A METHOD FOR EVALUATION OF UV AND BIOLOGICALLY EFFECTIVE EXPOSURES TO PLANTS

A.V. Parisi[†*¶], J.C.F. Wong[†], V. Galea[#]

[†]Affiliated with Centre for Medical and Health Physics, Queensland University of Technology, GPO Box 2434, BRISBANE 4001 AUSTRALIA

[*]Centre for Astronomy and Atmospheric Research, Faculty of Sciences, University of Southern Queensland, TOOWOOMBA 4350 AUSTRALIA

[#]Land and Food Systems, University of Queensland, Gatton College, LAWES, 4343 AUSTRALIA

Citation: Parisi, Alfio and Wong, J.C.F. and Galea, V. (1996) *A method for evaluation of UV and biologically effective exposures to plants.* Photochemistry and Photobiology, 64 (2). pp. 326-333. Authors' final manuscript version. Accessed from USQ ePrints (http://eprints.usq.edu.au)

Running title: Biologically Effective Exposures to Plants

Keywords: Ultraviolet radiation; Canopy exposures; Biologically effective UV; UV dosimeters; Plant canopy; Exposures to plants;

Abbreviations: 8MOP, 8-methoxypsoralen; ΔA, change in optical absorbance; CA, cellulose acetate; EST, Eastern Standard Time; NDA, nalidixic acid; UVA, ultraviolet waveband 320-400 nm; UVB, ultraviolet waveband 280-320 nm; UVBE, biologically effective UV; UVC, ultraviolet waveband less than 280 nm.

[¶] To whom correspondence should be addressed

Abstract: This paper presents a method for evaluating the UV and biologically effective exposures to a plant canopy during the irradiation of soybean with supplemental levels of UV radiation in a greenhouse study. The method employs four materials as dosimeters that allow evaluation of the UV spectra. The exposures evaluated at three growth stages were less by factors of 0.44, 0.49 and 0.56 compared to the ambient exposures. At the end of the irradiation period, the ambient biologically effective exposure for generalised plant response was higher by 180% compared to that calculated over the canopy. This is the magnitude of the error in UV studies that provide the ambient exposure as a measure of the UV incident on the plant. Additionally, the difference between the ambient and canopy exposures varied during the growth stages. These results indicate that the dosimetric technique applied to evaluating the UV exposures over a plant canopy is a more accurate representation of the UV exposure incident on a plant than any obtained by measuring the ambient exposures only.

INTRODUCTION

Studies in the literature of UV effects on plants measure the ambient exposure with radiometers and spectroradiometers and provide this as a measure of the UV exposure to plants. Due to factors such as the inclined surfaces of some of the individual plant canopy, self-shading and shading of the canopy by neighbouring plants, the UV exposure to the plant canopy may be significantly less than the ambient exposure. The incident UV spectrum to various parts of the plant canopy may be different to the ambient spectrum. This affects the biologically effective exposure which is wavelength dependent. Additionally, due to changes in the plant canopy with growth, the difference between the canopy and the ambient exposures may vary with the growth stage. As a result the ambient exposures may not be an accurate assessment of the UV exposure to the plant.

A number of studies[1,2] have reported that UV effects on plants are dependent on the exposure levels. Consequently, a more accurate measure of the UV exposure to the plant canopy is required. This is necessary for comparing studies between laboratories under different conditions. Radiometers and spectroradiometers provide only the ambient exposure and cannot be employed to provide the exposure to the canopy. No method currently exists for measuring the UV and biologically effective exposures to the plant canopy.

The object of this research was to apply a new technique utilising a composite system of four dosimeter materials for the evaluation of UV spectra to calculate UV and biologically effective exposures over a real plant canopy in an experiment designed to measure the amount of plant damage due to enhanced levels of UV radiation. This was to test if the dosimetric technique can be applied in a real plant study. The aim was to provide a more accurate representation of the UV exposure incident on a plant in studies of the effects of enhanced UV levels. A more accurate measurement of the exposures will facilitate the comparison of the effects on plants measured in greenhouse studies under different irradiation conditions. The exposures were measured at various sites over a selected plant which was surrounded by and potentially shaded by the neighbouring potted plants at three periods in a day and at three stages of growth to provide the exposures over the whole canopy at each growth stage and for the entire irradiation period.

Soybeans (*Glycine max* [L.] Merr.) were selected as the plants for the research for the following reasons:

- Soybean is a summer crop which corresponds to the highest levels of UV.
- The crop is relevant to agriculture in South-East Queensland.
- The plants can be easily grown in pot trials
- The plants are of a manageable size
- Several varieties of soybean have been reported in the literature to be UV sensitive.

The soybean cultivar Essex was selected for this research. This cultivar is not normally grown in Australia, but is popular in the USA and previous greenhouse[2,3,4] and field studies[5] have shown it to be sensitive to UVB radiation.

METHODS

Irradiation

Soybean (cv. Essex) were planted in April with two seeds per pot in one litre pots filled with potting mix comprising peat moss, vermiculite and sand (1:1:1) in the glasshouse at the University of Southern Queensland, Toowoomba (27.5^{o} S latitude). Upon seedling emergence forty-six of the pots were randomly selected and placed in the treated plots. Twenty-three of the pots were placed in the control plot. The plants were watered three times a week and fertilised weekly with Nitrosol (13% N, 2.3% P, 10% K) mixed 10 ml to 2.5 l water. The natural photoperiod was 10.5 to 11 hours per day.

The treated and control plots were within a frame constructed specifically for the purpose. The site of the frame was checked with a luxmeter for uniform levels of visible radiation. A plan of the frame is provided in Figure 1 with a photograph in Figure 2. The frame was divided into four plots, two for the treated and two for the control plants. Supplemental UVB radiation was provided using similar procedures to previous studies[3]. Philips TL40/12 lamps (Lawrence and Hanson, Toowoomba, Australia) were suspended in a horizontal rack above the plants as shown in Figure 2. This frame could be raised on the four uprights in order to maintain a constant height above the plant tops during plant growth. As seen in Figure 1, each plot contained two lamps spaced 0.3 m apart with each lamp 1.2 m long. Each of the lamps was fitted with a reflector for directing the radiation downwards. Prior to use, the lamps were preburnt for 100 hr in order to minimise irradiation changes with time[6]. The output of one lamp was measured with a double holographic grating spectroradiometer with calibration traceable to the primary Australian standard lamp housed at the National Measurement Laboratory[7].

The UVB radiation in the treated plot was provided by filtering the lamps with 0.13 mm cellulose acetate (CA) (Artery, Hobart, Australia). This allowed transmission down to approximately 292 nm. For the control group, the lamps were filtered with 0.13 mm Mylar (Cadillac Plastics, Australia) which provided transmission down to 320 nm. All the filter material was pre-solarised for eight hours and wrapped around the lamps. Both types of filter material degrade with use due to the effects of heat and UVB radiation[8]. Consequently the CA filters were replaced on a four day cycle and the Mylar filters were replaced weekly.

Each plot was separated by hanging sheets of Mylar. The entire frame was surrounded by hanging sheets of LLUMAR (Scotchline, Australia) to absorb all radiation below 400 nm and allow the transmission of photosynthetically active radiation. The spectral irradiance of a lamp at 0.75 m through LLUMAR and pre-solarised CA and Mylar was measured with the spectroradiometer. The spectral irradiance of a lamp through CA and Mylar that had been used for 24 and 42 hours respectively following pre-solarisation was also measured.

The plants were irradiated for six hours daily (09:00 to 15:00 EST) at a height of 0.75 m till the full expansion of the fifth tri-foliolate leaf above the unifoliolate node[4]. The irradiation period started on the 20th April and ended on the 4th June (a total of 46 days). Within each plot the plants were randomised twice weekly and if required the height of the lamps above the plant tops adjusted weekly. Over the

irradiation period the greenhouse day peak temperatures ranged from 17 to 26 ^{o}C and the night minimum temperatures ranged from 10 to 15 ^{o}C.

Measurement of Exposures

The dosimetric technique of measuring UV exposure employed the four materials polysulphone, nalidixic acid (NDA), 8-methoxypsoralen (8MOP) and phenothiazine in thin film form[9-12]. The materials were fixed in a holder 30 mm x 30 mm with four holes of 6 mm diameter with a different material over each hole. Upon exposure to UV radiation, each of the materials undergoes a change in optical absorbance (ΔA). The optical absorbance was measured before and after exposure with a spectrophotometer (Shimadzu Co., Kyoto, Japan) at a wavelength in the waveband for which the largest ΔA occurs, namely, 330 nm for polysulphone and NDA, 305 nm for 8MOP and 280 nm for phenothiazine. The change in optical absorbance of a dosimeter material as a result of exposure to a UV source spectrum, S(λ) over an interval, T, is:

$$\Delta A_i = T\int_{uv} S(\lambda)R_i(\lambda)d\lambda \qquad i = 1,...,4 \qquad (1)$$

where $R_i(\lambda)$ is the spectral response or wavelength sensitivity of the material and the subscript is used to designate one of the four different types of dosimeter material used. The spectral response of each material was measured with monochromatic radiation in 10 nm steps using an irradiation monochromator (Spectral Energy Co., 57 Woodland Ave., Westwood, New Jersey 07675, USA).

The spectrum was evaluated by exposing the dosimeters to the source and the resulting change in optical absorbance for each dosimeter, ΔA_i, measured. A predicted value for the change in absorbance for each dosimeter, $\Delta A_i'$, was calculated using an assumed function for the source spectrum of the form:

$$S(\lambda) = (\lambda - \lambda_0) * (\sum_{i=1}^{n} a_i \lambda^{i-1}) \qquad (2)$$

The parameters, a_i of the assumed S(λ) were found by an iterative method[13] by minimising the least squares function, χ^2, defined by:

$$\chi^2 = \sum_{i=1}^{4} \frac{1}{\sigma_i^2} (\Delta A_i - \Delta A_i')^2 \qquad (3)$$

where σ_i is the error in ΔA_i. The assumed function for S(λ) was constrained to possess a root at λ_o, the value of which was determined from a knowledge of the wavelength for which the source irradiance was zero. The value of n in Equation (2) was determined by an F test[13] which was used to calculate if there was a statistically significant improvement in χ^2 if the order of the fitted function was increased by one.

In order to allow comparison of the spectrum evaluated with the system 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[7]. The measurements were made at 08:54, 09:59 and 11:04 Eastern Standard Time (EST) in summer in Brisbane, Australia. Five minutes exposure to summer sunshine was sufficient to produce a measurable ΔA in each of the dosimeter materials.

For the treated plot in the irradiation facility, a preliminary experiment showed that an exposure of 90 minutes was required to provide an appreciable ΔA in each of the materials. The dosimetric system of the four materials was placed at nine sites over the plant canopy in the treated and in the control group. The soybean plant canopy approximated a hemispherical shape and the dosimeters were sited at the orientations in Table 1[14]. The dosimeters were located over the canopy on holders supported on arms constructed from 2 mm steel. Figure 3 is a photograph of the plant with the holders and dosimeters. The holders can be located at any point on the arms to allow measurements to be taken at different stages in the plants growth. This frame is lightweight and minimises any shading of the plant.

Following exposure, the measured values of ΔA allow the evaluation of the UV spectrum. Knowledge of the spectrum allows the UV exposure in a particular waveband to be determined or alternatively, the biologically effective (UVBE) exposure for a particular process may be calculated from:

$$UVBE = T \int S(\lambda)\, A(\lambda)\, d\lambda \qquad (4)$$

where $S(\lambda)$ is the evaluated spectrum, T is the exposure period and $A(\lambda)$ is the action spectrum for a particular process. In this work, the generalised plant response action spectrum[15] normalised at 300 nm and numerically fitted[16] and the action spectrum for a variety of photoresponses in intact cucumber[17] as shown in Figure 4 have been employed. The UV or biologically effective exposures evaluated as described above at each measurement site were interpolated between sites and summed to produce the exposures to the whole plant canopy[14].

The levels of UV exposure were also measured employing an instrumental technique. The instrumental technique consisted of employing radiometers fitted with filters to transmit UVB and UVA (Monitor Sensors, Caboolture, Australia). These sensors recorded UV irradiance averaged over six minutes with a data logger at six minute intervals. The radiometers were calibrated to sunshine on a clear day in late autumn against the calibrated spectroradiometer. The spectroradiometer provides the spectral irradiance in 1 nm intervals and the UV irradiance is calculated by:

$$UV = \int S(\lambda)\, d\lambda \qquad (5)$$

where $S(\lambda)$ is the solar spectral irradiance (W cm^{-2} nm^{-1}) and the integration is the summation over the appropriate waveband, namely, 280 to 320 nm for UVB and 320 to 400 nm for UVA.

The UV exposures were measured at three days during the irradiation period and three periods during each of these days. The first period commenced at the start of the irradiation period, the second was centred approximately about solar noon and the third ended at the end of the irradiation period. The days selected for the measurements were at the full expansion of the first, third and fifth trifoliolate leaves above the unifoliolate node (V2, V4 and V6 stages[4] of growth) and corresponded with 16, 30 and 46 days of irradiation respectively.

Plant Growth

At the V2 and V4 stages, the height of twelve plants from the treated group and six plants from the control group was measured. The pots were randomly selected from the appropriate group and the largest plant in each pot measured. At the end of the

irradiation period the plant height was measured. Following harvest, fresh weight was measured along with leaf area using a planimeter (Paton Electronic) and dry weight after oven drying at 70 to 80 ^{o}C for 48 hours.

RESULTS

Irradiation

The measured spectral irradiance of an unfiltered Philips sunlamp at 0.75 m is plotted in Figure 5. The lamp output comprises a broad emission spectrum in the UVB with lower emissions in the UVA and UVC. The transmission through LLUMAR is essentially zero for all UV wavebands as shown in Figure 5. The measured spectral irradiance filtered through CA (Figure 6) as employed for the treated group of plants provides a zero irradiance at approximately 292 nm. The sunlamp filtered through Mylar (Figure 6) as utilised in the control group of plants allows negligible transmission of UVB. As a result of the transmission properties of the greenhouse glass the control group of plants received negligible UVB radiation. Consequently, the UVBE using the generalised plant response action spectrum in Figure 4 for the control plot was zero. It is worthwhile noting that the predominance of UV studies on soybeans employ this action spectrum in calculating UVBE. The measured spectral irradiance of the lamp through CA and Mylar that has been used for 24 and 42 hours respectively following pre-solarisation is also plotted in Figure 6. The spectral irradiance through these aged filters is approximately halved. This verifies the requirement to replace the filter material on a regular basis as performed in this research.

Measurement of Exposures

The solar spectra evaluated at 08:54 and 11:04 EST are presented in Figure 7 as the solid lines along with the measured spectra as the square data points. The differences between the two spectra were quantified as an 'integrated difference' by summing the absolute differences between the spectra at 1 nm intervals and dividing by the integrated spectral irradiance of the measured spectrum. For each case, these differences were less than 20%. The biologically effective exposures for the generalised plant damage action spectrum[15] for both the measured and evaluated spectra are provided in Table 2. The difference between the two is less than 20%.

The values of ΔA for the four materials in the dosimetric system are provided in Table 1 for the treated plot for the exposure from 09:26 to 10:56 EST at the V2 stage of growth. The Table also provides information on the orientation of each dosimeter. At the time there was partial cloud of less than 4 octas. The values in parentheses are for the control plot. For the control plot the values of ΔA for polysulphone were zero or negligible. Polysulphone responds to UVB wavelengths only so this verifies the absence of UVB radiation in the control group of plants.

An example of the spectrum evaluated from the values of ΔA in Table 1 is provided in Figure 8 for the NM site. The fitted function was constrained to possess a root at 292 nm. The evaluated function is of the form:

$$S(\lambda) = (\lambda\text{-}292)(a_1 + a_2\lambda + a_3\lambda^2) \quad (6)$$

where a_1, a_2 and a_3 are the evaluated coefficients. The evaluated spectrum in Figure 8, consists of two components, namely, the UVB from the CA filtered lamps from 293

to 320 nm and the UVA due to the solar spectrum filtered through the greenhouse glass from 320 to 400 nm.

For the values of ΔA in Table 1, the spectra have been evaluated for each of the nine sites over the plant and the UVB, UVA and biologically effective UV exposures for the generalised plant damage[15] and plant damage[17] action spectra are calculated and provided in Table 3. This process was repeated for the other two exposure periods at this V2 growth stage and for the V4 and V6 stages. The various exposures to the whole plant canopy were calculated and shown in Table 4. From the comparison in Table 2 of the exposures calculated with the evaluated and measured spectra, the estimated error in the above results is 20% or less. Table 5 provides the UVB exposures to the entire canopy calculated by this method compared to those measured with the Monitor Sensors radiometers and calculated with the dosimetric technique to a horizontal surface. This is for the exposure period 11:07 to 12:37 EST for the V2 stage. This Table illustrates the differences that may exist in measuring the ambient exposure on a horizontal surface compared to evaluating the exposure to the entire plant canopy. Additionally, the Monitor Sensor radiometers were calibrated to full sunshine, whereas the spectrum being measured within the greenhouse plots is entirely different. From a previous study[7], the error introduced may be as high as 40% when radiometers are utilised to measure exposures where the source spectrum differs from that for which they were calibrated.

For the three growth stages, the data in Table 4 for the UVB and UVBE (generalised plant response) exposures to the canopy have been interpolated between measurement periods to provide exposures for the complete day for the treated plants. These were interpolated between measurement days to provide the respective cumulative exposures at each stage and for the entire irradiation period. The UVBE exposures are shown in Table 6. In a similar fashion, the ambient exposures on a horizontal surface measured at plant height with the dosimetric technique have been provided for comparison. Comparing the exposure measured over the canopy to the ambient shows that the latter is significantly higher in each case. Another point to note from Table 6 is that the differences between the exposures measured over the canopy and the ambient exposures varies with the growth stage. The UVBE exposures measured over the canopy are less by factors of 0.44, 0.49 and 0.56 at the V2, V4 and V6 stages respectively.

Plant Growth

Table 7 provides the results of the plant height at the three stages of growth and the leaf area, fresh and dry weight at the end of the irradiation period. The means for each parameter for the treated and control group are provided in the Table. The error is represented as one standard error in the mean. The plant height is plotted as a function of day number in Figure 9. The data was analysed with the standard t-test. There was a significant reduction in plant height due to the UV treatment at the V4 and V6 stages with 99.8% and 99.99% probability respectively with no significant difference at the V2 stage. There were no significant differences in the fresh weight, leaf area and dry weight between UV irradiated and control plants.

These results verify that the growth of Essex soybean is sensitive to UVB radiation and this shows as a difference in plant height. The plants in the treated group also

displayed patches of yellowing which were not evident in any of the plants in the control group. This indicates a UVB effect in chlorophyll breakdown. In this research, no difference was found in leaf area and plant fresh and dry weight. Murali *et al*.[4] did not measure plant height but found reductions in leaf area and total plant dry mass of 19 and 17% respectively at the V6 stage for Essex soybean. Teramura and Sullivan[2] measured plant height at the V4 stage for Essex soybean and found no statistically significant difference. These differences in results may be related to differences in the studies in the literature compared to this research, firstly in levels of UV exposure and secondly in microclimate conditions including the levels of photosynthetically active radiation which influences the UVB sensitivity of plants[2,3].

Murali *et al*.[4] and Teramura and Sullivan[2] measured an ambient daily UVBE exposure of 11.5 kJ m^{-2} using the generalised plant response action spectrum with the UV lamps at a height of 0.75 m. This present research employed an average ambient daily UVBE of 3.5 kJ m^{-2} or alternatively an average daily UVBE of 2.0 kJ m^{-2} to the individual plant canopy. This difference in ambient exposure is due mainly to the thickness of 0.08 mm of the CA filter material in the studies in the literature[2,4] and this study employing a thickness of 0.13 mm. This research showed that even these lower levels of UV (which to the authors knowledge have not been previously employed) produced an effect on Essex soybean. The difference in the levels of photosynthetically active radiation is due to the two studies being undertaken at different times of the year with the study by Murali *et al*.[4] from February to March and the work by Teramura and Sullivan[2] from May to July, with both at 39^{o} N latitude. The influence on plant response due to the level of UVB exposure emphasises the importance of this method. As the plant response is dependent on the level of UV exposure, a method that better assesses UV and UVBE exposures to a plant compared to measuring ambient levels is required. This method provides a more accurate assessment of the UV exposures to the plant canopy and consequently will allow an improved comparison of results on plant studies between different laboratories.

DISCUSSION

An irradiation facility for providing plants in greenhouse studies with supplemental levels of UVB radiation has been set up. The dosimetric method for evaluation of the UV spectrum and calculation of the UVB, UVA and biologically effective exposures for a particular process has been applied to a real plant study in this facility. Essex soybean were grown in control plots and plots treated with supplemental UVB. This soybean cultivar was verified to be UVB sensitive with a statistically significant reduction in plant height at the V4 and V6 growth stages between the treated and control plants. UV levels lower than had been previously employed produced an effect on Essex soybean.

The dosimetric technique was employed to evaluate the UV spectrum and from these the UV and UVBE exposures were calculated. Comparison of the results obtained with the evaluated spectra and the spectra measured with a calibrated spectroradiometer provided an agreement to better than 20%. The spectra were evaluated with the dosimetric technique at nine sites over a plant canopy in the treated plot at three points of the day at three growth stages. From these, the various UV and

UVBE exposures to the entire canopy were calculated at three growth stages. At the end of the V2, V4 and V6 stages, the plants in the treated plot had received total supplemental levels of 29, 57 and 94 kJ m^{-2} UVBE exposure (generalised plant damage) respectively over their canopy compared to zero UVBE received by the control plants. Compared to the ambient exposures measured with the dosimetric technique these exposures are less by factors of 0.44, 0.49 and 0.56 respectively for each stage. This is due to factors such as shading, self-shading and the inclined surfaces of the canopy receiving less exposure than the horizontal surfaces. At the end of the irradiation period, the ambient UVBE exposure was higher by 180% compared to that measured over the plant canopy. This is the magnitude of the error in UV studies that provide the ambient exposure as a measure of the UV incident on the plant. Furthermore, the difference factor varied for the three growth stages. This can be attributed to a number of variables, namely, changes in the plant canopies resulting in variability in the degree of self-shading and shading by other plants to the sides of the plant canopy, increases in the canopy area as the plant grows and degradation of the transmission properties of the lamp filter material. A further variable which is not relevant for UVB or generalised plant response UVBE, but which is significant for action spectra that extend into the UVA is the variability during the irradiation period of the solar UVA transmitted through the greenhouse glass.

This research highlights the advantages of the dosimetric technique for the evaluation of UV spectra and exposures. The method is portable, cost-effective and the dosimetric system may be deployed over or even within foliage to allow simultaneous multi-site measurements. The method allows the evaluation of the UVB and UVA exposures with the advantage over radiometers and single dosimeters of providing an evaluation of the source spectra at each site from which the biologically effective exposures may be calculated for any action spectrum. Existing methods employing radiometers and spectroradiometers measure the ambient exposure and do not provide any information on the UV and UVBE exposures to the canopy. This method provides the exposures to the canopy. This combined with the changing difference at various growth stages between the ambient and canopy exposures means that those evaluated by this method are a more accurate representation of the UV exposure incident on a plant than any obtained by measuring only the ambient exposures.

ACKNOWLEDGEMENTS

The authors would like to thank Mr Ron Matthews for constructing the facility, Ms Kym Deaves for advice on greenhouse procedures and Mr R.A. Fleming for proof reading the manuscript.

REFERENCES

1. Lydon, J., A.H. Teramura and E.G. Summers (1986) Effects of ultraviolet-B radiation on the growth and productivity of field grown soybean. In *Stratospheric Ozone Reduction, Solar Ultraviolet Radiation and Plant Life* (Edited by R.C. Worrest and M.M. Caldwell), pp.313-325, Springer-Verlag, Berlin.

2. Teramura, A.H. and J.H. Sullivan (1987) Soybean growth responses to enhanced levels of ultraviolet-B radiation under greenhouse conditions. *Am. J. Bot.* **74**, 975-979.

3. Mirecki, R.M. and A.H. Teramura (1984) Effects of ultraviolet-B irradiance on soybean V. The dependence of plant sensitivity on the photosynthetic photon flux density during and after leaf expansion. *Plant Physiol.* **74**(3), 475-480.

4. Murali, N.S., A.H. Teramura and S.K. Randall (1988) Response differences between two soybean cultivars with contrasting UV-B radiation sensitivities. *Photochem. Photobiol*. **48**(5), 653-657.

5. Teramura, A.H. and N.S. Murali (1986) Intraspecific differences in growth and yield of soybean exposed to ultraviolet-B radiation under greenhouse and field conditions. *Environ. Exp. Bot.* **26**, 89-95.

6. Sisson, W.B. and M.M. Caldwell (1975) Lamp/filter systems for simulation of solar UV irradiance under reduced atmospheric ozone. *Photochem. Photobiol*. **21**, 453-456.

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

8. Middleton, E.M. and A.H. Teramura (1993) Potential errors in the use of cellulose diacetate and mylar filters in UV-B radiation studies. *Photochem. Photobiol*. **57**(4), 895-902.

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

10. 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.

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

12. 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.

13. Bevington, P.R. and D.K. Robinson (1992) *Data Reduction and Error Analysis for the Physical Sciences*, McGraw-Hill, New York, pp.141-167.

14. 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.

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

16. Green, A.E.S., J. Mo and J.H. Miller (1974) The middle ultraviolet reaching the ground. *Photochem. Photobiol*. **19**, 251-259.

17. 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. The values of ΔA for the exposure in the treated plot from 09:26 to 10:56 EST at the V2 stage of growth. The values in parentheses are for the control plot. The second column (α) is the angle in degrees relative to north of each dosimeter and the third column (β) is the angle relative to the vertical.

			Change in absorbance, ΔA			
Site[14]	α	β	NDA	Polysulphone	8MOP	Phenothiazine
Top	_	90	0.09 (0.04)	0.14 (-0.01)	0.03 (0.01)	0.46 (0.30)
NB	0	0	0.05 (0.03)	0.02 (0.0)	0.02 (0.03)	0.11 (0.14)
NM	0	45	0.10 (0.04)	0.07 (0.0)	0.03 (0.02)	0.43 (0.27)
SM	180	45	0.06 (0.02)	0.08 (0.0)	0.04 (0.03)	0.47 (0.18)
SB	180	0	0.03 (0.01)	0.03 (0.0)	0.01 (0.03)	0.26 (0.03)
EB	90	0	0.04 (0.0)	0.00 (0.0)	0.02 (0.02)	0.13 (0.08)
EM	90	45	0.07 (0.02)	0.06 (-0.01)	0.02 (-0.01)	0.30 (0.21)
WM	270	45	0.02 (0.02)	0.01 (0.01)	0.01 (0.04)	0.18 (0.28)
WB	270	0	0.09 (0.02)	0.07 (0.0)	0.03 (0.05)	0.42 (0.21)

Table 2. Evaluated and measured biologically effective irradiances for generalised plant damage.

Time EST	Evaluated irradiance ($\mu W\ cm^{-2}$)	Measured irradiance ($\mu W\ cm^{-2}$)
08:54	21	18
09:59	29	25
11:04	36	31

Table 3. The UVB and UVA exposures calculated from the spectra evaluated with the dosimetric technique and the biologically effective exposures calculated from this evaluated spectra for action spectrum 1[15] and action spectrum 2[17]. These are for an exposure period of ninety minutes.

Site	UVB ($J\ cm^{-2}$)	UVA ($J\ cm^{-2}$)	Biologically effective exposure ($J\ cm^{-2}$)	
			Action spectrum 1	Action spectrum 2
Top	0.27	2.34	0.11	0.10
NB	0.04	0.29	0.01	0.02
NM	0.21	2.68	0.07	0.10
SM	0.17	2.66	0.06	0.07
SB	0.07	1.28	0.03	0.03
EB	0.12	0.54	0.04	0.05
EM	0.14	1.48	0.05	0.07
WM	0.05	1.60	0.02	0.04
WB	0.15	1.94	0.05	0.09

Table 4. The UV and biologically effective UV exposures to the whole plant canopy calculated from the exposures at each site over the plant for the various growth stages and exposure periods.

Growth stage	Exposure time (EST)	Evaluated exposure (J cm^{-2})			
		UVB	UVA	UVBE Action spectrum 1	UVBE Action spectrum 2
V2	0926-1056	0.13	1.68	0.049	0.064
	1107-1237	0.10	1.94	0.044	0.048
	1327-1457	0.10	2.41	0.043	0.054
V4	0900-1030	0.15	1.85	0.064	0.060
	1100-1230	0.12	1.90	0.055	0.051
	1327-1457	0.13	2.25	0.055	0.056
V6	0900-1030	0.16	2.30	0.069	0.069
	1100-1230	0.10	1.68	0.053	0.059
	1330-1500	0.13	1.84	0.057	0.051

Table 5. The UVB exposure to the entire canopy calculated by this method compared to the exposures measured with the Monitor Sensors radiometers (horizontal surface) and calculated with the dosimetric technique (horizontal surface) for 11:07 to 12:37 EST at the V2 stage.

Exposure to entire canopy ($J\ cm^{-2}$)	Monitor Sensor ($J\ cm^{-2}$)	Exposure to horizontal surface ($J\ cm^{-2}$)
0.10	0.28	0.23

Table 6. The UVBE (generalised plant damage) exposure to the canopy evaluated with the dosimetric technique and the ambient exposures on a horizontal surface evaluated with the dosimetric technique at three growth stages. The ratio of the canopy exposure to the ambient exposure measured with the dosimetric technique is provided in the final column.

	UVBE Exposures (kJ m^{-2})		
Growth stage	Canopy	Ambient - dosimetric technique	Canopy/Ambient
V2	29	66	0.44
V4	57	117	0.49
V6	94	169	0.56

Table 7. Growth parameters of Essex soybean for the treated and control groups. Values are means ± standard error.

Growth stage	Group	Height (cm)	Fresh weight (g)	Leaf area (cm^2)	Dry weight (g)
V2	Treated	15.5±0.4	_	_	_
	Control	16.1±0.9	_	_	_
V4	Treated	27.8±0.5	_	_	_
	Control	30.3±0.4	_	_	_
V6	Treated	51.9±1.2	9.5±0.4	393±16	1.22±0.06
	Control	62.1±1.4	8.9±0.4	389±19	1.17±0.06

FIGURE CAPTIONS

Figure 1. Plan of the irradiation set-up.

Figure 2. Photograph of the irradiation set-up.

Figure 3. Photograph of dosimeters placed over plant.

Figure 4. (1) The generalised plant damage action spectrum[15] and (2) the action spectrum for a variety of photoresponses in intact cucumber[17].

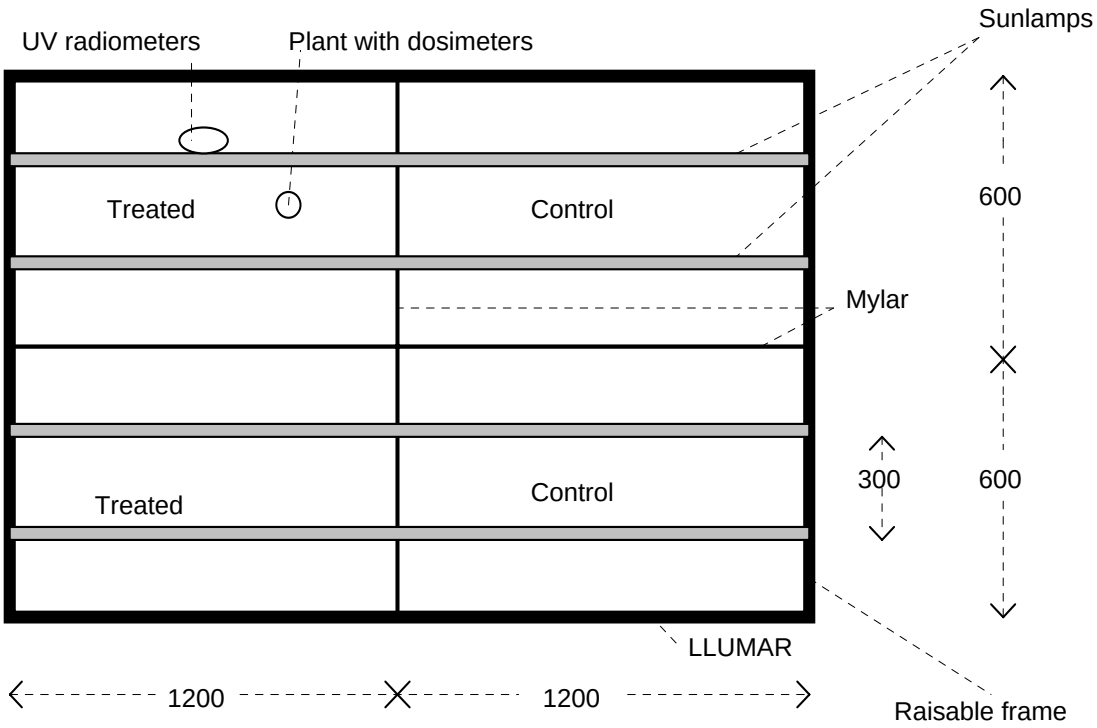
Figure 5. Spectral irradiance of the unfiltered UV lamp (1) and filtered through LLUMAR (2), both at a distance of 0.75 m.

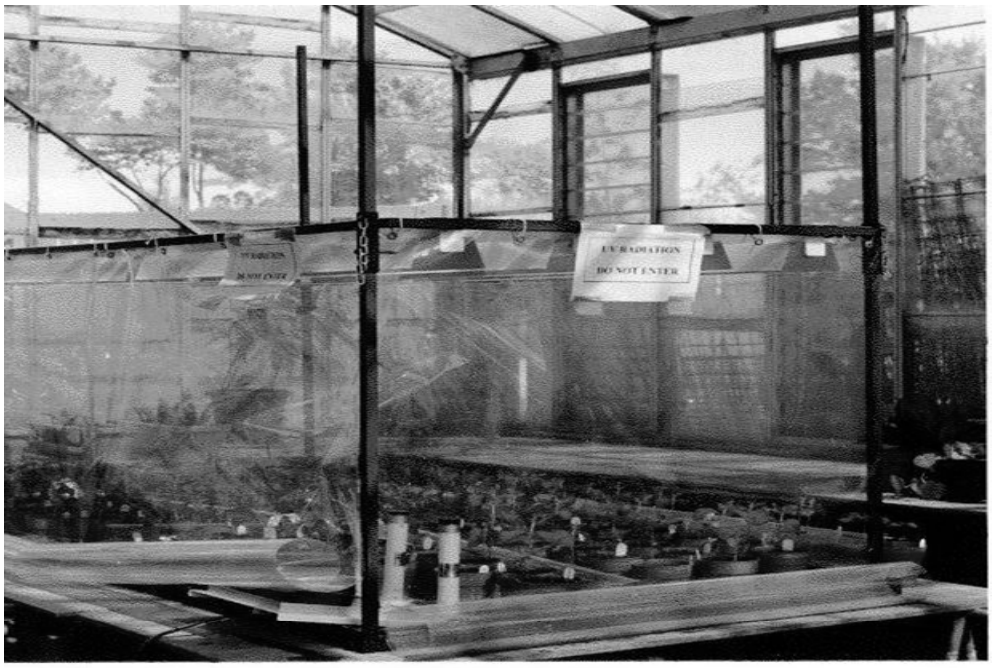
Figure 6. Spectral irradiance of the UV lamp at 0.75 m filtered through new (1) and aged (2) cellulose acetate filters and new (3) and aged (4) Mylar filters.

Figure 7. Evaluated (—) and measured (□) solar UV spectra in summer.

Figure 8. An example of an evaluated spectrum for the treated group with the lamp UVB and the UVA component from the Sun.

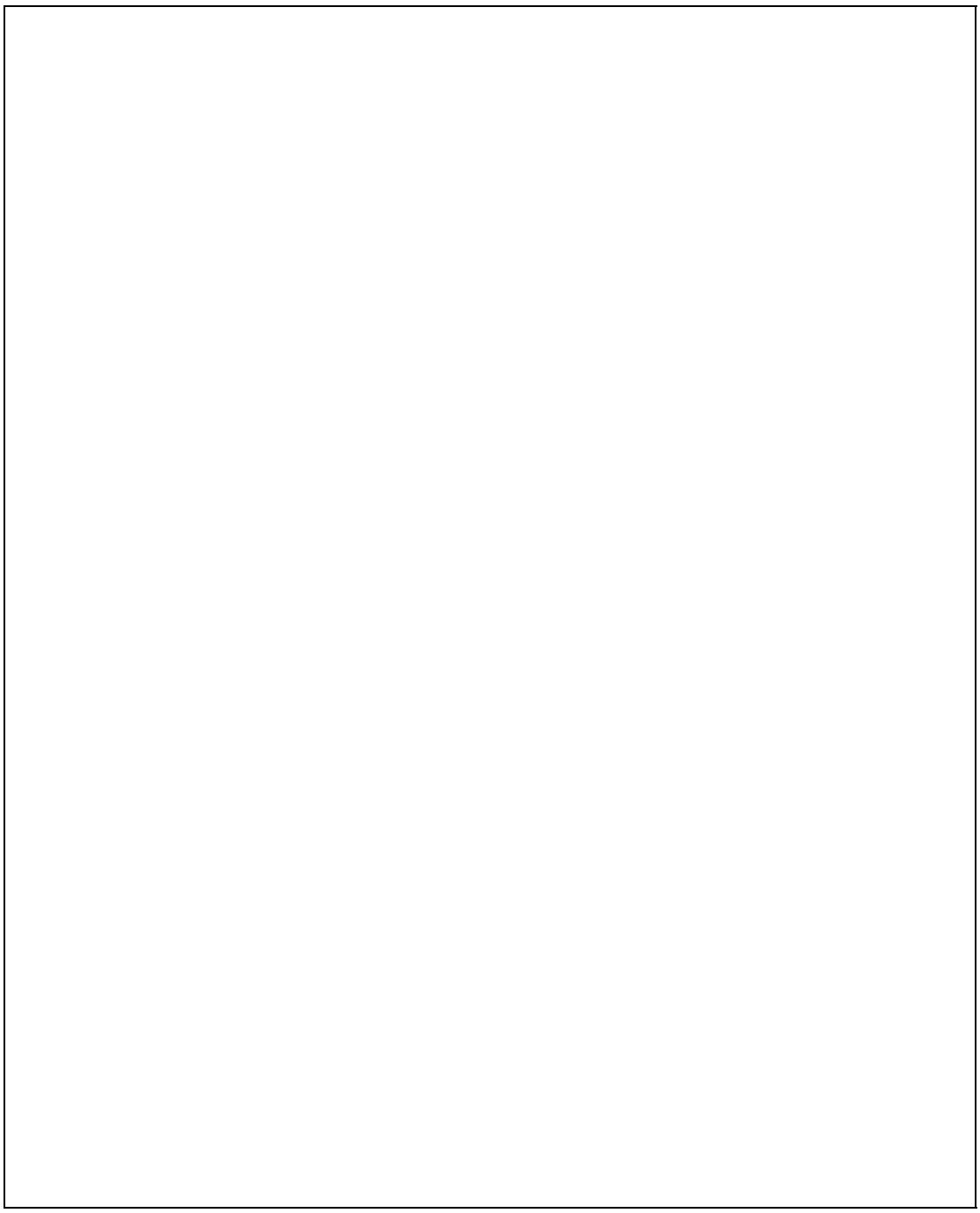
Figure 9. Plant height as a function of day number for the (1) treated and (2) control group of plants.

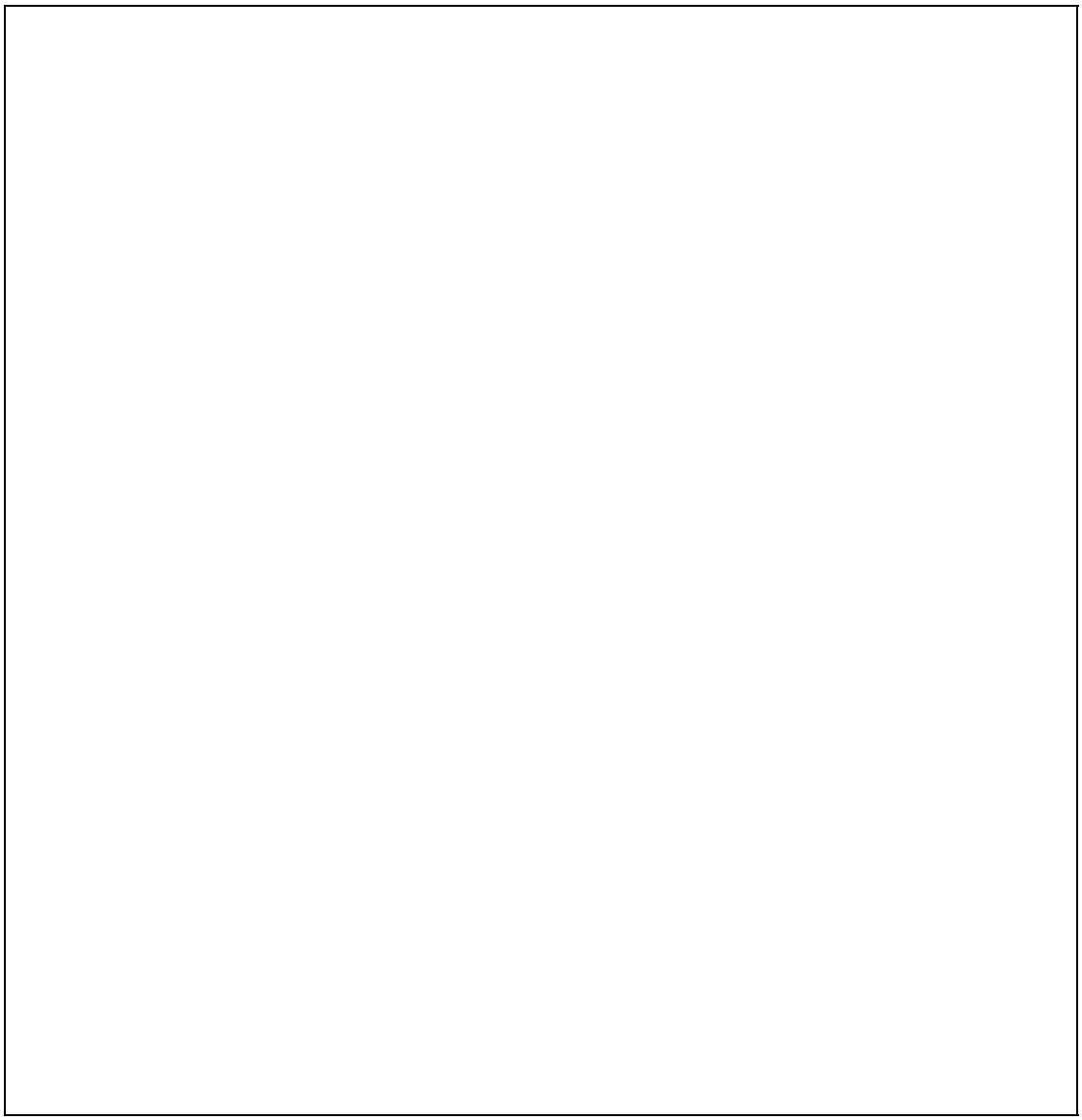

UV radiometers
Plant with dosimeters
Sunlamps
Treated
Control
600
Mylar
300
600
Treated
Control
LLUMAR
1200
1200
Raisable frame

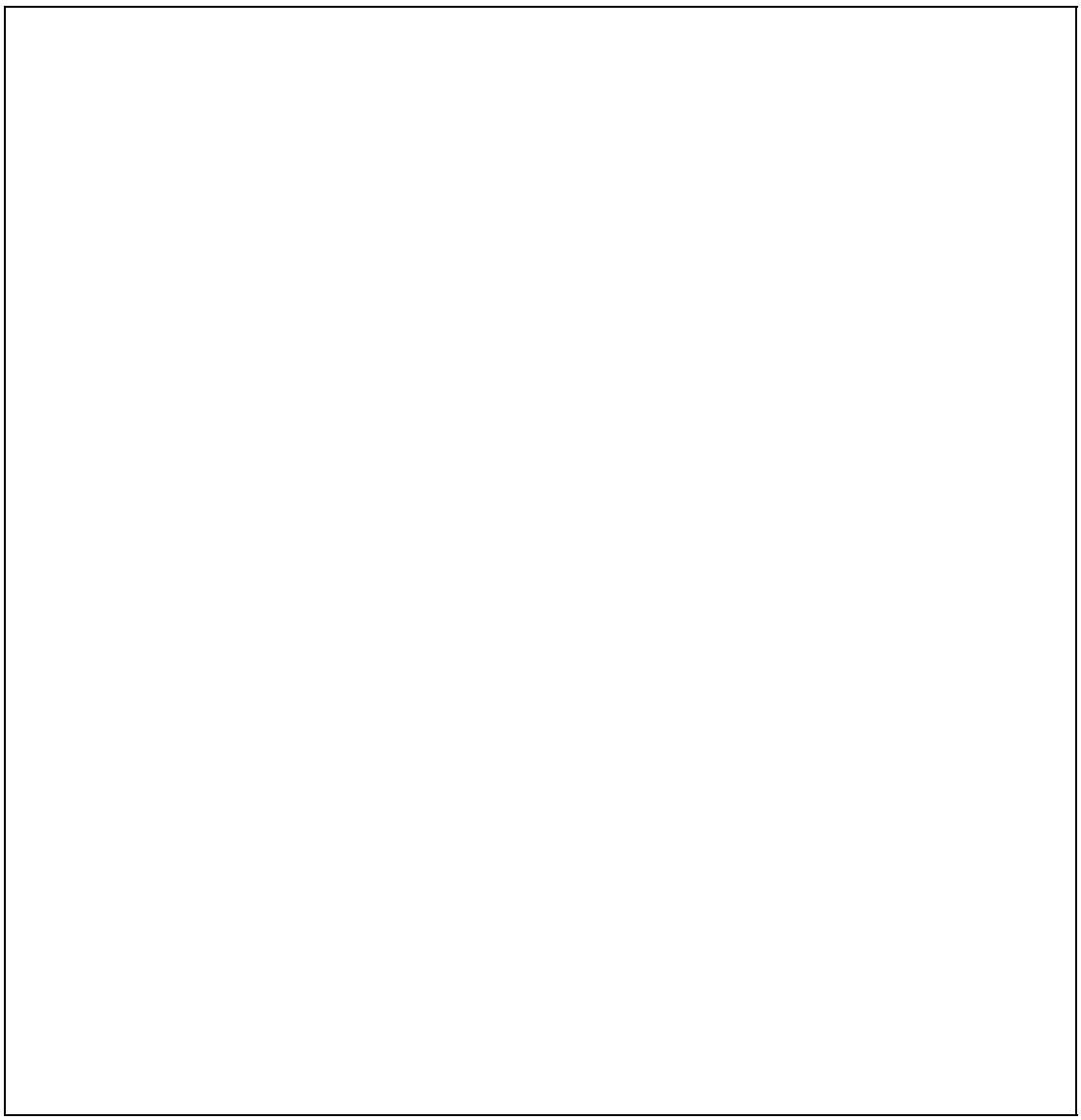

UV RADIATION
DO NOT ENTER

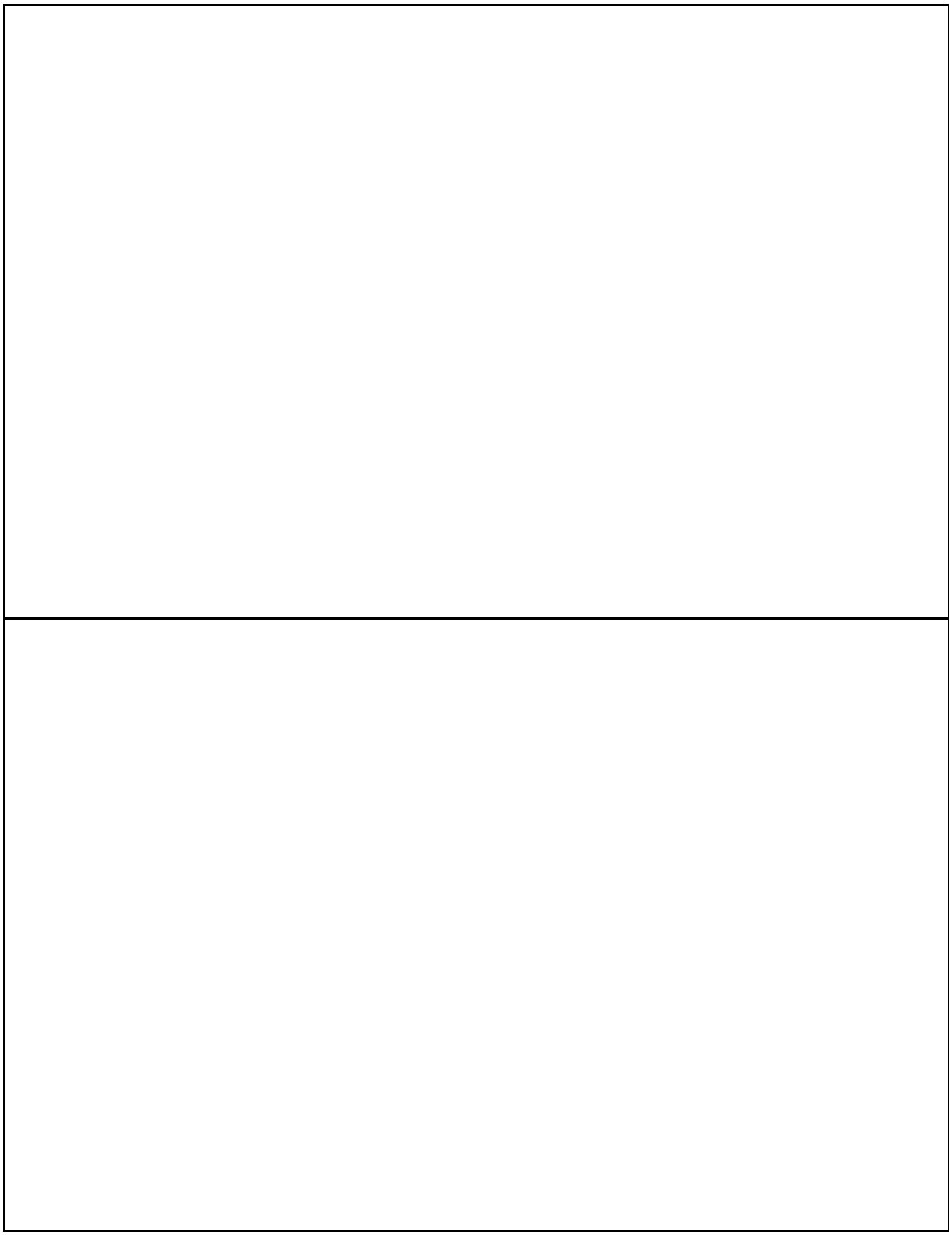
Dosimeters

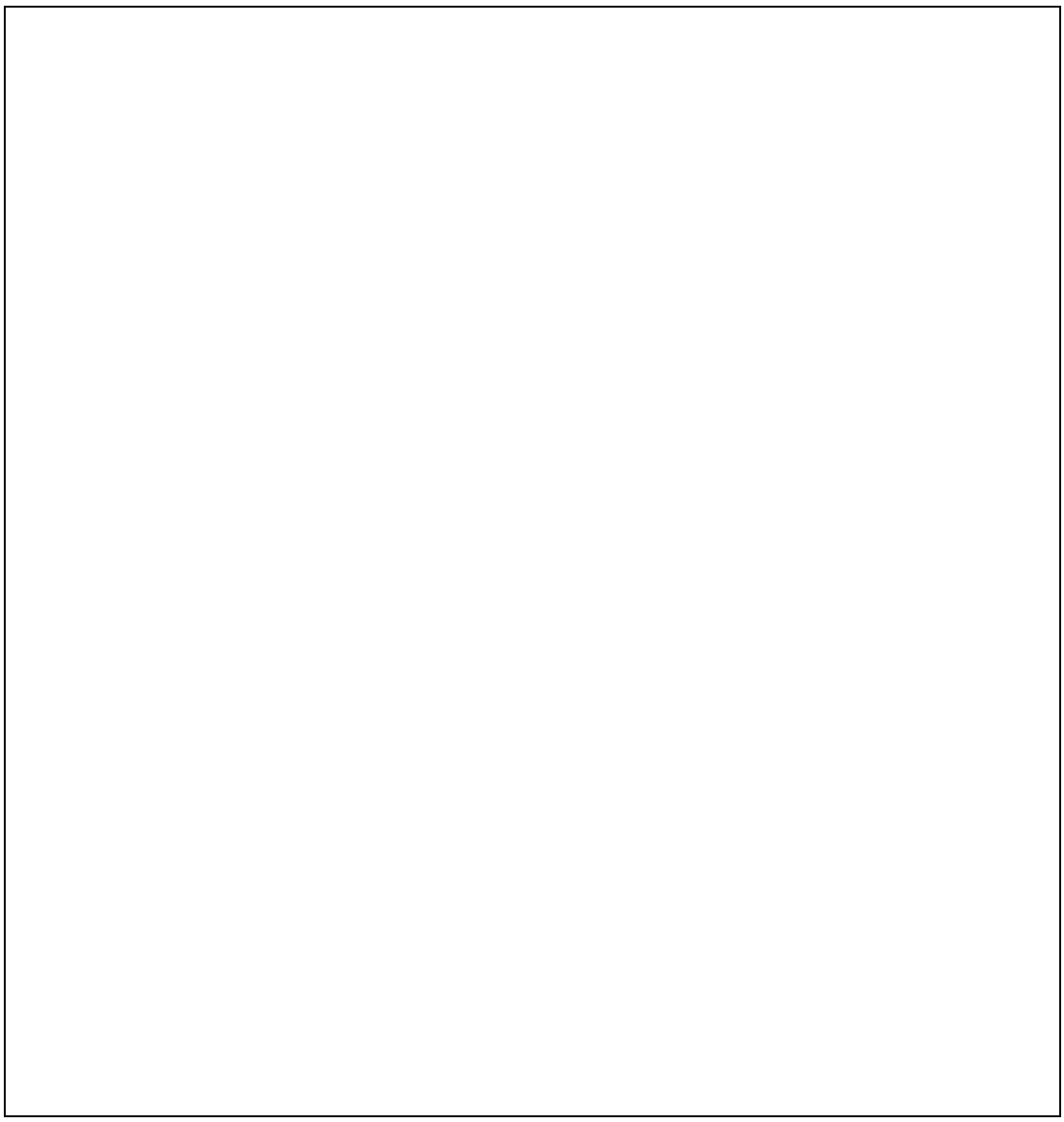
Lightweight frame with
Movable holders

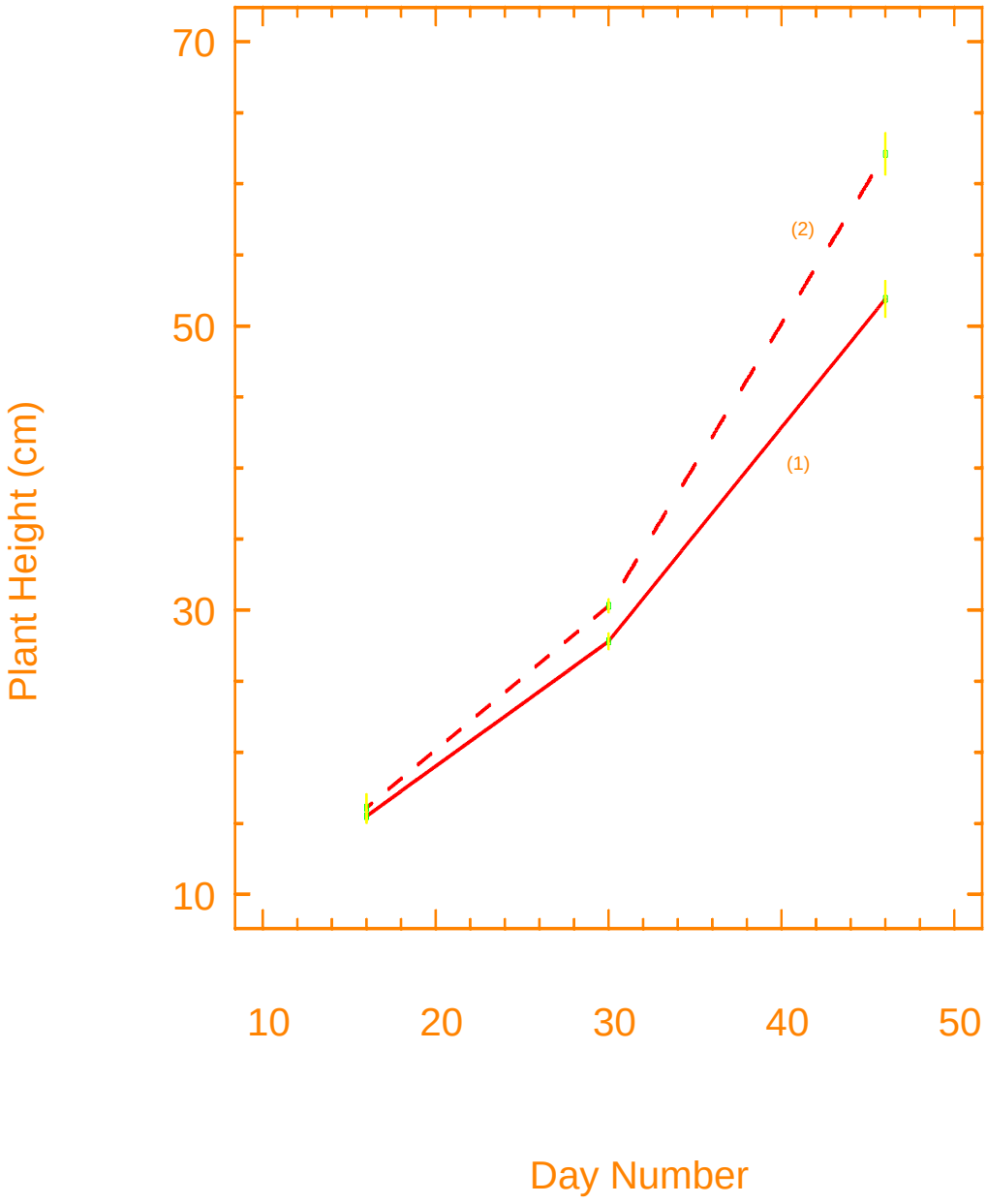











70
50
30
10
Plant Height (cm)
(2)
(1)
10
20
30
40
50
Day Number