda covering was approximately 7.0 m long, 1.5 m wide from the building wall and the eaves were 2.5 m high. A number of trees are located near this site and therefore have some influence over the scattered UV levels in the shade;
3. The sand pit covering was 2.6 m in diameter, approximately 3.0 m high at the apex and 2.0 m high at the eaves. Trees, shrubs and a building are located near the shade structure. The albedo of the sand was approximately 0.1 and the erythemal UV transmission of the cover was 4.8%;
4. The height of the walkway was approximately 4.0 m, the depth 2.5 m, length 6.0 m, and with an east/west path;
5. The vehicle used was a Ford Falcon GLi station wagon. The window glass (with no additional tinting) in this vehicle is Pilkington DOT 298 M50 AS2, EZ-KOOL. The overall size of the vehicle is 4.8 m long, 1.7 m wide and 1.5 m high. This particular vehicle is a popular Australian family station wagon with the driver's seat on the right-hand side of the vehicle as vehicles in Australia travel on the left-hand side of the road;
6. The type of tree used was an isolated tree with a medium density canopy *Cinnamomum camphora*. The dimensions of the tree were: canopy width of 4.2 m; tree height of 6.4 m; average trunk diameter of 0.27 m and height to the first branch of 0.4 m.

2.2. Spectroradiometric measurements

A scanning spectroradiometer fitted with a 15 cm diameter-integrating sphere (model OL IS-640, Optronics Laboratories, Orlando, FL, USA) was employed. The integrating sphere can be orientated at any angle between pointing directly upwards and pointing directly downwards. For this research, the integrating sphere was 1.0 m above ground level. The spectroradiometer has a double holographic grating (1200 lines mm^{-1}) monochromator (model DH10, Jobin-Yvon, France) connected to a R212 photomultiplier tube (Hamamatsu Co., Japan) temperature stabilized to $15.0 \pm 0.5^{o}C$.

Prior to each series of scans, the spectroradiometer was wavelength calibrated against UV mercury spectral lines and absolute irradiance calibrated against a quartz tungsten halogen lamp (250 W) operated at 9.500 ± 0.005 A D.C. and with a calibration traceable to the Australian National Standards Laboratory at the CSIRO, Lindfield**.** The current was supplied to this secondary standard lamp from a regulated power supply (model PD36 20AD, Kenwood). The error associated with the spectroradiometer and the irradiance calibration lamp is of the order of ±10%.

The solar UV spectrum and UV spectrum in the shade of the different environments were recorded with the spectroradiometer for clear sky conditions. The spectrum was scanned from 280 to 400 nm in 1 nm increments in the approximate centre of the visible shadow cast by the shade structure. Each scan took approximately 45 s to complete and the solar zenith angle (SZA) did not change significantly over this period. The measuring sequence was: measure the UV spectrum in the sun on a horizontal plane (with the entrance aperture of the integrating sphere directed upwards); measure the UV in the shade; and then measure the UV spectrum in the sun

a second time. The time difference between the sun and shade measurements was as short as possible, typically of the order of 5 minutes.

The spectral measurements for the vehicle were undertaken in the driver's seat of the northern facing vehicle, as this site is occupied by the driver of the vehicle at all times whilst the vehicle is in use. The measurement planes were a vertical plane, horizontal plane and on a plane 45^{o} to the vertical for each of the shade environments.

2.3. Biologically effective UV

To calculate the biologically effective UV irradiance in the shade, UVBE, the spectral irradiance, S(λ), may be weighted with the action spectrum for a particular biological process, A(λ), according to the following equation:

$$UVBE = \int_{UV} S(\lambda)A(\lambda)d\lambda \qquad (1)$$

For this research, the pre-vitamin D_3 action spectrum has been employed (see Figure 1). The UV wavelengths effective in the formation of pre-vitamin D_3 range from 290 to 315 nm.

3. Results

3.1. UV irradiances

Spectral irradiances taken beneath the shade umbrella at a cloud free time on 12 July, for a SZA of approximately 63^{o} are shown in Figure 2a for a relatively cloud free period. The unweighted spectral irradiances shown in Figure 2 illustrate the variation in scattering for the UVB (280 to 320 nm) and UVA (320 to 400 nm) wavebands when comparing full sun to shade, with higher proportionate levels of UVB in the shade than UVA. The spectral irradiances, in Figure 2a, show that there is an approximate 19% reduction in integrated UVB levels and a reduction of approximately 38% for integrated UVA in the shade compared to full sun. This is due to the greater scattering of the shorter UVB wavelengths. All spectral irradiance calculations are from 290 – 400 nm due to the high levels of noise in the spectral irradiances below 290 nm. As a comparison, the UV spectra under the covered walkway and corresponding full sun spectra are in Figure 2b. In this case, the relative reduction in the solar UVA in the shade is higher.

Table 1 shows the maximum of the measured irradiance levels in the full sun and shade for UVB and UVA and the subsequent ratios of shade to full sun irradiances for the different shade environments. The highest UVB irradiances of 1.28 W/m^2 and 1.11 W/m^2 were observed for the shade umbrella and tree shade, respectively. Whereas the lowest UVB levels of 0.22 W/m^2 and 0.0 W/m^2 were observed in the shade of the veranda and in the car with windows closed, respectively. UVB levels in the car with windows closed were zero due to complete attenuation by the glass of the windows and windshield. The sand pit, covered walkway and car (with windows open) received similar irradiances of UVB in the shade of 0.47 W/m^2, 0.48 W/m^2 and 0.43 W/m^2, respectively. The ratios of the shade to sun irradiances are lower for the UVA waveband for each of the shade environments, with the exception of the car with the windows closed.

3.2. Biologically effective UV

Spectral irradiances taken beneath the shade umbrella on 12 July, for a SZA of approximately 63^o (Figure 2a and 2b), have been weighted with the action spectrum for pre-vitamin D_3 (Figure 1) and are shown in Figure 2c and 2d. The weighted spectral irradiances, in Figure 2c and 2d, show that there is only an approximate 20% reduction in total biologically effective UV levels for pre-vitamin D_3 in the shade of the umbrella compared to full sun. This reasonably low reduction is due to the high relative proportion of scattered UVB in the shade of the umbrella. In comparison, the UVBE is lower for the shade of the walkway.

Table 2 shows the full sun and shade irradiance levels for the biologically effective UV related to pre-vitamin D_3. From this it can be seen that the shade umbrella and tree shade had the highest levels of 0.15 W/m^2 and 0.13 W/m^2 respectively, which was expected due to the levels of UVB observed in Table 1. The lowest levels of 0.03 W/m^2 and 0.0 W/m^2 were observed for the veranda and car with windows closed, respectively. Measurements inside the car with windows closed showed no UVBE related to pre-vitamin D_3 due to negligible levels of UVB transmitted through the window glass. The ratios of the shade to sun UVBE irradiances are similar to the corresponding ratios for the UVB waveband. This is due to the response of the pre-vitamin D_3 action spectrum being only in the UVB waveband.

The pre-vitamin D_3 irradiances for each of the shade structures have been averaged for each of the SZA ranges 30-39^o, 40-49^o, 50-59^o and 60-69^o. They are shown for the four SZA ranges in Figure 3. For the cases where there is no data plotted for a particular SZA range, there is no data available. The error bars are ±10% which is the error estimated to be associated with the spectroradiometer. With the exception of the SZA range 30-39^o for the covered walkway, the maximum UVBE irradiance in the shade occurs for the SZA range of 50-59^o.The UVBE irradiance in the shade is a balance between the irradiance in the full sun and the amount of scattering which increases with the SZA.

The ratios of the pre-vitamin D_3 irradiances in the shade to the corresponding ones in the sun for each of the shade environments as a function of SZA are provided in Figure 4. The x-axis error bars are shown only for one of the data series in each plot, however they apply to each of the data points. Each data point is the average of the values over the 10 degree SZA range and it is plotted at the mid point of the range. The x error bars show the 10 degree SZA range corresponding to each data point. For each of the shade environments, the ratios are higher at the higher SZA.

4. Discussion

Solar UVB radiation is an initiator of pre-vitamin D_3 production in the human body. While numerous studies have been conducted in relation to the biologically damaging UV irradiances for the solar zenith angles observed during summer, less is known about UV levels recorded in the shade during the autumn and winter months. During winter, the UV in full sun at high latitudes is not sufficient for pre-vitamin D_3 synthesis [6]. In comparison, at the lower latitudes due to the higher irradiances, an MED (minimal erythemal dose) can be received in a short period. For example, in

tree shade an MED can be received in approximately 30 mins during summer [15]. From this research it can be concluded that some shade environments at sub-tropical locations, for example shade umbrellas and tree shade may perhaps be useful for irradiating the human skin with the sub-erythemal exposures to UV containing the specific wavelengths needed for the synthesis of pre-vitamin D_3. At the same time, the higher relative proportions of the UVA wavelengths present in shade are reduced. This is a significant finding for the aged population, which is at a greater risk of osteoporosis, osteomalacia, and fractures due to a number of factors that may include a change in sun exposure habits. Shade is important as a UV minimisation strategy; however at lower latitudes it may also play an important role in providing the human body with adequate levels of UVB radiation for vitamin D_3 production without experiencing the high levels of UVA observed in full sun. However, the levels of scattered UVB observed in the shade will vary with a change in latitude; for example, an increase in latitude will be accompanied by an increase in the volume of scattering atmospheric particles the UVB radiation has to travel through thereby reducing scattered UVB levels.

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Figure Captions

Figure 1. The pre-vitamin D_3 (right axis) and erythemal [18] (left axis) action spectra.

Figure 2. Full sun and shade spectral irradiances for: (a) the shade umbrella at a SZA of 63^o taken on 12 July 2001; and (b) the covered walkway at a SZA of 49^o taken on 15 July 2001. Full sun and shade spectral irradiances weighted with the pre-vitamin D_3 action spectrum for the (c) shade umbrella and (d) covered walkway.

Figure 3. The pre-vitamin D_3 effective irradiances for the four different solar zenith angle ranges of $30\text{-}39^o$, $40\text{-}49^o$, $50\text{-}59^o$ and $60\text{-}69^o$ for each of the shade environments.

Figure 4. The ratios of the pre-vitamin D_3 irradiances in the shade to the corresponding ones in the sun for each of the shade environments as a function of solar zenith angle. The error bars shown apply to each of the data points as they represent a 10^o variation in solar zenith angle (for example $30\text{-}40^o$, $40\text{-}50^o$, $50\text{-}60^o$ and $60\text{-}70^o$).

Table 1. Summary of average UVB (280 to 320 nm) and UVA (320 to 400 nm) levels in the full sun and in the shade for the different environments (n ≥ 2). Standard deviations are provided in the parentheses.

	UVB (W/m^2)			UVA (W/m^2)		
	Full Sun	Shade	Ratio	Full Sun	Shade	Ratio
Shade Umbrella	2.53 (0.61)	1.28 (0.53)	0.52 (0.18)	44.73 (8.87)	15.17 (5.17)	0.35 (0.12)
Covered Veranda	2.37 (1.06)	0.22 (0.03)	0.11 (0.05)	38.56 (8.45)	2.93 (0.78)	0.08 (0.03)
Sand Pit	2.40 (0.96)	0.47 (0.25)	0.22 (0.13)	44.00 (16.6)	5.14 (2.91)	0.13 (0.07)
Covered Walkway	1.71 (1.12)	0.48 (0.05)	0.37 (0.21)	34.08 (20.4)	5.37 (0.87)	0.21 (0.12)
Tree Shade	2.13 (0.51)	1.11 (0.09)	0.53 (0.09)	35.74 (4.86)	13.03 (0.99)	0.37 (0.02)
Car - open	1.60 (0.16)	0.43 (0.00)	0.27 (0.00)	34.33 (3.43)	7.86 (0.00)	0.23 (0.00)
Car - closed	1.26 (0.12)	0.00 (0.00)	0.00 (0.00)	28.50 (2.90)	2.02 (0.00)	0.07 (0.00)

Table 2. Summary of the average UVBE irradiances related to pre-vitamin D_3 formation for the different shade environments ($n \geq 2$). Standard deviations are provided in the parentheses.

	Pre-vitamin D_3 (W/m^2)		
	Full Sun	Shade	Ratio
Shade Umbrella	0.30 (0.09)	0.15 (0.08)	0.52 (0.19)
Covered Veranda	0.33 (0.23)	0.03 (0.01)	0.11 (0.04)
Sand Pit	0.29 (0.11)	0.06 (0.03)	0.22 (0.15)
Covered Walkway	0.21 (0.13)	0.06 (0.01)	0.42 (0.27)
Tree Shade	0.23 (0.08)	0.13 (0.03)	0.55 (0.06)
Car - open	0.15 (0.03)	0.04 (0.00)	0.26 (0.00)
Car - closed	0.12 (0.03)	0.00 (0.00)	0.00 (0.00)

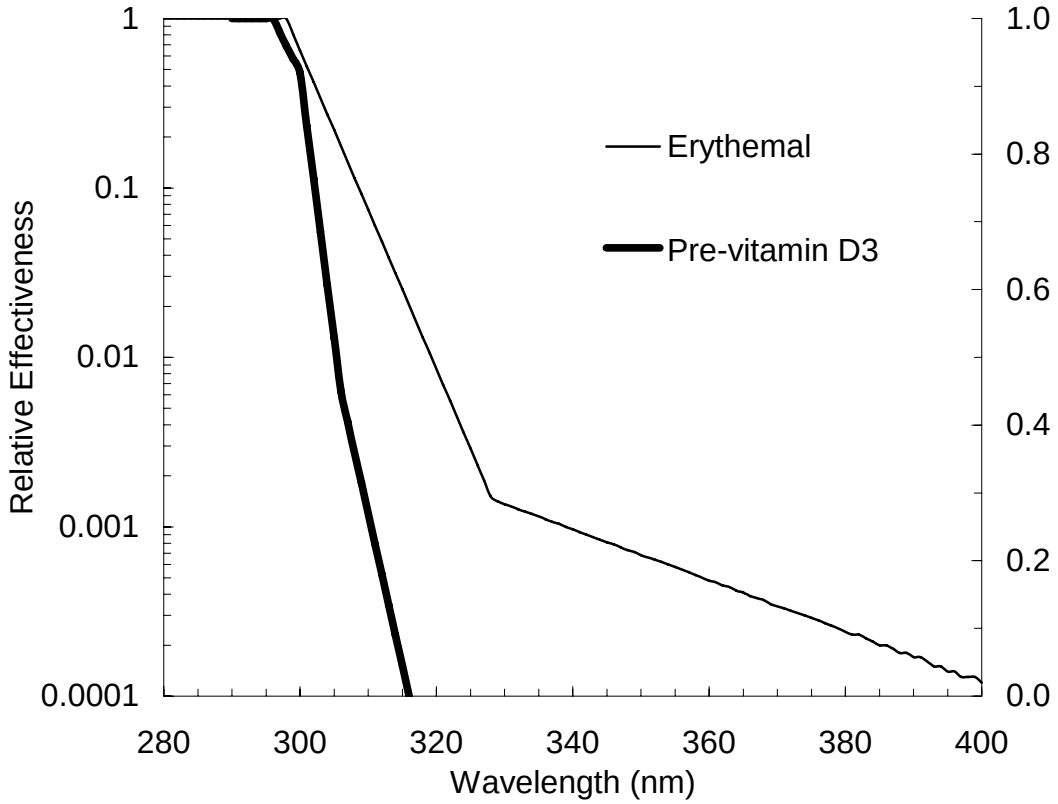

1
0.1
0.01
0.001
0.0001
Relative Effectiveness
1.0
0.8
0.6
0.4
0.2
0.0
Erythemal
Pre-vitamin D3
280
300
320
340
360
380
400
Wavelength (nm)

Figure 1.

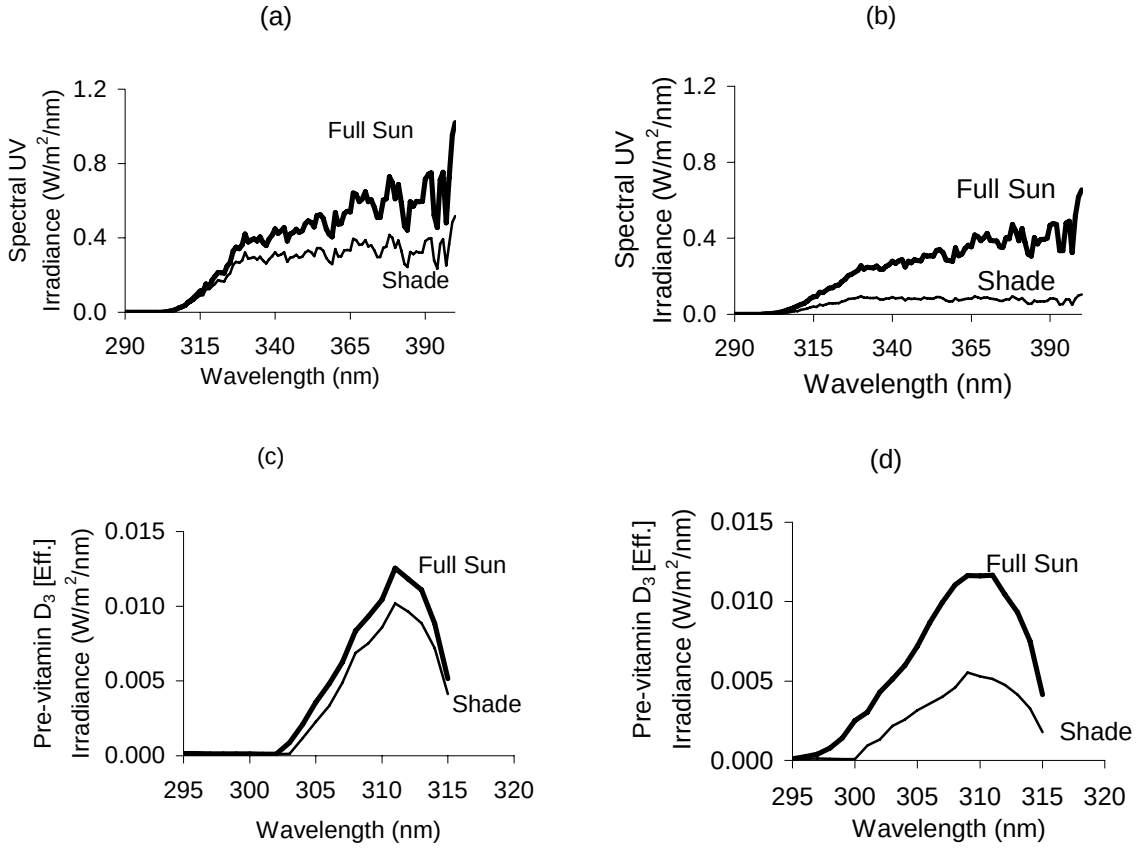

(a)
(b)
(c)
(d)
Spectral UV Irradiance (W/m2/nm)
Pre-vitamin D3 [Eff.] Irradiance (W/m2/nm)
Full Sun
Shade
Wavelength (nm)
1.2
0.8
0.4
0.0
0.015
0.010
0.005
0.000
290
295
300
305
310
315
320
340
365
390

Figure 2.

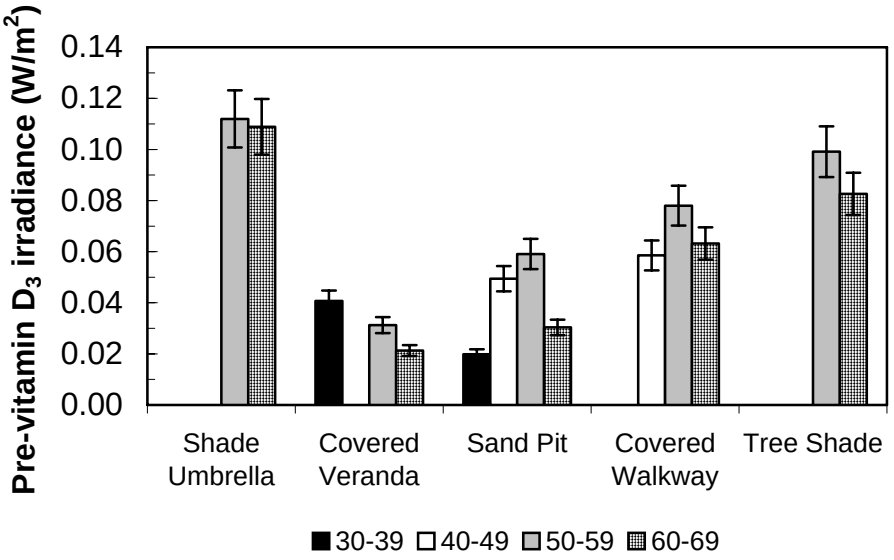
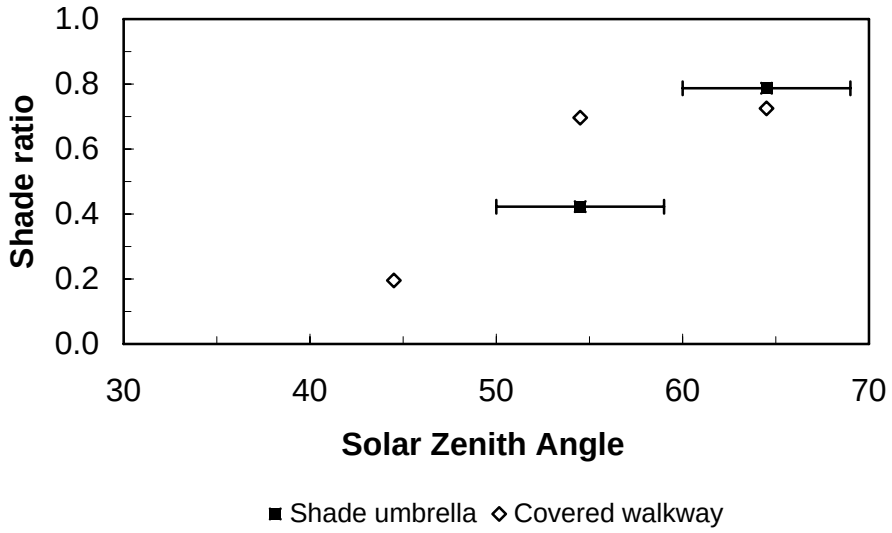

Pre-vitamin D3 irradiance (W/m2)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Shade Umbrella
Covered Veranda
Sand Pit
Covered Walkway
Tree Shade
30-39
40-49
50-59
60-69

Figure 3.


1.0
0.8
0.6
0.4
0.2
0.0
Shade ratio
30
40
50
60
70
Solar Zenith Angle
Shade umbrella
Covered walkway

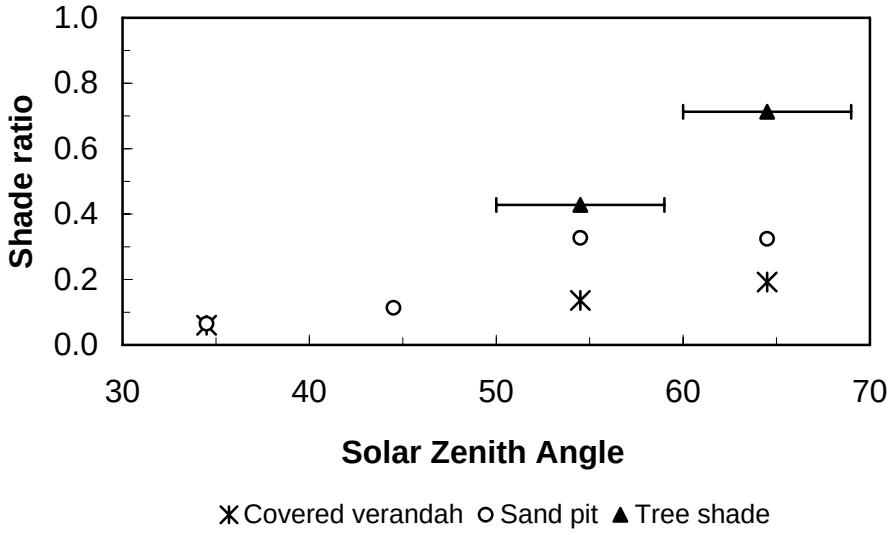

1.0
0.8
0.6
0.4
0.2
0.0
Shade ratio
30
40
50
60
70
Solar Zenith Angle
Covered verandah
Sand pit
Tree shade

Figure 4.