

Dosimeter for the measurement of plant damaging solar UV exposures

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Abstract

The development of a dosimeter for the measurement of the biologically effective UV exposures (UV_{PGI}) for plant growth inhibition in higher plants based on a recently reported action spectrum is presented. The new dosimeter is based on the two photoactive materials polysulphone and nalidixic acid, each in thin film form layered on top of one another to provide a combined response. The quantitative characteristics of the UV_{PGI} dosimeter were measured, including the spectral response, dose response, dark reaction and cosine response. The spectral response of the new dosimeter has been successfully extended into the UVA waveband. The dark reaction was within a reasonable limit that could be taken into account when measurements are taken by measuring the post-exposure absorbances at a consistent time period after the exposure. The cosine response approximated the cosine function to better than 15% for solar zenith angles up to 50° . The dose response shows that the new dosimeter can be employed for the measurement of UV_{PGI} exposures and has reproducibility comparable to other dosimeters calibrated to a biological action spectrum.

Keywords: dosimeter, UV, plant, action spectrum, solar

Introduction

Dosimetry in the ultraviolet waveband (UV) has been employed to measure erythemal UV exposures using polysulphone dosimeters. The potential of the photochemical polysulphone (PS) as an erythemal UV dosimeter was reported by Davis et al., (1976a) who found that exposure of PS in thin film form to UV radiation resulted in optical density darkening of the polymer, with the maximum change at 330 nm. PS is responsive only to wavelengths shorter than 330 nm and when cast as a thin film of approximately 40 µm thickness possesses a response spectrum that approximates the erythemal action spectrum (CIE, 1987) for wavelengths shorter than 330 nm (CIE, 1992). In this form, PS has been employed extensively for the measurement of personal erythemal UV exposures in different environments.

UVB (280 – 320 nm) radiation is known to produce biological damage in higher plants. Additionally, UVA (320 - 400 nm) radiation has also been found to elicit a biological response (Flint et al., 2004) and an action spectrum for plant growth inhibition in higher plants has been recently developed (Flint and Caldwell, 2003) that extends into the UVA to 366 nm. The UV exposures to plants can be measured on a horizontal plane and on a number of inclined planes with instrumentation. However, the measurement of UV exposures to the plant leaves with dosimeters at a series of locations and orientations will provide a more accurate representation of the UV exposures incident on a small plant in studies of the effects of enhanced UV levels (Parisi et al., 1998). This allows simultaneous multi-site measurement taking into account shading by neighbouring plants and shading by other leaves in the plant.

Previous research has investigated the use of dosimeters fabricated from polysulphone and supported on a light weight frame over the canopy of a plant for the measurement of the UVB over a plant canopy (Parisi et al., 2003). The recently developed action spectrum for UV plant growth inhibition to higher plants has a response that extends into the UVA waveband (Flint and Caldwell, 2003). In order to measure with dosimeters the biologically effective UV exposures weighted with this action spectrum for plant growth inhibition in higher plants (UV_{PGI}), a dosimeter that possesses a spectral response that is high in the UVB and extends into the UVA is required. This paper reports on the development and testing of the properties of a dosimeter with this spectral response, that can be employed for the measurement of the biologically growth inhibiting UV exposures to higher plants.

Methodology

Selection of Photoactive Material

The approach employed in this paper was to employ two photoactive materials layered one on top of the other in a dosimeter that possesses a response that is high in the UVB and extends into the UVA. The reason for this approach is that there is no chemical dosimeter that responds to more than one waveband, such as UVB and UVA radiation and that also approximates the Flint-Caldwell plant action spectrum (Flint & Caldwell, 2003).

Polysulphone (PS) is a photoactive material for a UV dosimeter, with a spectral response that is high in the UVB and can be used to approximate the Flint-Caldwell plant action spectrum for plant growth inhibition (A_{PGI}) for this waveband of the response. Its limiting factor is the lack of spectral sensitivity within the UVA

waveband. Due to polysulphone's ease of use and ruggedness for UV dosimetry, the approach employed in this research was to enhance the already useful features of the polymer and extend the response into the UVA with the use of a second photoactive material. Interchanging the photoactive material of the dosimeter changes the response waveband of the dosimeter, allowing alternative wavebands to be investigated.

A number of photoactive materials were considered: Nalidixic acid (Tate et al., 1979), 8-methoxypsoralen (Diffey and Davis, 1978), phenothiazine (Diffey et al., 1977, Wong and Parisi, 1996, Parisi and Kimlin 2004), allyl diglycol carbonate or CR-39 (Wong et al., 1992, Wong et al., 1995), polyphenylene oxide or PPO (Davis et al., 1976b, Berre and Lala, 1989, Lester et al., 2003), diazochromic film (Ali and Jacobson, 1980, Jackson, 1980, Mosely et al., 1984), benoxaprofen (Diffey et al., 1982) and triphenyl tetrazolium chloride dye doped in poly vinyl alcohol (PVA) and poly vinyl butyral (PVB) (Ebraheem et al., 2000). Nalidixic acid was identified as being the most appropriate candidate to investigate further for use with polysulphone, due to the appropriate ease of handling and a response spectrum that extends into UVA wavelengths with a spectral response in the range of 280-350 nm (Tate et al., 1979) that may result in an approximation of the plant growth inhibition action spectrum when combined with PS in a combined dosimeter. Nalidixic acid (NDA) undergoes a change in its optical properties when exposed to UV radiation, and has a measurable change in absorbance at 330 nm.

Sheets of PS and NDA in thin film form were used to construct the UV_{PGI} dosimeter that was in a holder with an overall size of 3 cm x 3 cm. In order to investigate

whether the location of each material within the dosimeter would affect the response of the dosimeter, a test of the change in optical absorbance due to UV exposure of four types of dosimeters consisting of PS, NDA, PS layered on top of NDA (PS/NDA) and NDA layered on top of PS (NDA/PS), was carried out. For each case four different exposure times were employed. Each dosimeter was exposed for four consecutive half hour intervals, and measured at the end of each interval. The photodegradation of PS dosimeters are quantified by measuring the optical absorbance pre and post exposure to UV radiation, due to the increase in optical absorbance at 330 nm due to UV exposure. At the wavelength of 330 nm, NDA has a decrease in optical absorbance due to UV exposure. In order to employ PS and NDA in a UV_{PGI} dosimeter, a new wavelength at which both materials undergo a change in absorption that is in the same direction for both materials is required. In order to determine this, the changes in the spectral optical absorbance of the two materials due to UV exposure were measured in a spectrophotometer (UV-1601, Shimadzu & Co, Kyoto). The error of the spectrophotometer is $\pm 0.004\%$. Variations in surface and thickness of the materials over each dosimeter were accounted for by measuring the change in absorbance at four sites over the dosimeter. This was achieved by using a rotating mount holder that takes a measurement on each side of the square dosimeter as it is rotated, and averaging these values.

Spectral Response

The spectral response of the UV_{PGI} dosimeter was measured by exposing a series of dosimeters to monochromatic radiation and recording the resultant degradation of the film. Monochromatic UV radiation was sourced from an irradiation monochromator consisting of a xenon arc lamp (model LX/450-2, Spectral Energy, New Jersey, USA)

and a monochromator (model GM 252, Spectral Energy, New Jersey, USA). The input and output slit widths were adjusted to provide an output beam with a FWHM of 6 nm. The output beam of UV from the irradiation monochromator had a diameter of the same order of magnitude as the aperture of a UV dosimeter.

The irradiances of the irradiation monochromator and the other UV radiation sources employed in this paper were measured using a mobile scanning spectroradiometer.

This instrument consists of a diffuser for the input optics (type D6, Bentham Instruments, Reading, UK) and a dispersion unit of a monochromator with double holographic gratings (model DH10, Jobin Yvon, France) at 1200 lines/mm. The diffuser and input slit of the monochromator are connected by a length of optical fibre. The UV detection system is a UV radiation photomultiplier tube (model R212, Hamamatsu Co., Japan) which is kept at $14.5^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ using a Peltier effect temperature control unit.

Wavelength calibration was carried out using an electric discharge mercury lamp, where the spectral emission lines at 365 nm and 405 nm were used. Absolute calibration was carried out using a quartz-tungsten halogen lamp (with a traceable calibration against a standard located at the National Measurements Laboratory, CSIRO, Lindfield) supplied with a current of 9.500 ± 0.005 A (DC) from a current regulated power supply (model PD36 20AD, Kenwood). The dark current, or the “noise” of the system was measured prior to each scan and all scans were carried out at 1 nm steps between 280 nm and 400 nm. It is estimated that the spectroradiometer measurement of spectral irradiances has an overall error of $\pm 5\%$ (Wong et al. 1995).

Cosine Response

The solar simulator (model 15S solar UV simulator, Solar Light Co., Philadelphia, USA) is an artificial UV radiation source. The output of the solar simulator varied in diameter, and was manually adjusted to the same size as the aperture of a UV dosimeter. The irradiance output was measured using the scanning spectroradiometer. Using a stand and a rotating dosimeter clamp, the dosimeter was positioned in front of the solar simulator aperture that emits the UV radiation. One dosimeter was exposed on a plane normal to the incident radiation (0°) and then used as a comparison for the measurements at the other angles of incidence. The mount holding the dosimeter was then rotated 10° from the normal plane and another dosimeter was exposed for the same period of time as the initial dosimeter at 0° . This was carried out for the following angles from the plane normal to the incident irradiance: 20° , 30° , 40° , 50° , 60° , and 70° . Using the dose response of the UV_{PGI} dosimeter to the UV radiation from the source, the change in absorbance of the dosimeter at a given angle was normalized by a previously given technique (Lester et al. 2003). In this technique, the dose-response equation in the form of a polynomial expression is calculated for the solar UV simulator, where change in absorbance is a function of time. The normalized response is a ratio of the dose response of this equation at a given incident angle to the dose response of the equation at normal incidence (0°).

Dark Reaction

Eleven dosimeters were exposed to solar UV for three hours on a clear day and the optical absorbance for each dosimeter was measured at four sites over the dosimeter surface before and immediately after exposure, with the calculated change in absorbance averaged. The dosimeters were then stored in a UV radiation free

environment for twenty-four hours and then measured again for absorbance. This was followed by storage in the same UV radiation free environment for a week after exposure and the absorbance measured again. The differences between absorbance measured immediately after exposure, twenty-four hours after exposure and a week after exposure indicated the dark reaction of the UV_{PGI} dosimeter.

Dose Response

A series of the UV_{PGI} dosimeters were exposed to solar UV on different cloudless days on a horizontal plane for varying periods of time: 5 minutes, 10 minutes, 15 minutes, 30 minutes, 45 minutes, 1 hour, 1 hour and thirty minutes, and then in 30 minute intervals up to a maximum of 5 hours. The dose response is expressed as the biologically growth inhibiting UV exposure for the A_{PGI} action spectrum versus the corresponding change in absorbance. The UV_{PGI} exposure was determined by measurement of the UV spectrum with a UV spectroradiometer that is permanently mounted on the roof of a building in a weather proof container and that automatically measures the UV spectral irradiance every five minutes from 280 nm to 400 nm in half nanometer steps (model DTM300, Bentham Instruments, Reading, UK). The measured UV spectral irradiances were then weighted with the A_{PGI} action spectrum to produce the UV_{PGI} irradiances at each five minute interval from which the UV_{PGI} exposures that each of the calibration dosimeters were exposed to were calculated. UV radiation varies according to solar zenith angle, clouds, ozone and aerosol levels, therefore the dose response is initially measured each day of UV measurements to account for the variations of conditions.

Although the agreement between the spectral response of the dosimeter and the action spectrum for the UV_{PGI} spectrum are not exact, it is possible to allow for this,

provided the relative spectral distribution of the incident irradiance is quantified and the reproducibility of the response of the dosimeter to the given spectral distribution is known (Davis et al, 1976a).

The ability of the dose response to predict UV_{PGI} irradiance values (reproducibility) was tested using a number of dosimeters exposed for certain time periods, using the dose response to calculate the corresponding UV_{PGI} irradiance and comparing to the weighted UV_{PGI} measured by the UV spectroradiometer. The dosimeters were exposed on a clear day, and also on a different day to when the dose response was calculated. Thirty-six dosimeters were separated into four groups and exposed for different time periods. The difference between the calculated UV_{PGI} irradiance and the measured UV_{PGI} irradiance was determined.

Results

Spectral scans of PS, NDA and PS over NDA were analysed and indicated a suitable wavelength in the UV spectrum with a maximum observable change in absorbance for both photoactive materials. The wavelength of 345 nm was selected as both PS and NDA undergo positive changes in absorbance at this wavelength. PS and NDA have opposite magnitude change in absorbance measured at 330nm. NDA undergoes a negative change in absorbance relative to PS, indicating the wavelength of 330 nm would not be suitable as a guide to the changes in absorbance of each material, when used in conjunction as a combined dosimeter.

Figure 1 shows the test for comparing how each photoactive material reacts in single and combined form. For the combined dosimeter, the Figure shows the change in absorbance for a combined dosimeter consisting of NDA/PS and PS/NDA. In this

case, each change in absorbance was measured at 330 nm as this was prior to the determination of a wavelength where the change in absorbance was positive. Nevertheless, this side by side dot plot shows that the materials do affect one another. The results show that the change in absorbance for NDA is similar to that for NDA/PS, indicating that the NDA filters nearly all UV radiation from reaching the PS, thus rendering the PS component almost inactive. The PS placed above the NDA responded to UV radiation, but did not act as a strong filter, allowing NDA to also respond to UV radiation. Therefore the combination of PS on top of NDA will be used within this study and all further references to a combined dosimeter will indicate the placement of PS over NDA within the UV_{PGI} dosimeter.

The variances of the absorbances of the UV_{PGI} dosimeter at different stages are provided in Table 1. The absorbance measurements were recorded at 345 nm. The data for 55 dosimeters (the total number of dosimeters that were used in all tests), were used to determine the overall accuracy for the UV_{PGI} dosimeter. This accuracy is attributable to thickness and surface variation of the photochemical materials. Different batches of the material can contribute to variation in absorbance. For the pre-exposure change in absorbance, measurements of the 55 dosimeters, using the average of the four side absorbance measurements, provided a mean absorbance of 0.334 and a standard deviation of 0.014. This gives 4.2% variance within pre-exposure absorbance measurements. The variance for immediate post-exposure and 24 hours post-exposure changes in absorbance was calculated from 11 of the total 55 dosimeters. These eleven dosimeters were irradiated at the same time for a two hour time period, and therefore received the same exposures. Variances found for these

dosimeters are taken as the variation in the dosimeters. The largest variance is 5.8% for the change in absorbance determined immediately post exposure.

The spectral response of the UV_{PGI} dosimeter between 300 nm and 380 nm, with each dosimeter at each wavelength exposed to 2000 Jm⁻² is shown in Figure 2. This spectral response is expressed as the absolute of the change in absorbance normalized to the change in absorbance measured at the wavelength where the largest change in absorbance occurs. The error bars represent ±10.8% error, consisting of the accumulated errors due to the variance of the change in dosimeter absorbance (5.8%), the scanning spectroradiometer (5%) and the spectrophotometer (0.004%). Although the agreement between the spectral response of the dosimeter and the action spectrum for the UV_{PGI} spectrum is not exact, it is possible to allow for this, if the relative spectral distribution of the incident irradiance is quantified (Davis et al, 1976a). The relative spectral distribution of the incident radiation was quantified with the spectroradiometer as reported in the methodology. By weighting the spectral distribution of the measured incident irradiance with the PGI action spectrum, only the irradiance that contributes to the biological effect of plant growth inhibition is correlated to the UV_{PGI} dosimeter's change in absorbance. This is achieved by the recording of a dose response at the approximate time of the field measurement. To find the UV exposure experienced by any dosimeter, the change in absorbance of that dosimeter is calibrated against the weighted UV exposures.

Table 2 indicates the dark reaction of the UV_{PGI} dosimeter measured at 345 nm for periods of 24 hours and one week after exposure. In comparison, PS has a dark reaction, when measured at 330 nm, of 4% after 24 hours and 5% after a week (Davis et al., 1976a), which is comparable to that of the UV_{PGI} dosimeter.

The cosine response of the UV_{PGI} dosimeter compared to the cosine curve for the range of 0° to 70° is provided in Figure 3. The error bars represent ± 5.8% dosimeter variance (due to the photochemical material thickness and surface variances observed when measuring the change in absorbance) for post-exposure immediate absorbance measurements. The cosine response of the UV_{PGI} dosimeter is within 23% of the cosine curve for the range up to 70°.

The dose response of the UV_{PGI} dosimeter for UV_{PGI} exposures is shown in Figure 4. The dose response is shown for three different days. The dose response for 1 February 2007 was carried out from 10.00am to 3.00pm. The dose response for 3 March 2008 was carried out from 2.10pm to 5.10pm. The dose response for 4 March 2008 was carried out from 9.30am to 1.30pm. An exponential function has been fitted to the calibration data points with an R² of 0.988. The UV_{PGI} dosimeter starts to saturate for a change in absorbance above 0.4, which corresponds to an exposure time of 4 hours in summer at a sub-tropical site. Saturation of the UV_{PGI} dosimeter is determined by the saturation level of polysulphone, which is defined by the lack of change in absorbance observed in the material after four to five hours exposure to solar radiation. The UV_{PGI} dosimeter has a linear response. Due to the changing solar UV irradiance, this can not be displayed satisfactorily in a separate graphic. However, an example of the linearity is given by Figure 4, using the last data value for 3 March 2008, and the seventh data value for 4 March 2008 (circled). The dose response for 3 March 2008, was carried out from 2.10pm to 5.10pm, with a decreasing UV irradiance over this time. The dose response for 4 March 2008 was carried out from 9.30am to 1.30pm with UV irradiance increasing until noon, then dropping slightly

again. The seventh data value for this dose response was recorded at 11.00am, one and a half hours from the beginning of the dose response. Therefore, the UV_{PGI} dosimeter responded to 6124mW/m^2 in three hours during the late afternoon, and to 6168mW/m^2 in one and a half hours in the morning, with a similar change in absorbance.

During the day the proportion of UVA to UVB radiation changes, with maximum ratios occurring in early mornings and late afternoons and the minimum ratio occurring at solar noon. Kimlin et al., (2002) reports this for the ratio of UVA to erythemal UV, although when considering the range of UVB to erythemal UV, the ratios obtained are likely to be higher as the waveband for UVB is smaller than the waveband for erythemal UV. The proportion of UVA to UVB radiation also changes seasonally (Cole, 2001) with summer always having the lowest proportion and winter the highest proportion, although total irradiance values are lower in winter than summer, due to the position of the sun in the sky. At the location of this research, the proportion of UVA to UVB ranges from mid-morning to noon values of 13.5 to 10 for February 2007, while March 2008 ranges from 16.4 (mid morning) to 37 (later afternoon). Since the UV_{PGI} dosimeter has been shown to have a linear response, the changing proportion of UVA to UVB during the day does not appear to affect the dose response. PS has been previously found to have a changing dose response for winter and summer (Kimlin, 2003) and this is believed to be due to the difference in its spectral response compared to the erythemal action spectrum. With the spectral response in the UVA waveband of the UV_{PGI} dosimeter, we may see much less variation in seasonal dose responses. Even from month to month, variation can be seen in the PS dose response, but surprisingly, even with one month separation (in different years) between the dose responses measured for the UV_{PGI} dosimeter, there is

little variation observed. There should be some variation between winter and summer dose responses due to the changing total values of UVA to UVB (for example Cole (2001) shows there is a fifth of total UVB in winter compared to summer and a third of total UVA in winter compared to summer).

The variance of the dosimeter when used to predict weighted irradiance values from the dose response was calculated by exposing a series of dosimeters for the same time period and comparing the calculated weighted irradiance to the measured weighted irradiance by the spectroradiometer. The four groups of dosimeters, exposed for different time periods, had the weighted irradiance calculated for each change in absorbance, and compared to the known weighted irradiance measured. The average difference between the calculated and measured weighted irradiance was 13.7%. The error associated with the change in dosimeter absorbance, the scanning spectroradiometer and the spectrophotometer equates to 10.8% so an additional error of 2.9% is incurred through using the dose response of only a portion of the UV_{PGI} dosimeters to calculate the remaining UV_{PGI} dosimeters and their associated weighted irradiances.

Discussion

The biological responses in higher plants to UV radiation have been previously shown to extend from the shorter wavelengths to 366 nm. This research has reported on a new dosimeter that consists of two types of photoactive materials that possesses a spectral response that extends to 380 nm for the measurement of UV_{PGI} exposures. The UV_{PGI} dosimeter was found to be most effective when constructed with a thin film of PS placed on top of a thin film of NDA in the dosimeter holder. The dosimeter

of this combination had a maximum change in absorbance at 345 nm and this wavelength was employed for the quantification of the change in the dosimeter due to UV radiation.

The characteristics of dose response, spectral response, dark reaction and cosine response of the UV_{PGI} dosimeter have been quantified. The dark reaction of the UV_{PGI} dosimeter is similar in magnitude to the dark reaction of polysulphone. After twenty-four hours, the average of the change in absorbance was 2.7% with an increase to 6.3% after a week. The dark reaction will be taken into account during the field use of the dosimeter by measuring the post exposure absorbance of the UV_{PGI} dosimeters after a consistent time period following exposure, in a similar manner to that employed for personal UV exposure dosimeters (CIE, 1992).

The cosine error of the UV_{PGI} dosimeter is within 15% for angles up to 50°, and less than 23% for angles up to 70°. The solar irradiances decrease with increasing solar zenith angles (SZA), so the cosine error of more than 15% for SZA greater than 50° is not too significant as the exposures measured by the dosimeter during use for SZA greater than 50°, would be less than those measured for SZA less than 50°. The normalized cosine value is in most cases, systematically lower than the cosine function. This suggests that at larger incident angles the cosine value is more likely to be underestimated rather than overestimated. The normalized cosine value at an incident angle of 20° is likely to be a measurement error as the dosimeter was used from the same batch as the other dosimeters for all incident angles.

The response spectrum of the UV_{PGI} dosimeter showed a spectral response up to 380 nm, extending the response into the UVA spectrum. This data is the absolute of each change in absorbance, as the change in absorbance measured at 349 nm and 359 nm were negative. These two values are possibly due to the influence of the NDA undergoing a negative change in absorbance due to the response at these wavelengths. Further investigation of the spectral response at 5 nm increments is required. However, this research has shown that the response of the UV_{PGI} dosimeter extends into the UVA as required.

The dose response was collated using the cumulative change in absorbance of the UV_{PGI} dosimeter compared against periods of weighted UV_{PGI} exposure, on three different days. The UV_{PGI} dosimeter responds to the weighted UV irradiance that it is exposed to, and changes in the time required to expose the dosimeter does not affect the response of the dosimeter. The error of the UV_{PGI} dosimeter at predicting the weighted UV irradiance from the calculated dose response averaged at 13.7%. Diffey (1989) reports a minimum error of 10% for the reproducibility of polysulphone, so in comparison, the error of the UV_{PGI} dosimeter is considered reasonable.

At a minimum, dose responses should be calculated for changes in season and for each new sheet of PS and NDA, but until seasonal calibrations are established, calibrations are recommended for each new measurement.

Seasonally the proportion of UVA to UVB changes, which contributes to PS having different dose responses in different seasons and even month to month. The UV_{PGI} dosimeter shows no variation between the dose response recorded in the months of February and March, and may be suggested to be representative of a seasonal

grouping. PS will contribute to a different dose response seasonally, but the combination of PS and NDA in the UV_{PGI} dosimeter responding to UVA should decrease this seasonal difference observed in PS by itself. This means the UV_{PGI} dosimeter's response to longer UVA wavelengths should reduce variation in the dose response over the year, by accounting for UVA radiation as well as UVB radiation. It is recommended that dose responses for the UV_{PGI} dosimeter should be carried out for each new measurement conducted until seasonal calibrations are established. The dosimeter that has been developed will be important for further research into the biological effects of UV radiation on higher plants. The dosimeter will allow simultaneous measurements of the UV_{PGI} exposures at multiple sites over and within a plant canopy.

ACKNOWLEDGEMENTS: *The authors acknowledge the technical staff in Physics and the Sciences workshop for assistance in this project.*

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Table 1 Variance of the absorbance measurements of the UV_{PGI} dosimeter throughout the absorbance measurement process. Absorbance is measured at 345 nm.

	Mean	Standard deviation	% variance
Pre-exposure absorbance	0.334	0.014	4.2
Immediate post-exposure absorbance	0.598	0.016	2.7
Immediate change in absorbance	0.263	0.015	5.8
24 hours post-exposure absorbance	0.614	0.012	2.0
24 hours post-exposure change in absorbance	0.279	0.005	1.9

Table 2 Average dark reaction of eleven UV_{PGI} dosimeters.

Period of time	Change in absorbance	% change
24 hours	0.016	2.7
1 week	0.021	6.3

Figure Captions

Figure 1 - Side-by-side dot plot of four types of dosimeter, the change in absorbance measured on four sites over four time periods of 30 minutes each, group 1= PS, group 2= NDA, group 3= NDA/PS, group 4 = PS/NDA. The change in absorbance was measured at 330 nm.

Figure 2 – Spectral response from 300 nm to 380 nm of the UV_{PGI} dosimeter. The thick line is the PGI action spectrum (Flint and Caldwell, 2003).

Figure 3 – Comparison of the cosine response of the UV_{PGI} dosimeter to the cosine curve.

Figure 4 – Calibration of the UV_{PGI} dosimeter for the measurement of the UV_{PGI} exposures. The diamond (◆) represents the dose response carried out from 10.00am to 3.00pm on 1 February, 2007, the square (■) represents the dose response carried out from 2.10pm to 5.10pm on 3 March, 2008 and the triangle (▲) represents the dose response carried out from 9.30am to 1.30pm on 4 March, 2008.

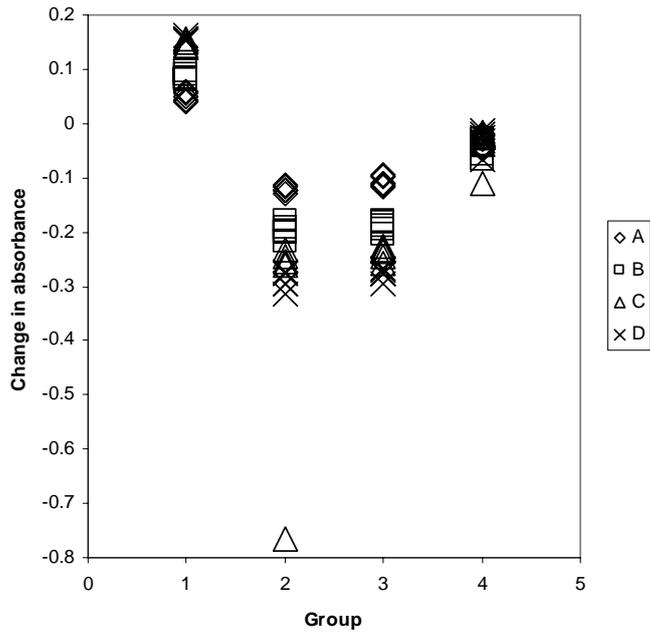


Figure 1 - Side-by-side dot plot of four types of dosimeter, the change in absorbance measured on four sites over four time periods (A, B, C, D) of 30 minutes each, group 1= PS, group 2= NDA, group 3= NDA/PS, group 4 = PS/NDA. The change in absorbance was measured at 330 nm.

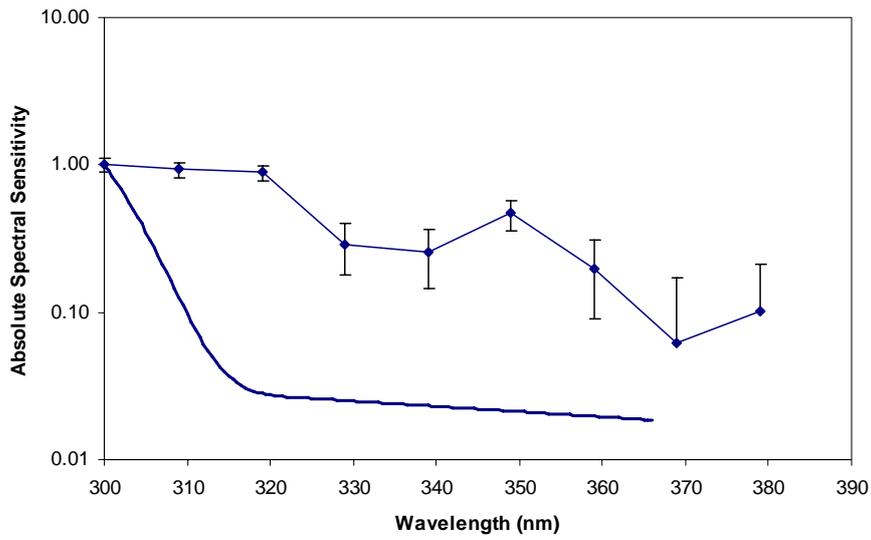


Figure 2 - Spectral response from 300 nm to 380 nm of the UV_{PGI} dosimeter. The thick line is the PGI action spectrum (Flint and Caldwell, 2003).

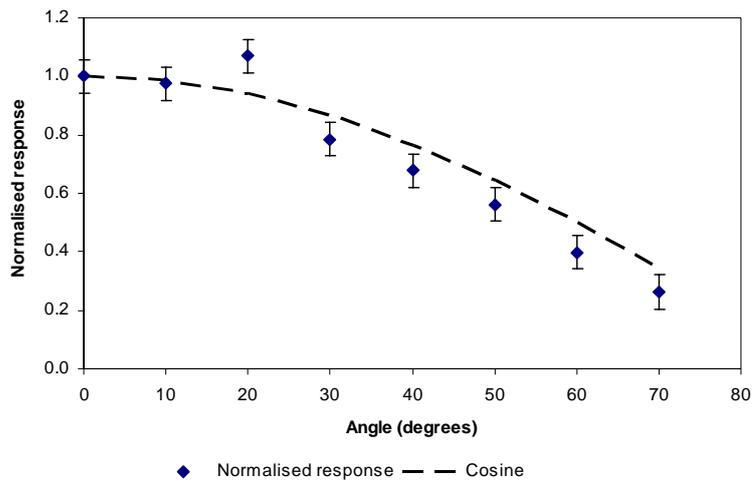


Figure 3 – Comparison of the cosine response of the UV_{PGI} dosimeter to the cosine curve.

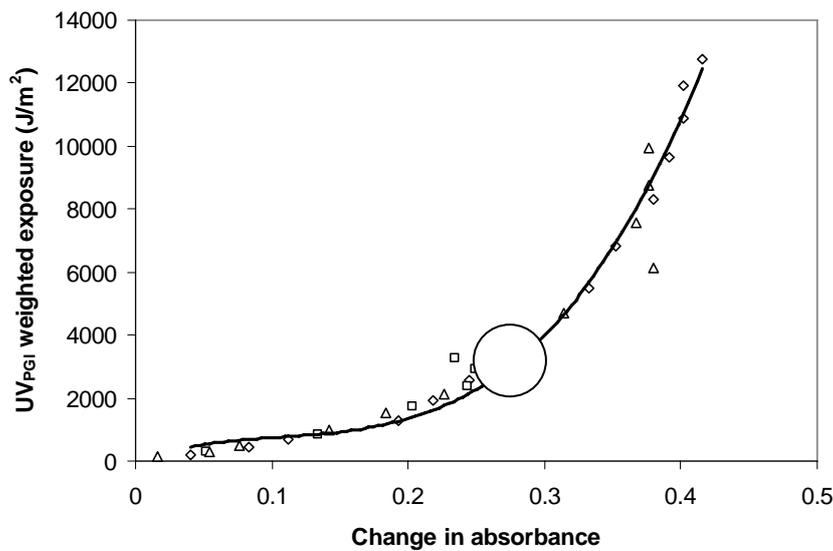


Figure 4 – Calibration of the UV_{plant} dosimeter for the measurement of the UV_{PGI} exposures. The diamond (◆) represents the dose response carried out from 10.00am to 3.00pm on 1 February, 2007, the square (■) represents the dose response carried out from 2.10pm to 5.10pm on 3 March, 2008 and the triangle (▲) represents the dose response carried out from 9.30am to 1.30pm on 4 March, 2008.