PLANT CANOPY SHAPE AND THE INFLUENCES ON UV EXPOSURES TO THE CANOPY

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[†]Abbreviations: 8-MOP, 8-methoxypsoralen; ΔA, change in optical absorbance; EST, eastern standard time; NDA, nalidixic acid; UV, ultraviolet radiation (280-400 nm); UVA, ultraviolet radiation (320-400 nm); UVB, ultraviolet radiation (280-320 nm); UVBE, biologically effective ultraviolet radiation.

Abstract - The solar spectra at selected sites over hemispherical, conical and pinnacle plant canopy models has been evaluated with a dosimetric technique. The irradiance at the sites varies by up to a factor of 0.31 compared to the irradiance on a horizontal plane. The biologically effective (UVBE) exposures evaluated with the dosimetric technique at sites over the plant canopy are up to 19% of that on a horizontal plane. Compared to a spectroradiometer, the technique provides a more practicable method of measuring the UVBE exposures at multiple sites over a plant canopy. Usage of a dosimeter at one site to provide the exposures at that site for different sun angles introduces an error of more than 50%. Knowledge of the spectra allowed the UV and UVBE exposures to be calculated at each site along with the exposures to the entire canopies. These were dependent on the sun angle and the canopy shape. For plant damage, the UVBE was a maximum of about 1.4 mJ cm^{-2} min^{-1}. Compared to the hemispherical canopy, the UVBE exposure for generalised plant damage was 45% less for the pinnacle canopy and 23% less for the conical canopy. The canopy exposures could not be determined from measurements of the ambient exposure.

INTRODUCTION

The prospect of increased UVB† (280 to 320 nm) as a result of the decreased levels of stratospheric ozone has generated concerns about the effects on plants. The reasons for this are that biologically important macromolecules such as DNA, proteins and phytohormones have appreciable absorption coefficients in the UV[1,2]. In UV sensitive plants, this may reduce by various degrees plant characteristics such as, plant height, leaf area and photosynthesis[3,4]. Additionally, plant yield can be influenced in some varieties of food crops[5]. Due to the complexity and numerous interactions between plant responses, generalisations of the consequences of stratospheric ozone depletion are very speculative[6] and more research and data are needed before a reliable assessment can be made of the effects of increased UVB on global food production. In this research, it is necessary to measure the levels of UV and biologically effective (UVBE) exposures to plants.

Single polysulphone dosimeters have been applied to the measurement of ultraviolet (UV) exposures over hemispherical, conical and pinnacle plant canopy models[7]. Employing a single dosimeter provides the UV exposures to the plant canopy. However, no information is provided regarding the UV spectrum. Knowledge of the source spectrum allows the calculation of the biologically effective ultraviolet radiation for a particular biological process[8]. The UV spectrum may be measured with a

spectroradiometer[9]. Due to its bulk and expense, this equipment is not feasible for repeated usage in the field. Additionally, it is not possible to obtain simultaneous multi-site measurements over a plant canopy.

This paper applies a dosimetric method employing the four materials polysulphone, nalidixic acid (NDA), 8-methoxypsoralen (8-MOP) and phenothiazine in a system to provide an evaluation of the UV spectrum at a number of sites over models of plant canopies. The object of this was to measure the UV and UVBE exposures to the various shaped canopies and as a result compare the exposures to each of the canopies and also to the ambient exposures along with the effect of the sun angle. The topography of plant canopies is complicated and changing. As a result, a simplified representation is utilised by considering plants with canopies approximating hemispherical, conical and pinnacle shapes.

MATERIALS AND METHODS

The dosimetric system consists of the four materials polysulphone, NDA, 8-MOP and phenothiazine in thin film form[10-13]. As a result of exposure to UV radiation, these materials undergo degradation which is quantified by measuring the change in optical absorbance (ΔA) with a spectrophotometer at the respective wavelength at which the largest ΔA occurs, namely, 330 nm for polysulphone and NDA, 305 nm for 8-MOP and

280 nm for phenothiazine. The materials were placed in close proximity to one another in a holder 3 cm x 3 cm. The materials undergo a reproducible ΔA with exposure that is independent of the dose rate and temperature. The dosimeters have different spectral responses with sensitivity to different UV wavebands. Their combined responses cover the entire UV waveband. As a result, the four measurements of ΔA allow evaluation of the UV source spectrum. The exposure periods of 10 and 15 minutes employed were a compromise between a time sufficiently long to produce a detectable ΔA and short enough so that any changes in the solar spectrum were minimal (less than 5%).

In order to allow comparison of the spectrum evaluated with the technique of four dosimeters and the actual spectrum, the system of four dosimeters was exposed to solar UV radiation on the same plane and within 30 cm of the input aperture of a calibrated spectroradiometer[9]. The plant canopy models have been exposed to solar radiation with the dosimetric system at nine sites over the hemispherical and conical canopies and eight sites over the pinnacle canopy as described in Table 1[7] which provides the angle of inclination, α relative to the horizontal and the azimuth angle, β relative to north.

Figure 1 is a photograph of the hemispherical, conical and pinnacle canopy models spaced several metres apart with the

dosimetric system at the selected sites over the canopy. The exposures were performed in autumn at Toowoomba (27.5^{o} S latitude), Australia. The first exposure was carried out on 1 March 1995 between 11:00 and 11:15 EST with 3 octas cloud. This was repeated on 9 March 1995 from 11:05 to 11:15 EST with 2 to 3 octas cloud. The final set of exposures were on 31 March 1995 for the three periods 09:00 to 0910, 12:00 to 12:10 and 15:00 to 15:10 EST. The first period on this day was with zero cloud and the final one with 2 octas cloud. For all of the exposure periods there was no cloud over the solar disc.

The spectrum incident at each site has been evaluated and from this, the UVB, UVA and biologically effective (UVBE) exposures at each site have been calculated. The action spectra (Figure 2) for generalised plant damage[14] and for a variety of photoresponses in intact cucumber[15] have been employed as examples of two action spectra relevant to plants. Any other action spectrum relevant to plants may have been employed. The generalised plant damage action spectrum has a zero response in the UVA. In comparison the plant damage action spectrum has a response that extends into the UVA. The respective exposures at each site for the hemispherical, conical and pinnacle canopies have been interpolated and summed over each canopy with computer software[7] to provide the total exposures to the entire canopies.

In order to establish if the exposures to the canopies can be determined from measurements of the ambient exposures, the ambient UV exposures for each exposure period were measured with radiometers (Monitor Sensor, 7-9 Industry Drive, Caboolture, 4510, Australia). These were calibrated against a double holographic grating spectroradiometer with calibration traceable to the primary Australian standard lamp housed at the National Measurement Laboratory[9]. Additionally, the ambient spectra were evaluated with the dosimetric system placed on a flat surface to allow comparison of the UVBE exposures.

RESULTS

The differences between the solar spectra evaluated with the dosimetric technique and measured with the calibrated spectroradiometer were quantified by summing the absolute differences between the spectra at 1 nm intervals and dividing by the integrated spectral irradiance of the measured spectrum. These were less than 20%. The differences in UV and UVBE exposures for the measured and evaluated spectra were less than 20%.

For every exposure, the values of ΔA for each material at all the sites have been measured and the spectrum incident at each site has been evaluated. An example of two evaluated spectra for the 12:00 to 12:10 EST exposure on the 31 March 1995 at the NM and SM sites are plotted in Figure 3. For the two

spectra the differences in irradiance at each site is greater than the 20% difference between the evaluated irradiance and that measured with a calibrated spectroradiometer. This is further illustrated in Table 2 where the ratios of the irradiance at a wavelength of 320 nm at each site compared to the irradiances at the Top site for the same wavelength are presented. These results are for the 11:05 to 11:15 EST exposure on 9 March 1995 for the hemispherical canopy. For this exposure, the irradiance varies by up to a factor of 0.31 compared to the Top site. The ratios vary as the spectrum incident at each site changes as the solar zenith angle varies with time of day and season. The ratios will also vary with any influences that affect the ratio of diffuse to direct UV radiation, for example, reflective structures, clouds, or other particulate matter in the atmosphere.

For this exposure, the UVB, UVA and UVBE exposures employing the action spectrum for generalised plant damage[14], (Action spectrum 1) and for photo-effects on cucumbers[15] (Action spectrum 2) are provided in Table 3 for each site on the hemispherical canopy. For the hemispherical canopy exposure between 11:00 and 11:15 EST on 1 March, the UVBE spectral irradiances are plotted in Figure 4 for both action spectra for the Top and NB sites. This illustrates the difference in biologically effective exposures received by different sites on a plant canopy.

The various exposures are not necessarily proportional to one another. The ratios between them may change with site due to the variation in the source spectrum. For example, the ratio UVA/UVB varies from 16.0 for the NM site to 22.4 for the WB and SB sites. For this exposure, the last two sites were shaded whereas the first site was in direct sun. To study the variation of the biologically effective exposure for generalised plant damage, the ratios of the exposure at each site compared to the exposure at the Top site for the hemispherical canopy on 31 March for the exposures 12:00 to 12:10 and 15:00 to 15:10 EST were calculated (Table 4). The ratios vary as the spectrum at each site changes. These variations in the ratios illustrate the advantage of evaluating the spectrum at a number of sites over the canopy in order to provide a more accurate assessment of the UV exposures to the plant canopy. For the first period in Table 4, the exposure at the NM site is equal to the exposure at the Top site. In comparison the exposure to the SB site is less by a factor of 0.19 relative to the Top site. These are realistic if the geometry of the hemispherical canopy and the zenith angle of the sun are taken into account. This means that the UVBE exposure at a site on a plant canopy may be a variable fraction of that determined from a spectral measurement on a horizontal plane. The ratios for the second period from 15:00 to 15:10 EST illustrate the variation of the exposures at each site with the sun angle. For example, the ratio WB/Top changes from 0.30 for the noon exposure to 0.91 for the afternoon

exposure. Therefore, if a single dosimeter with a scaling factor of 0.30 (based on the noon exposure) for the WB site is used, the error for the estimation of the exposure in the afternoon to the same site is more than 50%.

The exposures to the entire canopies (energy/surface area) for each canopy shape are provided in Table 5. Note that the exposures on the 1 March are for fifteen minutes whereas the others are for a ten minute period. The biologically effective exposure for generalised plant damage (Action spectrum 1) ranges from about 0.4 to 1.4 mJ cm^{-2} min^{-1}. The biologically effective exposure for photo-effects on cucumbers (Action spectrum 2) ranges from about 3 to 9 mJ cm^{-2} min^{-1}. The difference in the results of the two action spectra may be related to the large ratio of UVA to UVB (20). These results also show that for all the exposure periods, the UVB, UVA and UVBE exposures are dependent on the shape of the canopy. For these exposures, the hemispherical canopy received the highest canopy exposure of the three canopies.

Table 6 provides the ratios of the hemispherical/conical and hemispherical/pinnacle canopy exposures. Compared to the hemispherical canopy, the conical canopy exposures may be more than 30% less and the pinnacle canopy exposures may be up to 50% less. Additionally, in some cases the ratios also vary with different exposures. For example, for action spectrum 2, the hemispherical/pinnacle ratio varies from 1.3 to 2.2. These

two extremes occur on 31 March for the 09:00 to 09:10 and the 12:00 to 12:10 EST exposures. Again, the variation is attributed to the difference in solar zenith angle between the morning and noon exposures and variations in the diffuse component of the UV spectrum due to changes in the atmosphere. As a result, it is impossible to obtain the exposure to a particular shaped canopy from the exposure to another canopy. It is interesting to note that the biologically effective exposure for plant damage is closely related to the UVB exposure.

For every irradiation period, the ambient exposures measured on a horizontal surface with both the dosimetric technique and the Monitor Sensor instrument is higher than the exposures over each of the three canopies. For the 31 March exposures, Table 7 provides the ratio of the canopy exposures over the hemispherical, conical and pinnacle canopies compared to the ambient UVBE exposure for generalised plant damage on a horizontal surface evaluated with the dosimetric system. The final three columns are the ratio of the canopy UVB exposures compared to that measured with the Monitor Sensor radiometer.

In each case, the exposure to the canopy is less compared to the ambient exposure. For example, the pinnacle canopy receives a UVB exposure at noon which is less by a factor of 0.21 compared to the ambient UVB exposure. In addition, the ratio changes firstly with the canopy shape and secondly for

the same canopy shape, the ratio changes with the sun angle. The UVBE exposure to the pinnacle canopy is less than the ambient exposure by a factor of 0.31 compared to a factor of 0.61 for the afternoon period. Consequently, the application of a multiplication factor to the ambient exposure for conversion to canopy exposure would not produce an accurate representation of the canopy exposure. The variation throughout the day is attributed to variations in the solar zenith angle, changes in cloud cover and other transmission properties in the atmosphere. For these reasons, the application of the dosimetric technique at various sites over the canopy provides a better assessment of the UV exposure incident on the plant canopy.

The exposures for the 31 March in the morning, noon and afternoon have been interpolated between irradiation periods to provide the integrated exposures between 09:00 and 15:10 EST for the three canopy models. These results are provided in Table 8. For each type of exposure, the hemispherical canopy received the highest exposure and the pinnacle received the least. For example, for the UVBE exposure for generalised plant damage (Action spectrum 1), the conical canopy received 23% less than the hemispherical canopy and the pinnacle canopy received 45% less. For the reasons outlined above, these exposures could not be obtained by measuring the ambient exposures with a radiometer or spectroradiometer.

CONCLUSIONS

The dosimetric technique has been applied to the evaluation of solar spectra at various sites over hemispherical, conical and pinnacle plant canopy models at various times of the day and on a number of days. The technique provides the exposures averaged over the exposure period, however, relatively short periods were employed (10 and 15 minutes) so that any changes in the solar spectrum were minimised. Comparison of the results from the spectra on a horizontal plane evaluated with the dosimetric technique and measured with a calibrated spectroradiometer provided an agreement to better than 20%. The spectrum was found to vary by up to 320% between sites for a given exposure time and canopy. The exposures were site dependent and for a particular site varied with the time of day and the day. The UVBE exposures evaluated with the dosimetric technique at sites over the canopy were up to 19% of those on a horizontal plane (exposure to the top site). This large difference is attributed to the effect of the orientation of the sites over the plant canopy. For a certain site, the use of a single dosimeter at the top site with a scaling factor based on one exposure period to provide the exposures to that site for different sun angles or times of the day could introduce an error of more than 50%.

The exposures to the entire canopies have been calculated from the individual exposures at each site. For plant damage, the biologically effective exposure amounts to a maximum of about

1.4 mJ cm^{-2} min^{-1}. The exposures to the canopies were dependent on the time of the exposure and the canopy shape. Compared to the hemispherical canopy, the exposures to the conical canopy may be more than 30% less and up to 50% less to the pinnacle canopy. Additionally, the differences vary during the day with the ratio of the exposures to the hemispherical canopy to that of the pinnacle canopy changing from 1.3 to 2.2 with the time of the day. Integrated over the day from 9:00 to 15:10 EST, the hemispherical canopy received the highest exposure with the pinnacle the least. For example, compared to the hemispherical canopy, the UVBE exposure for generalised plant damage to the pinnacle canopy was 45% less and 23% less for the conical canopy.

These results indicate that it is not possible to use radiometers or dosimeters to measure the ambient exposures and then scale these accordingly to produce the exposure to a particular canopy. Also the exposure to a canopy shape differs from the exposure to another canopy shape. Additionally, it is not possible to determine the exposure at one site and scale this to obtain the exposures at other sites. The scaling factors change with the time of the day and on different days with the variations in the solar zenith angle, changes in cloud cover and other transmission properties of the atmosphere and any possible changes in reflective structures and ground cover.

The application of the dosimetric technique to evaluate the UV spectrum at sites over a plant canopy allows a more practical and accurate assessment of the UV and UVBE exposures to the plant canopy in studies into the UV effects on plants. This will allow better intercomparison between various studies in different laboratories. Additionally, the knowledge of the evaluated spectra allows the UVBE to be calculated for any action spectra and also permits the postprocessing of the data at a later date with different action spectra.

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REFERENCES

1. Teramura, A.H. (1990) Implications of stratrospheric ozone depletion upon plant production. Hortscience 25(12), 1557-1560.

2. Diffey, B.L. (1991) Solar ultraviolet effects on biological systems. Phys. Med. Biol. 36(3), 299-328.

3. Tevini, M. (1993) Effects of enhanced UV-B radiation on terrestrial plants. In UV-B Radiation and Ozone Depletion: Effects on Humans, Animals, Plants, Microorganisms, and Materials (Edited by M. Tevini), pp.125-153, Lewis Publishers, Boca Raton.

4. Tevini, M. (1994) Physiological changes in plants related to UV-B radiation: An overview. In Stratospheric Ozone Depletion/UV-B Radiation in the Biosphere. (Edited by R.H. Biggs and M.E.B. Joyner), pp.37-56, Springer-Verlag, Berlin, Heidelberg.

5. Krupa, S.V. and R.N. Kickert (1989) The greenhouse effect: Impacts of ultraviolet-B (UV-B) radiation, carbon dioxide (CO_2) and ozone (O_3) on vegetation. Environ. Pollut. 61, 263-393.

6. Teramura, A.H. and J.H. Sullivan (1994) Effects of UV-B radiation on photosynthesis and growth of terrestrial plants. Photosynth. Res. 39, 463-473.

7. Parisi, A.V. and C.F. Wong (1994) A dosimetric technique for the measurement of ultraviolet radiation exposure to plants. Photochem. Photobiol. 60(5), 470-474.

8. Caldwell, M.M., L.B. Camp, C.W. Warner and S.D. Flint (1986) Action spectra and their key role in assessing biological consequences of solar UV-B radiation. In Stratospheric Ozone Reduction, Solar Ultraviolet Radiation and Plant Life. (Edited by R.C. Worrest and M.M. Caldwell), pp.87-111, Springer, Heidelberg.

9. Wong, C.F., S.Toomey, R.A. Fleming and B.W. Thomas (1995) UV-B radiometry and dosimetry for solar measurements. Heal. Phys. 68(2), 175-184.

10. Davis, A., G.H.W. Deane and B.L. Diffey (1976) Possible dosimeter for ultraviolet radiation. Nature 261, 169-170.

11. Tate, T.J., B.L. Diffey and A. Davis (1980) An ultraviolet radiation dosimeter based on the photosensitising drug, Nalidixic Acid. Photochem. Photobiol. 31, 27-30.

12. Diffey, B.L. and A. Davis (1978) A new dosemeter for the measurement of natural ultraviolet radiation in the study of photodermatoses and drug photosensitivity. Phys. Med. Biol. 23(2), 318-323.

13. Diffey, B.L., A. Davis, M. Johnson and T.R. Harrington (1977) A dosimeter for long wave ultraviolet radiation. Br. J. Dermatol. 97, 127-130.

14. Caldwell, M.M. (1971) Solar ultraviolet radiation and the growth and development of higher plants. In Photophysiology Vol.6 (Edited by A.C. Giese), pp.131-177, Academic Press, New York.

15. Coohill, T.P. (1989) Ultraviolet action spectra (280 to 380 nm) and solar effectiveness spectra for higher plants. Photochem. Photobiol. 50(4), 451-457.

Table 1. Orientation of the dosimeters[7] on each canopy where β is the azimuth angle in degrees relative to north of each dosimeter and α is the inclination angle relative to the horizontal.

Hemispherical			Conical			Pinnacle		
Site	β	α	Site	β	α	Site	β	α
Top	-	0	Top	-	0	NT	0	90
N	0	90	N	0	55	ET	90	90
NEB	45	90	NEB	45	55	ST	180	90
E	90	90	E	90	55	WT	270	90
SEB	135	90	SEB	135	55	NB	0	90
S	180	90	S	180	55	EB	90	90
SWB	225	90	SWB	225	55	SB	180	90
W	270	90	W	270	55	WB	270	90
NWB	315	90	NWB	315	55			
NM	0	45	NM	0	55			
EM	90	45	EM	90	55			
SM	180	45	SM	180	55			
WM	270	45	WM	270	55			

Table 2. Ratios of the irradiances at 320 nm for each site compared to the Top site for the 11:05 to 11:15 EST exposure on 9 March 1995 for the hemispherical canopy.

NB/Top	WB/Top	SB/Top	EB/Top	NM/Top	WM/Top	SM/Top	EM/Top
0.71	0.48	0.31	0.48	1.0	0.83	0.77	1.0

Table 3. The exposures at the sites over the hemispherical canopy calculated from the evaluated spectra for 1 March exposure. The UVBE exposures were calculated by employing the action spectrum for generalised plant damage[14], (Action spectrum 1) and photo-effects on cucumbers[15] (Action spectrum 2).

Site	UVB (J cm^{-2})	UVA (J cm^{-2})	UVBE (mJ cm^{-2})	
			Action spectrum 1	Action spectrum 2
Top	0.22	3.56	26	165
NB	0.14	2.21	16	102
WB	0.09	2.02	11	77
SB	0.05	1.12	6	44
EB	0.07	1.45	8	56
NM	0.19	3.05	22	141
WM	0.18	2.95	22	136
SM	0.14	2.35	17	109
EM	0.17	2.79	21	130

Table 4. Ratios of the biologically effective exposure for generalised plant damage at each site compared to the exposure at the Top site for the hemispherical canopy exposures on 31 March.

Time EST	NB/Top	WB/Top	SB/Top	EB/Top	NM/Top	WM/Top	SM/Top	EM/Top
1200-1210	0.71	0.30	0.19	0.21	1.0	0.83	0.59	0.83
1500-1510	0.71	0.91	0.27	0.28	1.1	1.2	0.50	0.42

Table 5. The canopy exposures (total energy/surface area) for each period for the hemispherical (H), conical (C) and pinnacle (P) canopy models.

Date	Time EST	UVB ($J\ cm^{-2}$)			UVA ($J\ cm^{-2}$)			UVBE ($mJ\ cm^{-2}$) Action spectrum 1			UVBE ($mJ\ cm^{-2}$) Action spectrum 2		
		H	C	P	H	C	P	H	C	P	H	C	P
1 Mar	1100-1115	0.14	0.12	0.07	2.4	2.2	1.4	17	14	8	111	92	57
9 Mar	1105-1110	0.12	0.09	0.07	1.9	1.6	1.1	14	11	8	89	70	51
31 Mar	0900-0910	0.06	0.04	0.04	1.2	0.8	0.9	7	5	5	47	32	35
31 Mar	1200-1210	0.08	0.06	0.04	1.5	1.1	0.7	10	8	5	65	50	30
31 Mar	1500-1510	0.06	0.05	0.04	1.2	1.1	0.7	7	6	4	48	39	29

Table 6. The ratios of the hemispherical/conical (H/C) and hemispherical/pinnacle (H/P) canopy exposures for each exposure period.

Date	Time EST	UVB ($J\ cm^{-2}$)		UVA ($J\ cm^{-2}$)		UVBE ($mJ\ cm^{-2}$) Action spectrum 1		UVBE ($mJ\ cm^{-2}$) Action spectrum 2	
		H/C	H/P	H/C	H/P	H/C	H/P	H/C	H/P
1 Mar	1100-1115	1.2	2.0	1.1	1.7	1.2	2.1	1.2	1.9
9 Mar	1105-1110	1.3	1.7	1.2	1.7	1.3	1.7	1.3	1.7
31 Mar	0900-0910	1.5	1.5	1.5	1.3	1.4	1.4	1.5	1.3
31 Mar	1200-1210	1.3	2.0	1.4	2.1	1.3	2.0	1.3	2.2
31 Mar	1500-1510	1.2	1.5	1.1	1.7	1.2	1.7	1.2	1.7

Table 7. Ratio of the canopy exposures over the hemispherical, conical and pinnacle canopies (H,C,P) compared to the ambient UVBE exposure on a horizontal surface evaluated with the dosimetric system (DS) and compared to the UVB exposure measured with the Monitor Sensor radiometer (MS).

Time	UVBE - Action spectrum 1			UVB		
EST	H/DS	C/DS	P/DS	H/MS	C/MS	P/MS
0900-0910	0.68	0.45	0.50	0.62	0.41	0.45
1200-1210	0.67	0.51	0.31	0.45	0.34	0.21
1500-1510	0.97	0.84	0.61	0.68	0.59	0.42

Table 8. Integrated exposures between 09:00 and 15:10 EST on 31 March for the three canopy models.

Canopy	UVB ($J\ cm^{-2}$)	UVA ($J\ cm^{-2}$)	UVBE ($J\ cm^{-2}$)	
			Action spectrum 1	Action spectrum 2
Hemispherical	2.6	49	0.31	2.1
Conical	2.0	39	0.24	1.6
Pinnacle	1.5	27	0.17	1.2

Figure 1. Photograph of the hemispherical, conical and pinnacle canopy models with the dosimetric system deployed at various sites over the canopies.

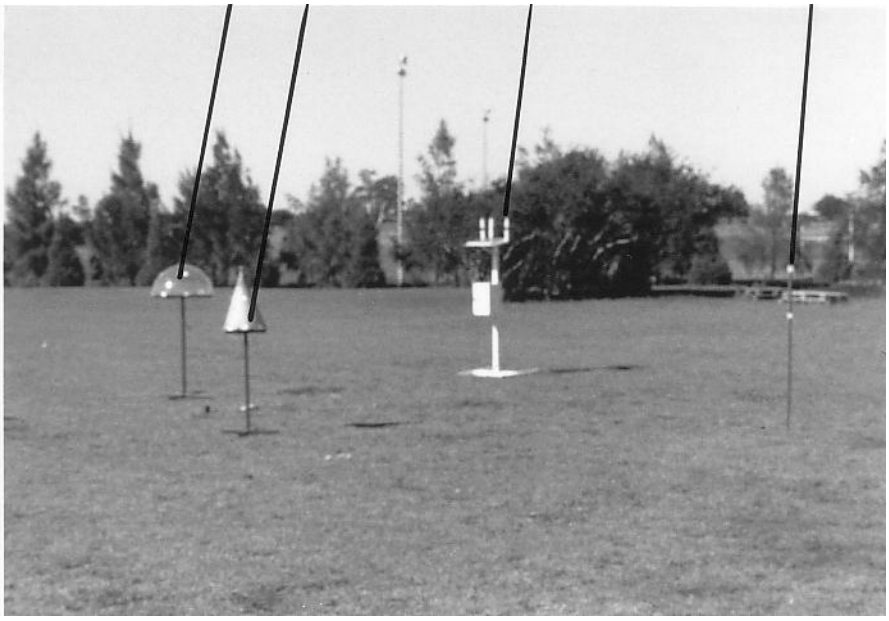
Figure 2. (1) The generalised plant damage action spectrum[14] and (2) the action spectrum for a variety of photoresponses in intact cucumber[15].

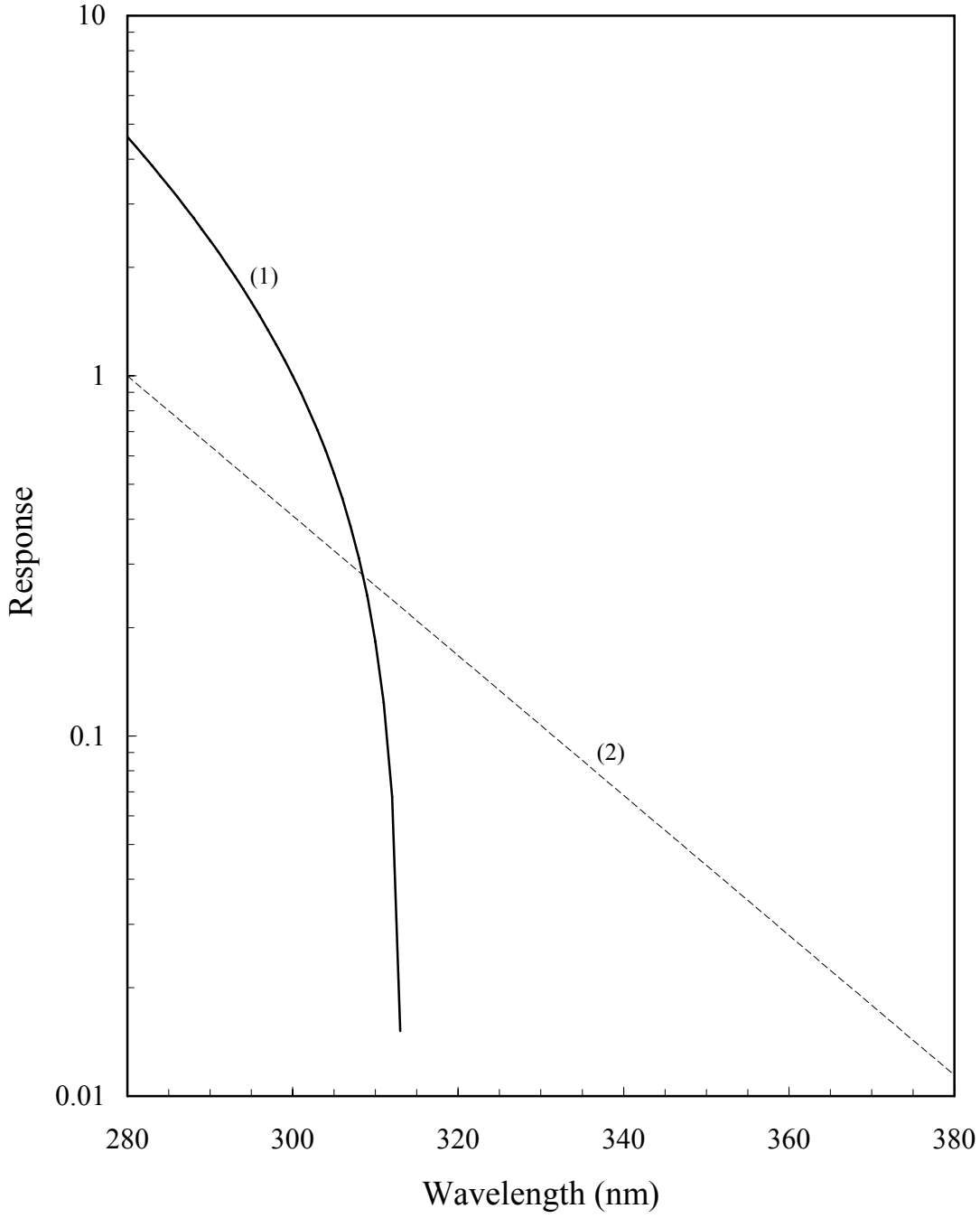
Figure 3. Two evaluated spectra at the (1) NM and (2) SM sites for the 12:00 to 12:10 EST exposure on the 31 March 1995.

Figure 4. Biological effectiveness calculated from the evaluated spectra for the hemispherical canopy exposure on 1 March, 1995 for generalised plant damage at the (1) Top site and the (3) NB site and for photo-effects in cucumbers at the (2) Top site and the (4) NB site.

Hemispherical Radiometers

Conical Pinnacle

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0.01
Response
(1)
(2)
280
300
320
340
360
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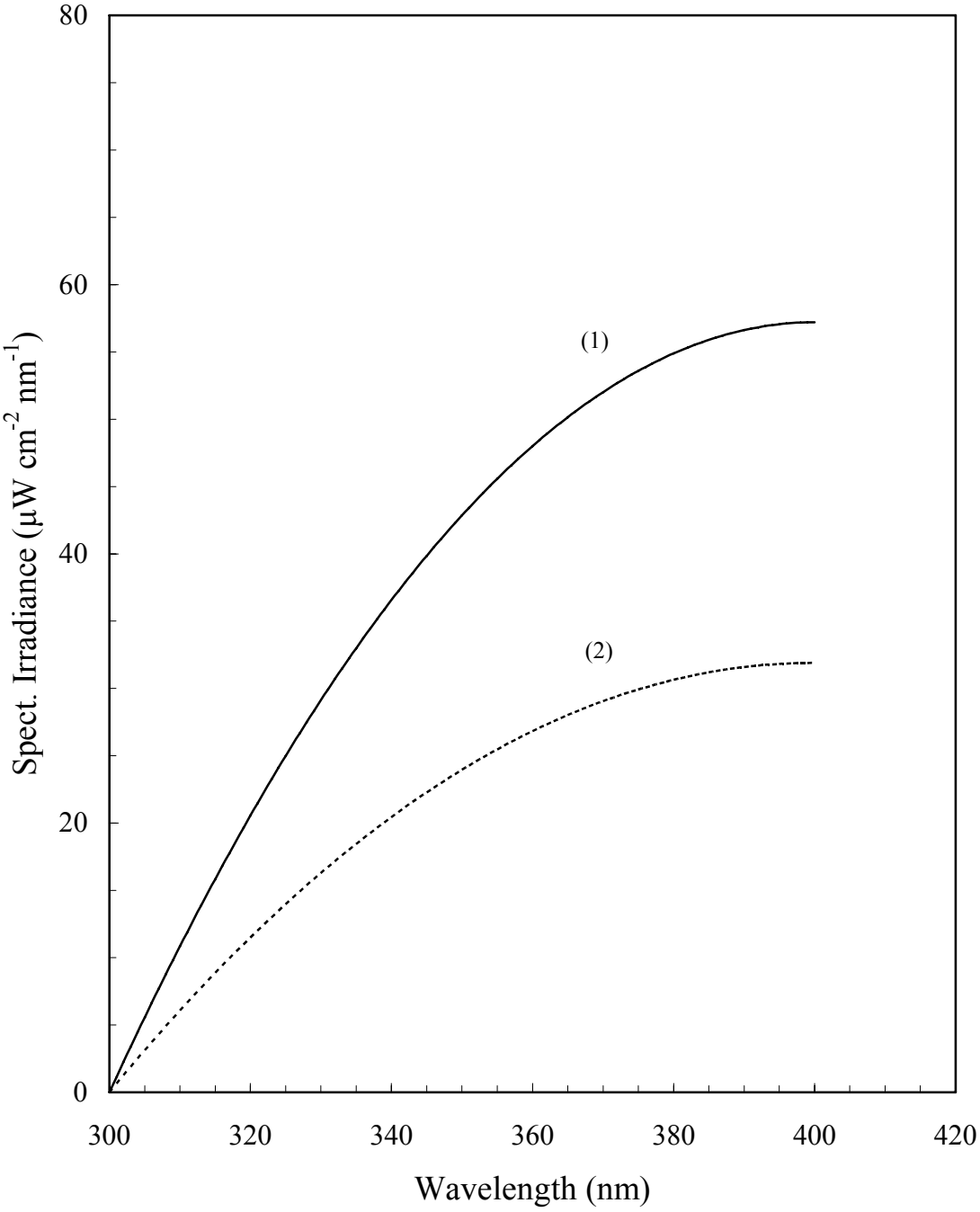
Wavelength (nm)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60
40
20
0
300
320
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360
380
400
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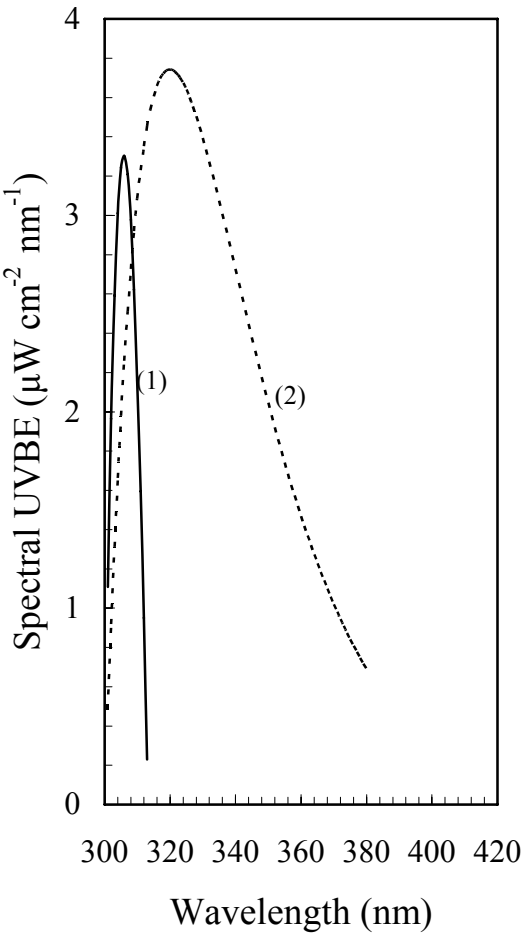
Spect. Irradiance (μW cm-2 nm-1)
Wavelength (nm)
(1)
(2)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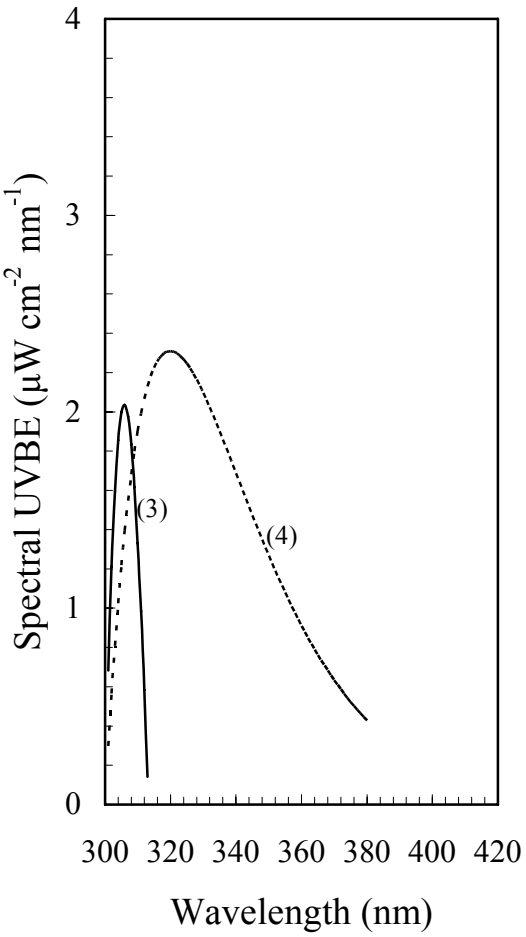
1
2
3
4
(1)
(2)
300 320 340 360 380 400 420
Wavelength (nm)


Spectral UVBE (μW cm-2 nm-1)
0
1
2
3
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(3)
(4)
300 320 340 360 380 400 420
Wavelength (nm)