ESTIMATE OF ANNUAL ULTRAVIOLET-A EXPOSURES IN CARS IN AUSTRALIA

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Short Title: Annual UVA Exposures in a Car

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ABSTRACT

The annual solar UVA exposures in four cars were estimated by measuring the UVA irradiances in the vehicles in each of the four seasons and in the morning, noon and afternoon. For the cars with untinted windows the maximum UVA irradiances in cars do not necessarily occur at noon when the outside irradiances are at their highest. Additionally, they do not occur in summer. The range of annual UVA exposures between 9:00 and 15:00 EST is 1918 to 6177 J cm^{-2} for the cars without the after market window tint. These correspond to 5% to 17% of the ambient UVA on a horizontal plane over the same period outside the cars. The range is for the different sites in the car. For the car with the aftermarket window tint, the range of the annual UVA exposures were 489 to 2969 J cm^{-2} or 1% to 8% of the ambient UVA.

INTRODUCTION

With the publicity and education campaigns on sun exposure, the general population may be aware of the dangers of ultraviolet (UV) radiation at the beach, sportsground or in the garden and take appropriate protective measures. However, no guidelines exist for the reduction of exposures to filtered UV and the general population may underestimate or not be aware of the skin cancer risks and as a result not take any protective measures. Terrestrial UV is comprised of UVA (320-400nm) and UVB (280-320nm) radiation. Transparent screens such as glass and automobile windscreens and window glass act as a barrier to some of the shorter solar UV wavelengths [1,2] and as a result can provide some UV protection for humans. Although filtered solar UV radiation is predominantly in the UVA band, its harmful effect is not to be underestimated because of the high level of irradiance of the UVA compared to the UVB. UVA wavelengths have been found to contribute to skin damage [3]. Additionally, the erythemal action spectrum [4] extends into the UVA wavelengths. Anders et al. [5] re-evaluated the erythemal action spectrum with a tunable dye laser and found a second maximum of lower relative response than the first maximum at 298 nm in the UVA waveband at 362 nm. Recent research [6] has shown that repetitive exposures to relatively low UVA exposures have a damaging cumulative effect on human tissue and can produce skin alterations indicative of early tissue damage.

Research has measured the UV transmission of polycarbonates and shadecloth [7] and in the field for glass and greenhouses [2,8,9]. Previous research has measured the UV transmission of different types of vehicle window tints, glass and windscreens [1,10]. These UV transmission measurements in the laboratory have been extended by researchers measuring the UV in cars in the field. Parisi and Wong [11] measured the personal UV exposures in two cars in winter. Kimlin and Parisi [12] measured the solar UV spectrum in two cars in winter and the UVA irradiances in four types of cars in winter. These provide the UV exposures at one point in time. This may vary throughout a year due to changes in the solar zenith angle and the relative ratios of the direct and diffuse UV components. The annual exposure to unfiltered solar UVA by the British population has been estimated [13]. The research in this paper extends the previous research to provide an estimate of the annual exposure to filtered UV in cars in Australia.

MATERIALS AND METHODS

Estimate of Annual UVA in Cars

The annual UVA in a car between the hours of 09:00 and 15:00 Australian Eastern Standard Time (EST) was estimated for a sub-tropical Southern Hemisphere latitude. These hours were selected as they span the period of the day with the highest UV irradiances. This is significant as they are the hours of a business day and most workers are using their cars within these hours, for example, travelling salespeople. The calculation was performed by firstly estimating the monthly UV exposures in a car and these summed to provide the annual UV exposures in a car. The monthly UV exposure to each site in the car, $UV_i(S)$, for the i th month, was estimated by employing an exposure model previously described [14-17] as follows:

$$UV_i(S) = N_i \sum_{H=9}^{15} ER_i(S).AE_i(H) \qquad \text{J cm}^{-2} \tag{1}$$

where $AE_i(H)$ is the ambient UVA exposures outside the car on an unshaded horizontal plane averaged over the month for each 15 minute period between 09:00 and 15:00 EST, N_i is the number of days in the i th month and $ER_i(S)$ is the exposure ratio for each site during the i th month. For each site the exposure ratio is defined as the ratio of the UVA irradiance to each site compared to the UVA irradiance on an unshaded horizontal plane outside the car. This definition of the exposure ratio as the ratio of the exposure to a human body site divided by the exposure on a horizontal plane has been previously employed by other researchers (for example, Diffey [15]).

Selection of Cars

Four late model cars that are available in Australia were selected for this research. A car was selected from the small and family size class respectively and a car with aftermarket window tint applied and a car of the same make and model without the window tint were selected. The small car was a Holden Barina, 3 door hatchback, 1998 model (window glass: Sekurit E9) and the family size car was a Holden VT Commodore sedan, 1998 model (window glass: Pilkington DOT 298 M40 AS2). These will be referred to as cars S (small) and F (family) respectively. To investigate the effect of after market window tinting, two Ford Falcon GLi station wagons, 1997 model (window glass: Pilkington DOT 298 M50 AS2, EZ-KOOL) were employed. The first vehicle had an aftermarket window tint film (window Tint: Solace T35 V.L.T) applied to all windows (except the windscreen as it is illegal in Australia to apply aftermarket tint to the windscreen) and the second had no aftermarket window tint. These two cars will be referred to as cars FT and FU respectively.

UV Measurements in Cars

In order to calculate the exposure ratios, the transmitted UVA irradiances in each of the four cars were measured in the grounds of the campus of the University of Southern Queensland, Toowoomba (27.5 °S), Australia with a meter (model 3D, V2.0, Solar Light Co., Philadelphia, USA) fitted with a broadband UVA detector and an erythemal UV [4] detector. The UVA detector has a peak response at 355 to 365 nm and the response has dropped to 50% of the peak response at 327 nm and 382 nm. The two detectors were calibrated against a calibrated spectroradiometer with calibration traceable to the Australian standard lamp at the National Measurement Laboratory, Lindfield, Australia. The calibration was undertaken each season for the solar spectrum in an unshaded, open field between 09:00 EST and noon on a relatively cloud free day. A series of solar UV spectra were measured between these times with the spectroradiometer while concurrently measuring the erythemal UV and UVA with the detector. The spectra weighted with the erythemal action spectrum [(4)] and summed over the UV waveband were employed to calibrate the erythemal UV detector and the unweighted spectra summed between 320 and 400 nm were utilized to calibrate the UVA detector.

The area selected for the research was an unshaded, open field with an unobscured field of view. The UVA irradiances were measured at sites in the vehicles with the detector surface parallel to the side and rear windows and windscreen and with the detector aligned normal to the horizontal in each of the front and rear seats and at the steering wheel as employed in previous research [(12)]. All of the windows were fully wound up and all the doors closed. The irradiances in each of the seats were measured on a plane 20 cm above the seat. The sites on the seats were selected to mimic the position of the thighs of occupants wearing shorts in the seats and the site on the steering wheel was to mimic the hands of the driver on the steering wheel. The arms and shoulders on the window sides were represented by the sites against the side windows and the backs of the necks of rear passengers were approximated by the rear window sites. These sites are shown schematically in Figure 1(a), with the sites measured on a horizontal plane shown in bold and the others measured normal to the window glass and windscreen. In Australian cars, the steering wheel is on the right hand side. The UVA irradiances at each site were measured between 08:45 and 9:15 EST, 11:45 and 12:15 EST and 14:45 and 15:15 EST. These three time periods will be referred to as 09:00 EST, noon and 15:00 EST in the following.

The irradiances were measured at each site with each car in each of four orientations with the front of the car facing north, south, east and west respectively. This was done to simulate, to a first approximation, the different orientations that a car will have during a trip. For each orientation, the ambient UVA irradiances and the ambient erythemal irradiances outside the car were measured. All of the irradiances for the four orientations were averaged to produce an irradiance at each site in each car for each of the three measurement times. The irradiances at each site in each car and the ambient irradiances outside the cars were linearly interpolated between the three measurement times to provide, to a first approximation, the cumulative UVA exposures between 09:00 and 15:00 EST in each car. The exposure ratios for each of the sites were calculated as the ratio of the exposure between 09:00 and 15:00 EST to each site in each car and the ambient UVA exposure outside the cars.

The exposure ratios may change with time of year due to changes in the optical pathlength through the window glass and changes in the ratio of the diffuse UV to total UV. Consequently, the exposure ratios were measured for each of the four cars in winter (August, 1998), spring (October, 1998), summer (December – February, 1998/99) and autumn (May, 1999). The cloud conditions varied between clear sky and seven eighths of the sky dome covered in cloud as determined by an observer. Linear interpolation was used to provide, to a first approximation, the exposure ratios for the intervening months. The only exception was the car S that was unavailable in autumn 1999. For this car, the autumn ER values were obtained by interpolation between the summer and winter values.

Ambient UVA Exposures

A broadband UVA meter permanently mounted outdoors was required to provide the ambient UVA irradiances for the year in Equation (1). As this instrument was not available, the ambient UVA exposures have been obtained by scaling the erythemal UV exposures measured with an erythemal UV Biometer (model 501, Solar Light Co., Philadelphia, USA). This instrument was permanently mounted on a horizontal unshaded plane on the roof of a building at the University of Southern Queensland. The Biometer was calibrated each season against the calibrated spectroradiometer. The Biometer was calibrated each season on a relatively cloud free day between 09:00 EST and noon. A series of scans of the solar UV spectrum were recorded between these times and the UV spectrum weighted with the erythemal action spectrum [(4)], summed over the UV waveband and compared to concurrent measurements with the UV Biometer for calibration.

The Biometer provides the erythemal UV in 15 minute intervals. The Biometer data was averaged over each respective month for each 15 minute interval. The erythemal UV at 09:00 EST, noon and 15:00 EST and at each season were scaled by the ratio of the ambient UVA to erythemal UV irradiances as measured outside the cars with the hand held detector, in the previous section, to estimate the UVA irradiances in each season at each of the three times. For the intermediate times, the UVA to erythemal UV ratio was interpolated between the three measurement times and between the intermediate months and the erythemal UV scaled by the interpolated ratios. The standard error of the mean of the ratios at each of the times in each season for all the cars was calculated and the standard error averaged over all the seasons was 16%. These estimated UVA irradiances were applied in Equation (1).

RESULTS

UVA Irradiances

The UVA irradiances in summer for car FU parked in a north direction are shown in Figure 1 for 09:00 EST and noon. For this orientation, the highest irradiances of 0.7 mW cm^{-2} occur at the window sites on the eastern side in the morning instead of at noon. The ambient UVA irradiances on a horizontal plane outside the car were 3.0 and 4.2 mW cm^{-2} for 09:00 EST and noon respectively. The irradiances in the car are approximately twice those at noon on the eastern side windows for the same orientation. The azimuth and zenith angle of the sun in the morning means that the irradiance is predominantly through the eastern side windows of the car. For comparison, the UVA irradiances in car FT at noon with the front of the car facing north are provided in Figure 1(c). The UVA irradiances outside the car in this case were 4.4 mW cm^{-2}. The effect of the window tint is to reduce the irradiances at the side and rear windows and the seats to 0.1 mW cm^{-2} compared to the irradiances in car FU at noon. In Australia, no window tinting can be legally applied to the windscreen. Consequently, the irradiances through the front windscreen and to the steering wheel site are not influenced significantly by the tinting to the side and rear windows.

The UVA irradiances measured in the four cars at 09:00 EST, noon and 15:00 EST in the four seasons are shown in Figure 2. The UVA irradiance plotted for each of the times in each season for each car is the average of the irradiances measured with each car in the four orientations. The largest range of irradiances is for the side window sites and the rear window sites. The highest irradiance is approximately 1.0 mW cm^{-2}. The irradiances for the windscreen and steering wheel sites are all less than 0.4 mW cm^{-2} except for one set of data. This set corresponds to the measurement on a summer day for car S when the ambient UVA irradiances were higher than that on the other measurement days.

For each of the sites, the UVA irradiances averaged over the four orientations have been interpolated between the three measurement times to provide the UVA exposures for the six hour period. These are provided for car F in Table 1 for each of the four seasons. The highest exposure in the car occurred in spring rather than in summer. This is most likely due to the lower solar zenith angle in summer resulting in less irradiances through the glass area of the cars.

UVA Exposure Ratios

The UVA exposure ratios for each of the cars are provided in Figure 3 for winter, spring, summer and autumn. The only exception is the ER for car S in autumn. This could not be measured due to the unavailability of the car. Calculation of the exposure ratios takes into account variations in the UVA irradiances outside the car due to atmospheric conditions. A seasonal variation is visible in the ER values between winter and summer. In winter, the exposure ratios are higher for cars S, F and FU for the sites normal to the side and rear windows, namely, LFPW, RFDW, RRDW, LRPW, LRW and RRW. For these sites, the highest ER is 0.33 in winter. In comparison, the ER for the sites on the four seats, namely, LFPS, RFDS, RRS and LRS, are lower with the lowest value being 0.034. The reason is that these last ER's are measured on a horizontal plane and on the car seats. On the car FT, the effect of the window tint on the side and rear windows was to reduce the ER to below 0.05 for all of the seat, side and rear window sites. The values of the ER for the two sites against the windscreen (LPW and RDW) and the site on the steering wheel (SW) that received the majority of the UVA through the windscreen were between 0.04 and 0.12 for all four cars. These exposure ratios were not influenced by the window tinting or type of car.

The ER values for summer do not show the variation between the sites on a horizontal plane and the sites with the detector surface parallel to the window that was measured in winter. The highest ER value in summer was 0.14. The most likely reason for the small variation and the smaller ER is the lower solar zenith angles in summer. This results in additional shading by the roof of the car, longer optical pathlength through the glass and the sun angle is higher with respect to the normal to the glass.

Each of the sites in the cars has been grouped into four zones according to similar exposure ratios. The zones are Front (LPW, RDW and SW), Sides (RFDW, LFPW, RRDW and LRPW), Seats (RFDS, LFPS, RRS and LRS) and Rear (LRW and RRW). The exposure ratios for the sites in each of the zones have been averaged for each car in each season to produce the exposure ratios in Table 2. The uncertainty is represented as the standard error in the mean.

Estimate of Annual UV in Cars

The monthly UVA exposure between 09:00 and 15:00 EST to each zone in the four cars has been estimated with Equation (1) and the monthly exposures presented in Figure 4 for the Front and Seat zones. The seasonal variation from winter to summer is seen for the Front zone for all four cars. For the Seat zone, the effect of the window tint on car FT is to lower the UVA exposures throughout all of the months of the year. For the remaining three cars, the highest exposure occurs in March for the Seats zone rather than in summer, despite the higher UVA irradiances in December. This is due to the lower ER in December for the Seat zone.

The estimates of the annual UVA exposures between 09:00 and 15:00 EST to each zone of each car are provided in Table 3. The beneficial influence of the window tint is seen on car FT with the reduction of the UVA exposures to the Side, Seats and Rear zones. However, there is no significant reduction in the UVA irradiances in car FT for the Front zone. The reduction is largest for the Sides and Rear zones with a reduction by a factor of approximately 11 to 12 compared to a reduction by a factor of approximately 5 for the Seats zone. The probable reason for the difference in the reduction factor is that for the Sides and Rear zones, the irradiances were measured against the window glass with the contribution to the UVA exposures from the scattered UVA through the untinted front windscreen being minimal. In comparison for the Seats zone, there may be a contribution to the exposures from the scattered UVA through the windscreen.

DISCUSSION

This paper has presented for a sub tropical Southern Hemisphere latitude, the temporal variation with season of the UVA irradiances in a small and a family size car and in a family size car with tinted windows and untinted windows along with the spatial variation of the irradiances in each of the four cars. The irradiances were measured with the windows wound up and all the doors closed to allow measurement of the UVA irradiances filtered through the window and windscreen glass. This was done as many vehicles in Australia drive with the windows up and the air conditioner on due to the high ambient air temperatures. For the cars with untinted windows the maximum UVA irradiances in cars do not necessarily occur at noon as expected when the outside irradiances are at their highest. Additionally, they do not occur in summer. Instead for some orientations in the cars, they may occur at the larger solar zenith angles. This corresponds to a similar result for erythemal UV in greenhouses [(8)]. Additionally, the maximum exposures do not necessarily occur in summer.

The research paper has provided quantitative estimates of the UVA exposures at sites in four different zones inside cars in Australia corresponding to the side windows, seats, rear windows and windscreen and steering wheel. The spectral transmission of windshields of cars in other countries have been provided elsewhere [(18)], with the UVA below 380 nm blocked. The spectral transmission for the side windows of the FU car [(12)] shows that this glass blocks UV wavelengths below 340 nm. For car FT, the tinted side window glass blocked below approximately 380 nm. Consequently, the measured UVA exposures for car FU are more biologically damaging compared to those for car FT. This paper has made no attempt to weight the irradiances in the car with any action spectrum.

This is a pilot study considering the broad band irradiances within cars over a year. Solar spectral data and biologically weighted irradiances in cars have been previously reported for one time of the year [12]. However, further research may develop to measure the biologically weighted irradiances within cars over longer time periods in all seasons of the year.

The range of annual UVA exposures is 1918 to 6177 J cm^{-2} for the cars without the after market window tint. These correspond to 5% to 17% of the ambient UVA exposures on a horizontal plane over the same period outside the cars. For the car with the aftermarket window tint, the range of the annual UVA exposures were 489 to 2969 J cm^{-2} or 1% to 8% of the ambient UVA. These exposures are for continual exposure between 09:00 and 15:00 EST every day of the year. No attempt was made to take into account the activity index of the passengers or drivers as the aim was to measure the UVA exposures in the car. The personal exposures to humans will be lower if the activity index of the drivers who may spend less time of the day or less number of the days of the year in cars is taken into account. As a comparison to the exposures estimated in this research, Diffey [13] estimated an annual exposure to indoor workers in Britain during their outdoor activities of 1500 J cm^{-2} to unfiltered solar UVA. This paper provides a quantitative insight into the UVA exposures received in cars. Research quantifying UVA irradiances are essential for the appropriate authorities to develop preventative guidelines and strategies. This is particularly relevant in a country like Australia with the associated long road distances and exposures to filtered solar UVA in cars.

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Table 1 – The UV exposures between 09:00 and 15:00 EST within car F calculated by interpolation between the three measurement times.

Site	UVA exposures (J cm^{-2})			
	Winter	Spring	Summer	Autumn
LPW	2.2	3.1	6.6	4.2
RDW	2.1	3.0	6.9	4.0
SW	2.1	3.0	6.3	4.0
LFPW	11.9	17.8	6.5	9.1
LFPS	4.6	4.9	6.6	5.4
RFDS	2.0	3.6	4.1	3.8
RFDW	12.8	14.4	4.0	9.2
RRDW	12.7	14.4	5.9	11.4
RRS	2.4	5.9	4.7	7.9
LRS	3.6	3.0	3.8	6.1
LRPW	12.0	11.2	5.1	7.6
LRW	15.0	9.8	5.3	7.6
RRW	15.0	9.9	5.3	7.1

Table 2 – The UV exposure ratios for the four zones in each of the cars. The error is the standard error in the mean.

Season	Car	Exposure Ratios			
		Front	Sides	Seats	Rear
Winter	FT	0.074±0.002	0.013±0.002	0.017±0.008	0.0090±0.0001
	F	0.048±0.001	0.271±0.005	0.069±0.013	0.3280±0.0001
	FU	0.080±0.001	0.134±0.007	0.049±0.011	0.144±0.004
	S	0.083±0.003	0.242±0.007	0.089±0.012	0.249±0.003
Spring	FT	0.074±0.003	0.006±0.003	0.010±0.002	0.004±0.001
	F	0.040±0.001	0.195±0.018	0.058±0.009	0.133±0.001
	FU	0.078±0.004	0.063±0.004	0.048±0.004	0.061±0.002
	S	0.084±0.002	0.139±0.007	0.044±0.004	0.115±0.001
Summer	FT	0.078±0.002	0.013±0.001	0.013±0.001	0.011±0.001
	F	0.087±0.002	0.072±0.007	0.064±0.008	0.070±0.001
	FU	0.069±0.003	0.082±0.004	0.043±0.003	0.065±0.001
	S	0.120±0.002	0.100±0.010	0.054±0.007	0.142±0.002
Autumn	FT	0.093±0.006	0.024±0.003	0.027±0.003	0.030±0.002
	F	0.094±0.001	0.215±0.018	0.13±0.02	0.169±0.005
	FU	0.090±0.002	0.092±0.006	0.071±0.003	0.069±0.005

Table 3 – Estimates of the annual UVA exposures in each zone of the cars.

Car	Annual UVA Exposures (J cm^{-2})			
	Front	Sides	Seats	Rear
FT	2969	508	594	489
F	2624	6177	2889	5473
FU	2894	3238	1918	2850
S	3706	5680	2301	6210

FIGURE CAPTIONS

Figure 1 – The UVA irradiances at each site in summer in car FU with untinted windows with the front of the car facing north at (a) 09:00 EST, (b) noon and (c) in car FT at noon with the front of the car facing north. The irradiances in bold are on a horizontal plane on the seats and the other irradiances are normal to the window and windscreen glass.

Figure 2 – The UVA irradiances at 09:00 EST, noon and 15:00 EST in winter (x), spring(-), summer (◊) and autumn (○) in the cars (a) FT, (b) FU, (c) F and (d) S.

Figure 3 - The exposure ratios for each of the cars in (a) winter, (b) spring, (c) summer and (d) autumn.

Figure 4 – The UVA exposures for each month for each of the cars for the (a) Front zone and (b) Seats zone.

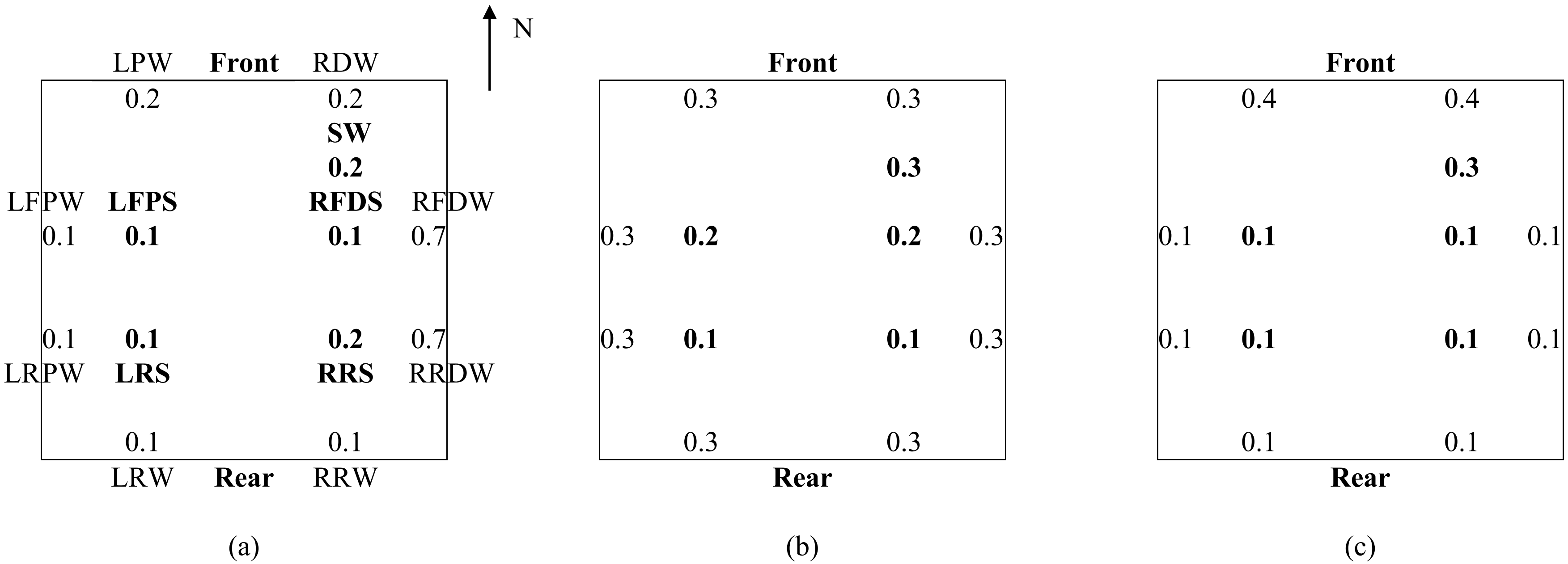

N
LPW Front RDW
0.2 0.2
SW
0.2
LFPW LFPS RFDS RFDW
0.1 0.1 0.1 0.7
0.1 0.1 0.2 0.7
LRPW LRS RRS RRDW
0.1 0.1
LRW Rear RRW
(a)
Front
0.3 0.3
0.3
0.3 0.2 0.2 0.3
0.3 0.1 0.1 0.3
0.3 0.3
Rear
(b)
Front
0.4 0.4
0.3
0.1 0.1 0.1 0.1
0.1 0.1 0.1 0.1
0.1 0.1
Rear
(c)

Figure 1

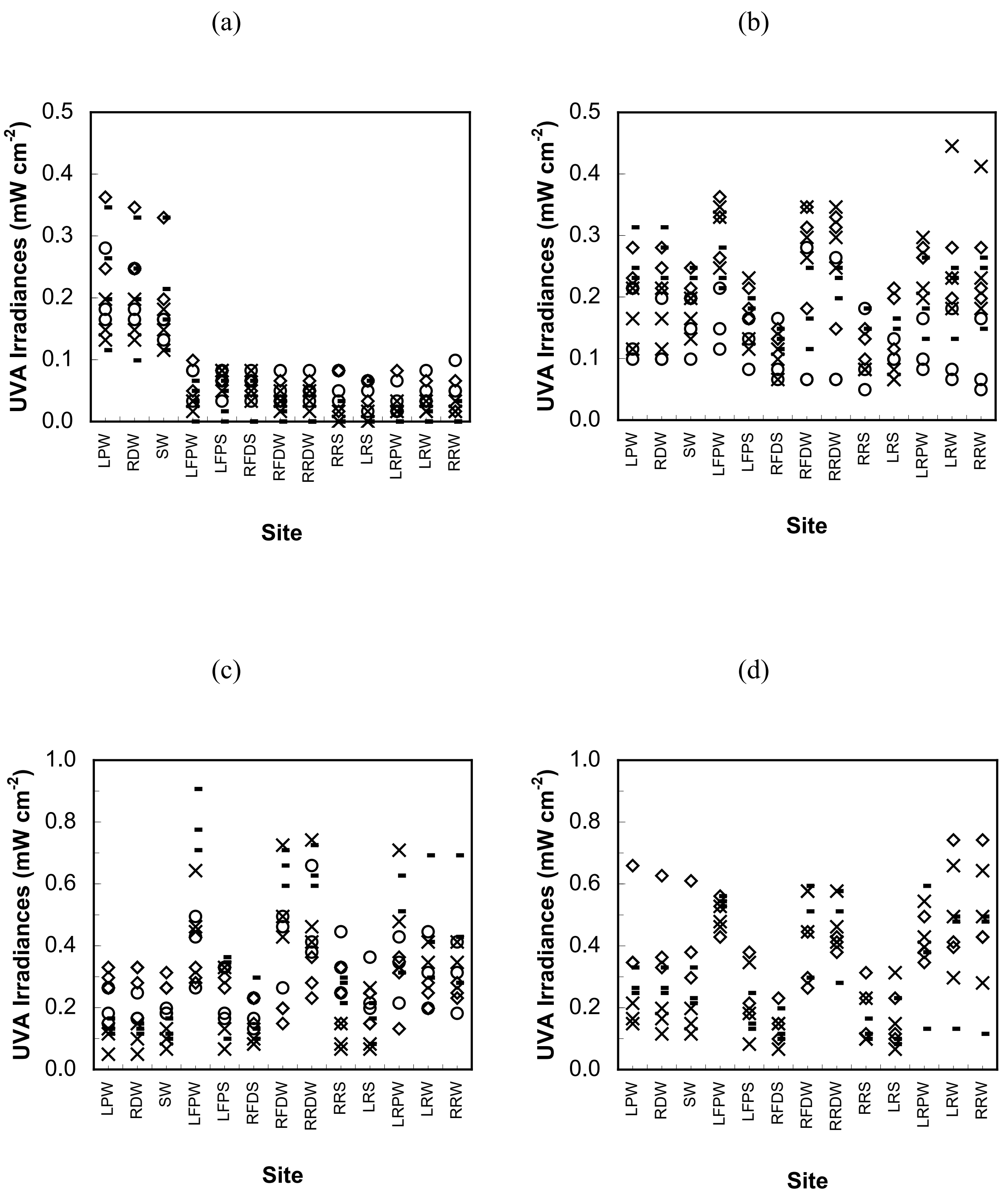

(a)
(b)
(c)
(d)
UVA Irradiances (mW cm-2)
Site
LPW
RDW
SW
LFPW
LFPS
RFDS
RFDW
RRDW
RRS
LRS
LRPW
LRW
RRW
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1.0

Figure 2

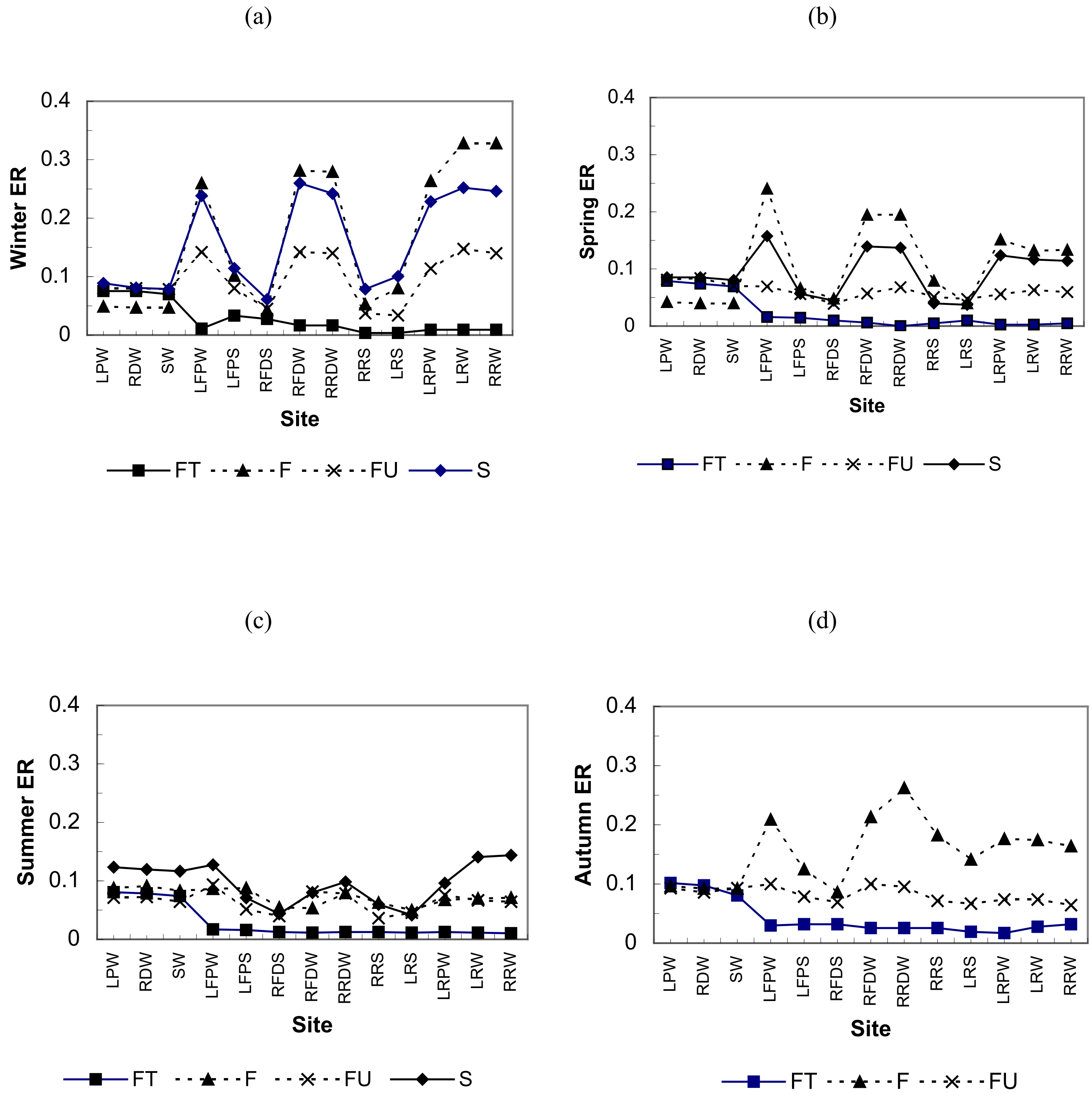
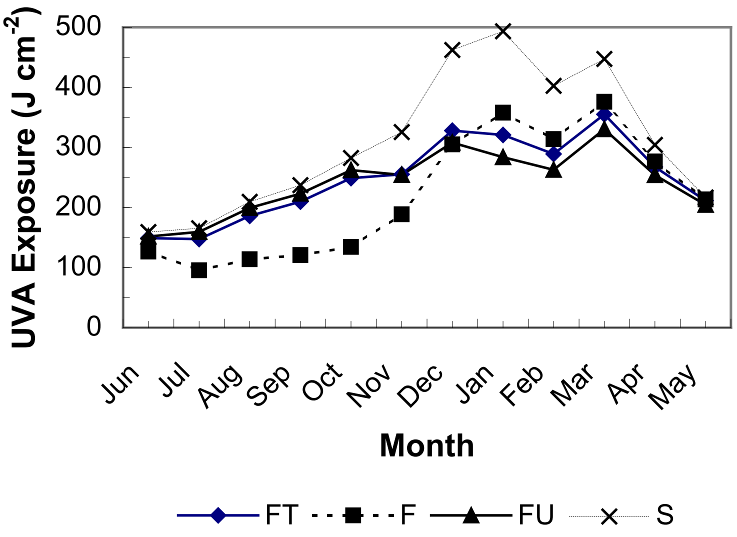

(a)
(b)
(c)
(d)
Winter ER
Spring ER
Summer ER
Autumn ER
0.4
0.3
0.2
0.1
0
LPW
RDW
SW
LFPW
LFPS
RFDS
RFDW
RRDW
RRS
LRS
LRPW
LRW
RRW
Site
FT
F
FU
S

Figure 3

(a)


500
400
300
200
100
0
UVA Exposure (J cm-2)
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Month
FT
F
FU
S

(b)

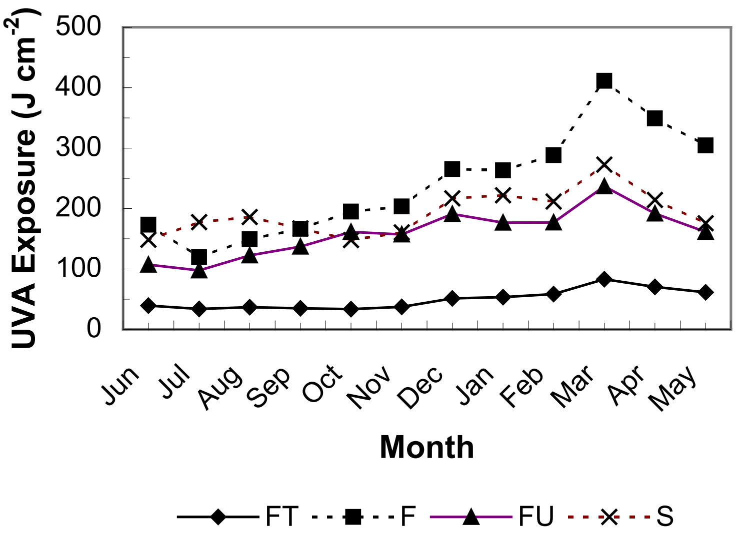

500
400
300
200
100
0
UVA Exposure (J cm-2)
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Month
FT
F
FU
S

Figure 4