A Supplemental Ultraviolet-B Radiation System for Open-Top Field Chambers

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ABSTRACT

Studies suggest that increased ultraviolet-B (UV-B) radiation at the earth's surface due to stratospheric ozone (O_3) depletion may affect crop production. Current levels of tropospheric O_3 are known to decrease crop yields. To assess the combined effects on plants of increased UV-B radiation and chronic exposure to O_3, a commonly used constant-addition supplemental UV-B radiation system was modified for use in open-top field chambers. Lamp banks containing 14 filtered UV-B-313 fluorescent lamps were suspended in 33 chambers to which either charcoal-filtered, nonfiltered, or nonfiltered air plus O_3 was added. Lamp banks provided ample levels and distribution of biologically effective UV-B ($UV\text{-}B_{BE}$) radiation for stimulating up to a 29% loss of column O_3, according to a radiative transfer model. However, ground-based measurements of solar $UV\text{-}B_{BE}$ radiation provided a more realistic base than the model for simulations of column O_3 loss using supplemental UV-B radiation. Shading by the lamp bank and chamber assembly reduced the daily solar $UV\text{-}B_{BE}$, UV-A, and visible irradiances inside the chamber on average by 24% ± 5% compared with ambient levels. Biweekly adjustments of the supplemental $UV\text{-}B_{BE}$ irradiance level and exposure period provided treatments that were proportional to the seasonal trend in solar $UV\text{-}B_{BE}$ radiation. Control of supplemental $UV\text{-}B_{BE}$ irradiance in proportion to solar $UV\text{-}B_{BE}$ irradiance during the day would better simulate the effects of stratospheric O_3 depletion. However, the constant-addition system was a simpler and less expensive method than the proportional-addition system for examining the relative sensitivity of plants to the combined effects of increased UV-B radiation and O_3 under field conditions.

SOLAR ultraviolet B (UV-B) radiation from 290 to 320 nm may be increasing at the earth's surface in temperate latitudes due to stratospheric ozone (O_3) depletion caused by photochemical reactions of certain chlorofluorocarbons in the stratosphere (Albritton, 1989) Research suggests that increased UV-B radiation might affect agricultural crop production. Studies have shown that UV-B radiation reduced growth and yield in some crops, altered competitive relationships among several crop and weed species, and possibly inhibited pollen germination and flower induction (Tevini and Teramura, 1989) Studies have also indicated that the effect of increased UV-B radiation can be modified by other environmental factors (Tevini and Teramura, 1989). For example, the effect of increased UV-B radiation on several soybean [*Glycine max* (L.) Merr.] cultivars decreased under conditions of phosphate deficiency (Murali and Teramura, 1987), water stress (Murali and Teramura, 1986a; Sullivan and Teramura, 1990), or concurrent illumination with sunlight (Warner and Caldwell, 1983; Mirecki and Teramura, 1984).

There is little information, however, on how plants respond to the combined effects of increased UV-B radiation and gaseous pollutants (Krupa and Kickert, 1989; Fiscus et al., 1990). Tropospheric O_3 is the most phytotoxic regional air pollutant, and current levels significantly reduce crop production (Heagle et al., 1989; Krupa and Kickert, 1989). In addition, the photochemical conversion of precursors into O_3 is driven by solar UV-B radiation, which suggests that levels of both stressors could increase. To assess the combined effects of increased UV-B radiation and O_3 on crop plants, an economically feasible system is needed that can accommodate a sufficient number of plants for a dose-response experiment in the field. Field studies are desirable because plant responses to UV-B radiation under field conditions have usually been less than in the greenhouse and controlled environments

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Abbreviations: UV-B, Ultraviolet-B; PVC, polyvinyl chloride; CD, cellulose diacetate; POLY, polyester; PPF, photosynthetic photon flux.

(Caldwell et al., 1983; Tevini and Teramura, 1989). The moderated UV-B effect under field conditions was probably the indirect result of alterations in leaf morphology and physiology that reduced UV-B penetration into the leaves when they developed in full sunlight (Warner and Caldwell, 1983; Mirecki and Teramura, 1984).

Supplemental UV-B radiation studies have been conducted for some time using mercury-vapor fluorescent UV lamps fitted with plastic filters (Sisson and Caldwell, 1975; Caldwell et al., 1983; Murali and Teramura, 1986b). We adapted this type of supplemental UV-B radiation system for use in open-top field chambers and designed it to be capable of providing the range of irradiance needed to conduct dose-response studies. Open-top chambers equipped with gas dispensing systems have been widely used to study the effects of air pollutants on crops in the field (Heagle et al., 1989; Krupa and Kickert, 1989). To evaluate this approach to studying the combined effects of O_3 and UV-B radiation in the field, the quality and quantity of UV and visible radiation inside an open-top chamber equipped with a lamp bank were characterized to determine how ambient and chamber environments compared. This article reports on the design and performance of this system.

METHODS

Cylindrical open-top chambers (3.05 m diam. × 2.44 m tall) were constructed of channel aluminum, and their perimeters were covered with clear polyvinyl chloride (PVC) film 0.2 mm thick (Heagle et al., 1989). The PVC film contains an inhibitor of photodegradation and transmits less than 1 mW m^{-2} nm^{-1} below 350 nm. Charcoal-filtered air, ambient air, or ambient air-plus 1.5 times ambient O_3 were dispensed and monitored in the chambers as previously described (Heagle et al., 1989).

Supplemental UV-B radiation was provided in the open-top chambers by banks of commercially available UV-B-313 fluorescent lamps (Q-Panel Co., Cleveland, OH).[1] Fourteen lamps per bank were secured with vinyl-covered steel clips to a frame constructed of electrical conduit (1.9 cm diam.) (Fig. 1). A strip of 1.3 cm wide aluminum tape was placed along the length of each lamp to facilitate lamp starting. Lamps were connected with weather-protective molded PVC sockets and PVC-insulated wire to 1.0 A, dual-lamp dimming ballasts (Advance Transformer Co., Chicago, IL). Ballasts were located outside a chamber in a steel box equipped with a small cooling fan. Lamps were wired in opposite phase to minimize lamp flicker. Ballast input voltage was regulated by a fluorescent lamp dimmer control (Model FD-20, Lutron Co., Coopersburg, PA). Spectral irradiance measurements of UV-B-313 lamps operated at a range of ballast input voltages showed no change in spectral energy distribution as voltage changed. One lamp bank was suspended in each of 33 open-top chambers by vinyl-coated, twisted steel cable. The cable was supported by a system of pulleys so the height of the lamp bank could be adjusted to maintain a prescribed distance above the plant canopy (0.4 m).

In the supplemental UV-B radiation treatments, each lamp was covered with 0.13 mm thick cellulose diacetate (CD) film (Cadillac Plastic and Chemical Co., Baltimore, MD), which absorbed radiation emitted by the lamps below 292 nm. This filter was used because the absorption coefficient of O_3 below 290 nm is so great that shorter wavelength radiation would not penetrate the stratosphere, even with drastic depletion of stratospheric O_3 (Caldwell, 1981). In the control treatment, lamp banks were placed in chambers so that changes in solar radiation and chamber temperature caused by the lamp bank would be similar to those in the supplemental UV-B radiation treatments (Sisson and Caldwell, 1975). In addition, lamps in this treatment were covered with 0.13 mm thick polyester (POLY) film (Cadillac Plastic), which absorbed radiation emitted by the lamps below 315 nm. The POLY-filtered lamps thus served as a control for the UV-A and visible radiation emitted by the lamps in the supplemental UV-B radiation treatments (Sisson and Caldwell, 1975). Percent transmittance scans of the films were obtained with a spectrophotometer (model 8452A, Hewlett-Packard, Palo Alto, CA). Film samples from different allotment purchases were scanned to check for consistency among filters.

Biologically effective UV-B ($UV\text{-}B_{BE}$) irradiance was calculated using the generalized plant action spectrum, normalized at 300 nm (Caldwell, 1971). Column O_3 loss simulations and supplemental UV-B radiation treatments were calculated using the radiative transfer model C of Green et al. (1980). Supplemental UV-B radiation was administered during the 1990 field season as a constant addition at two levels that simulated the daily solar $UV\text{-}B_{BE}$ irradiances corresponding to stratospheric O_3 depletions of 14 and 29% at Raleigh, NC (35.75° N latitude, 0.1 km elev.). The supplemental $UV\text{-}B_{BE}$ irradiance administered daily during the treatment period provided a flux equal to the difference between the desired simulation and the daily solar $UV\text{-}B_{BE}$ irradiance indicated by the radiative transfer model. Model parameters for column O_3 thickness, albedo, and the aerosol scaling coefficient were set at 0.314 atm cm, 3% (Blumthaler and Ambach, 1988) and 1.0, respectively. To track seasonal changes in photoperiod and solar $UV\text{-}B_{BE}$ irradiance, both the duration and total daily flux of supplemental $UV\text{-}B_{BE}$ irradiance needed for a desired simulation were adjusted biweekly throughout the growing season (Fig. 2). Supplemental UV-B radiation was administered when the solar $UV\text{-}B_{BE}$ irradiance indicated by the model exceeded an arbitrary threshold of 20% (80 mW m^{-2}) of the maximum $UV\text{-}B_{BE}$ irradiance calculated for our location on 21 June. Supplemental UV-B treatments were manually discontinued under overcast skies when solar $UV\text{-}B_{BE}$ irradiance dropped below 80 mW m^{-2} for more than 30 min. Solar $UV\text{-}B_{BE}$ irradiance as evaluated every 2 h afterward, and treatments were resumed if the overcast cleared.

Irradiance was measured with a UV-visible spectroradiometer equipped with a monochromator with dual holographic gratings (model 742, Optronic Laboratories, Inc., Orlando, FL). The monochromator was fitted with a 3.7 m long quartz fiber-optic cable and diffuser head so that irradiance measurements could be made inside a chamber while the spectroradiometer remained outside. When the instrument was used in the field, it was shaded to keep it from overheating in the sunlight. The spectroradiometer was periodically calibrated using a NIST-traceable 200-W tungsten-halogen lamp standard of spectral irradiance (model 220A, Optronic Laboratories) powered by a regulated-current source (model 65, Optronic Laboratories). The wavelength calibration of the spectroradiometer was periodically checked by comparison with the Hg spectral emission line at 312.6 nm from a UV-B-313 lamp.

Solar UV radiation was monitored continuously with a weatherproof Robertson-Berger (RB) meter (Solar Light Co., Philadelphia, PA) (Berger, 1976). The output from the RB meter was calibrated against the spectroradiometer under sunny conditions on 6 Oct. 1990 and 25 Apr., 2 May, 3 May, and 5 June 1991. The calibration provided an estimate for the conversion of RB meter readings to energy units: J m^{-2} $UV\text{-}B_{BE}$ = 2.09 ± 0.14 RB counts (± SD).

[1]The use of trade names in this publication does not imply endorsement by the USDA or the North Carolina Agricultural Research Service.

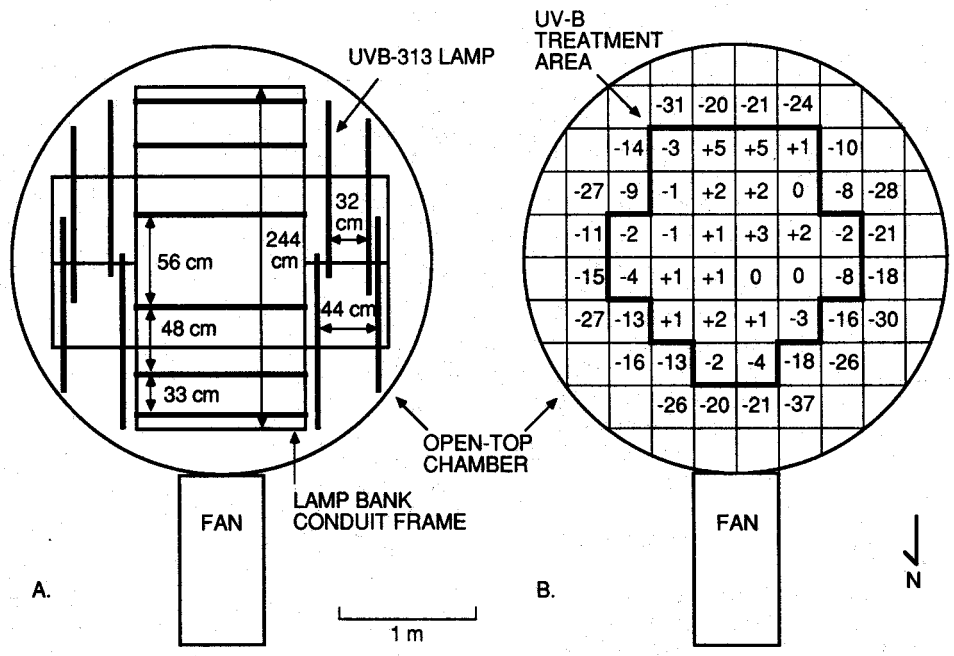

Fig. 1. (*A*) Schematic diagram of an overhead view of a UV-B lamp bank for a 3.05 m diam. open-top chamber (adapted from Krizek et al., 1990). (*B*) A chart showing the variation in UV-B irradiance at different positions below the lamp bank. Values are percent differences from the mean UV-B_{BE} irradiance within the treatment area as measured 0.4 m below a lamp bank in an open-top chamber. Mean ± SD UV-B_{BE} irradiance within the treatment area was 269 ± 8 mW m^{-2}.

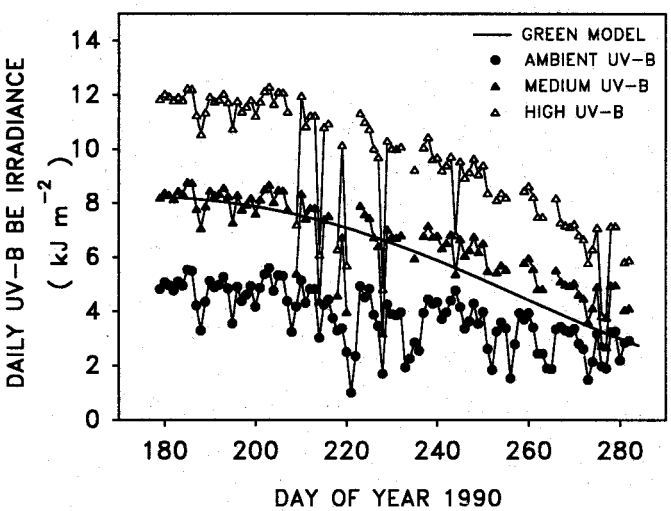

Fig. 2. Seasonal profile of daily UV-B_{BE} irradiances for ambient sunlight and the supplemental UV-B treatments. The daily solar UV-B_{BE} irradiances calculated by the Green et al. (1980) radiative transfer model are also shown. Because of shading by the chamber and lamp bank assembly, irradiance values for the control treatment were calculated by decreasing the RB measurements of ambient solar UV-B_{BE} irradiance by 24% (data not shown). Irradiance values in the medium and high supplemental UV-B treatments were calculated by adding the average supplemental UV-B_{BE} irradiances provided in the treatments biweekly to the solar UV-B_{BE} irradiances calculated for the control treatment. Noticeably low values or breaks in the lines for the supplemental UV-B treatments reflect days on which treatment was only administered for half a day or discontinued due to overcast skies.

A portable erythemal meter (Model 2D, Solar Light Co.) was used daily to set lamp outputs in the supplemental UV-B treatments to correspond to the desired irradiance. Adjustments to lamp outputs were required because CD films photodegraded, which decreased UV transmission. Cellulose diacetate filters were replaced three times a week in the high UV-B treatment and weekly in the medium UV-B treatment. Output from lamps covered with POLY film was controlled by setting the ballast input voltage equal to the average input voltage used in the high UV-B treatment. Polyester filters were changed monthly.

Because solar and supplemental UV-B spectral distributions differ, the calibration curve for the portable erythemal meter, as determined by the spectroradiometer, differed depending on the source of the UV-B radiation. When spectral irradiance from each source was weighted separately by the sensitivity spectrum of the portable meter, the calibration curves were approximately the same. Thus, the meter could not be used to measure both solar and supplemental UV-B_{BE} irradiance at the same time. To use the meter to measure supplemental UV-B_{BE} irradiance from a lamp bank during the day, the meter value for solar irradiance in the chamber with the lamps off was deducted from the meter value taken with the lamps on; the difference indicated supplemental UV-B_{BE} irradiance. This method was used to calibrate the portable erythemal meter against the spectroradiometer (mW m^{-2} supplemental UV-B_{BE} irradiance = $88.7x - 2.5$, where x = meter value). Calibration curves for the portable erythemal meter obtained in a darkroom with CD-filtered UV-B-313 lamps differed by less than 10%.

To characterize the chamber environment, solar UV-B_{BE} irradiance inside and outside a chamber was measured with the spectroradiometer every 30 min (cloud conditions permitting) from 0800 to 1200 h under sunny conditions on 11 June, 25 June, 23 July, and 6 Oct. 1990. Irradiance measurements inside a chamber were made with the spectroradiometer sensor placed it the chamber center 0.4 m below the lamp bank and 1.0 to 1.2 m above the ground.

Photosynthetic photon flux (PPF) was measured inside and outside a chamber every 90 min from 0900 to 1500 h on several days in June under partly cloudy skies. Measurements were made with a 1 m Line Quantum Sensor (Li-Cor, Inc., Lincoln, NE) 0.4 m below the lamp bank and at

0.75 and 1.25 m above the ground. The sensor was placed along the radius of the chamber at successive 45° intervals with one end of the sensor held at the chamber center so that the average PPF within the treatment area could be determined.

Temperature outside and inside chambers with lamp bank assemblies was measured every 90 min from 0900 to 1500 h on 23 July with shaded copper-constantan thermocouples. In each of four chambers, measurements were made with four thermocouples at different positions around the chamber at 0.4 to 0.7 m above the ground. Ambient temperature was measured with two thermocouples 0.4 m above the ground.

RESULTS

By daily adjustments to the ballast input voltage, the lamp bank provided an average maximum supplemental UV-B_{BE} irradiance of 275 mW m^{-2} (high UV-B treatment) for 16 h before photodegradation of the CD filters prevented adequate UV-B transmission. At an average supplemental UV-B_{BE} output from the lamp bank of 150 mW m^{-2} (medium UV-B treatment), adequate UV-B transmission could be maintained for 40 h by voltage adjustment. With the lamp configuration selected for this system, supplemental UV-B_{BE} irradiance 0.4 m below a lamp bank at maximum lamp output differed from average by 8% or less within the 2.4 m^2 treatment area (Fig. 1).

Absorption of UV radiation by the chamber panels and shading by the chamber and lamp bank decreased the integrated solar UV-B_{BE}, UV-A, and visible irradiances inside a chamber on average by 24% ± 5% (± SD) compared with ambient from 0900 to 1200. h. However, solar zenith angle strongly affected solar UV-B_{BE} and UV-A irradiance inside a chamber. Solar UV-B_{BE} irradiance inside a chamber on 25 June was 57% less than ambient at 0800 h and 40% less than ambient at 0900 h. Although shading by the chamber and lamp bank as substantial at 0800 and 0900 h, 90% of the daily solar UV-B_{BE} irradiance occurs between 0900 and 1500 h, and 74% occurs between 1000 and 1400 h (Green et al., 1980). By 1000 h, solar UV-B_{BE} irradiance inside a chamber was only 30% less than ambient. Solar UV-A irradiance inside a chamber was similarly affected.

Supplemental UV-B_{BE} radiation as a constant addition was also disproportionate to solar UV-B_{BE} radiation during the day. For example, with an average constant addition of 275 mW m^{-2} UV-B_{BE} irradiance, the supplemental plus solar UV-B_{BE} irradiance inside the chamber at 0800 h on 25 June was 5.3 times greater than the irradiance outside the chamber. From 0900 to 1200 h, however, this ratio decreased from 3.2 to 2.1 as solar UV-B_{BE} irradiance inside and outside the chamber increased during the morning.

The increase in solar UV-B_{BE} irradiance as solar zenith angle decreased also decreased the wavelength when solar UV-B irradiance equaled 1 mW m^{-2} nm^{-1}. From 0800 to 1200 h on 25 June, the wavelength of ambient radiation at this irradiance value decreased from 301 to 297 nm. Slightly smaller changes in the spectral distribution of solar UV-B radiation inside a chamber were observed. Supplemental UV-B radiation from the lamp bank fitted with new CD filters extended the spectrum down to 292 nm at 1 mW m^{-2} nm^{-1}.

Spectral irradiance measurements of the control treatment showed that the UV-A irradiance in this treatment was similar to that in the supplemental UV-B treatment. Ultraviolet-A irradiance from a lamp bank fitted with either CD or POLY filters was approximately 1 W m^{-2} at the ballast input voltage used in the highest supplemental UV-B treatment. The supplemental UV-A flux, however, was much lower than solar UV-A flux. From 0900 to 1200 h on 11 June, the integrated supplemental UV-A irradiance was only 3% of the integrated solar UV-A irradiance inside a chamber.

A comparison of the integrated solar UV-B_{BE} irradiances measured with out spectroradiometer and those calculated by the radiative transfer model showed that we measured on average 33% ± 14% less solar UV-B_{BE} radiation than was computed by the model for 0900 to 1200 h on the 7 d monitored from June 1990 to May 1991. Similarly, the RB meter indicated that solar UV-B_{BE} irradiance from 1 July to 9 Oct. 1990 was on average 36% ± 13% less than that calculated by the model. Solar UV-B irradiance was attenuated by hazy skies during the summer, but nearer to that calculated by the model under clearer skies in the spring and fall.

Biweekly adjustments of the supplemental UV-B_{BE} irradiance level in accordance with the radiative transfer model provided supplemental UV-B treatments that were proportional to seasonal levels of solar UV-B_{BE} radiation (Fig. 2). Values for the control treatment were calculated by decreasing RB measurements of ambient solar UV-B_{BE} by 24% to account for shading by the chamber and lamp bank assembly. Values for the high and medium supplemental UV-B treatments were calculated by adding the average supplemental UV-B_{BE} irradiance provided in the treatment biweekly to the solar UV-B_{BE} irradiance calculated for the control treatment. The ratio of UV-B_{BE} irradiances in the high and medium supplemental UV-B treatments to ambient UV-B_{BE} irradiance (derived from the RB measurements) averaged 2.43 ± 0.34 and 1.67 ± 0.19 d^{-1}, respectively, from July to October.

The average temperature in four chambers with lamp bank assemblies ranged from 0.9°C above ambient at 1030 h to 0.8°C below ambient at 1330 h on 23 July. Average ambient temperature at these two sampling periods was 32.4 and 33.6°C, respectively.

The open-top chamber and gas dispensing system allowed for adequate control of O_3 inside a chamber. When O_3 was dispensed during the 1989 field season, the mean proportion of ambient O_3 in individual chambers with either plus-O_3, nonfiltered, or charcoal-filtered air was 1.50 ± 0.14, 0.85 ± 0.05, and 0.34 ± 0.10, respectively. Measurements of O_3 concentration in chambers receiving charcoal-filtered air, with and without high supplemental UV-B treatments, showed no indication that supplemental UV-B radiation increased O_3 concentrations.

DISCUSSION

The open-top chamber and lamp bank system provided ample levels, range, and distribution of supplemental UV-B radiation and O_3 to conduct interaction and dose-response experiments in the field. The sys-

tem was durable and weather-resistant. In its present stage of development, the system requires daily attention by a technician to monitor and adjust O_3 concentrations, lamp bank irradiance levels, and lamp bank distance above the plant canopy to accommodate plant growth.

Inside the chamber, solar UV-B_{BE} irradiance was on average 24% less than ambient. This shading effect should be considered when UV-B_{BE} doses are calculated (Caldwell et al., 1983). By convention, UV-B_{BE} doses corresponding to a given stratospheric O_3 depletion are often expressed relative to the solar UV-B_{BE} irradiance under clear skies on 21 June as calculated by the Green et al. (1980) radiative transfer model. The model indicates that the daily solar UV-B_{BE} irradiance with a stratospheric O_3 layer of 0.314 atm cm at our location 21 June is 8.26 kJ m^{-2}. Due to shading by the chamber and lamp bank, daily solar UV-B_{BE} irradiance inside a chamber would thus be 6.28 kJ m^{-2}. The addition of average supplemental UV-B_{BE} irradiances of 275 and 150 mW m^{-2} for the period of time when the model indicates that solar UV-B_{BE} irradiance exceeds 80 mW m^{-2} (8.21 h) would provide daily supplemental UV-B_{BE} irradiances of 8.13 and 4.43 kJ m^{-2} in the high and medium UV-B treatments, respectively. Daily total UV-B_{BE} irradiances inside a chamber of 14.41 and 10.71 kJ m^{-2} would thus simulate 29 and 14% losses of stratospheric O_3 on 21 June.

In the chambers with POLY-filtered lamps, solar UV-B flux should also be considered to be on average 24% less than ambient. This means that the control treatment simulated a stratospheric O_3 addition of 16%. Chamber panels made of tetrafluorethylene, which transmits UV-B radiation, would help reduce solar UV-B flux loss inside the chamber.

The loss of solar PPF inside a chamber with a lamp bank was similar to other studies. Caldwell et al. (1983) reported that PPF was 26% less under the lamp banks used in their experiments, and Murali and Teramura (1986b) reported that 10% of PPF was shaded by their lamp banks. Average temperature in a chamber with a lamp bank was usually less than 1°C higher or lower than ambient under partly cloudy conditions, which is similar to that reported for chambers without lamp banks (Heagle et al, 1989).

Ground-based measurements of solar UV-B_{BE} irradiance with the spectroradiometer and RB meter showed that solar UV-B_{BE} radiation at our location was about 65% of that calculated by the Green et al. (1980) model (Fig. 2). Modifications to the Green et al. (1980) model by Schippnick and Green (1982) and Green (1983) reduced the discrepancies between calculated and measured clear sky UV irradiances (Rundel, 1986). However, column O_3 thickness and local weather conditions strongly affect the intensity and spectral distribution of solar UV-B radiation (Caldwell et al., 1983). Using RB data, Frederick and Snell (1990) estimated that annual mean transmission of erythemal irradiance at Philadelphia was only 62% of that expected under clear skies at 1200 h because of cloudiness. Our measurements of solar UV-B_{BE} irradiance with the spectroradiometer were made under sunny conditions, but indicated a similar degree of attenuation. Tropospheric air pollutants attenuate UV-B radiation and thus modify solar UV-B radiation levels at the earth's surface, particularly around urban areas (Frederick et al., 1989). Using a version of the Green (1983) model, Björn and Murphy (1985) found that differences between calculated and measured solar UV irradiance could be reduced to 0 to 20% in part by adjusting the aerosol level parameter to values ranging from 1 to 16. A correspondence between the aerosol level chosen and observed surface visibility was noted. In addition, the effect of column O_3 thickness on UV irradiance attenuation increases as wavelength decreases (Björn and Murphy, 1985), which makes an irradiance weighted by the plant action spectrum particularly sensitive to column O_3 thickness.

Therefore, calculations of average UV-B_{BE} dose that include the daily solar UV-B_{BE} irradiance computed by the Green et al. (1980) model using the parameters we specified almost certainly overestimate the solar component when used at locations with summer weather similar to ours. Sinclair et al. (1990) also noted that use of the model with parameter values for albedo and aerosol scattering similar to ours would likely cause overenhancement with supplemental UV-B radiation. Ground-based measurements of solar UV-B_{BE} radiation thus provide a more realistic base for supplemental UV-B radiation treatments.

Our ground-based measurements of solar UV-B_{BE} irradiance indicated that total UV-B_{BE} irradiance in the high and medium supplemental UV-B treatments was on average 2.43 and 1.67 times ambient UV-B_{BE} irradiance. If the solar UV-B_{BE} irradiance calculated by the model for 21 June is increased by these factors, the model indicates that the high and medium supplemental UV-B treatments simulated stratospheric O_3 losses of 44 and 27%, respectively.

Biweekly adjustments of supplemental UV-B_{BE} irradiance levels provided treatments that were proportional to the seasonal trend in solar UV-B_{BE} radiation. In addition, the total UV-B_{BE} irradiances in the high and medium supplemental UV-B treatments were maintained within reasonable limits of the treatment averages. The coefficients of variation for the average daily relative enhancements of solar UV-B_{BE} irradiances in the high and medium supplemental UV-B treatments were 14 and 11%, respectively.

The major drawback of the supplemental UV-B radiation system described herein was the lack of continuous proportional control of supplemental UV-B radiation during the day. Continuous proportional control of supplemental UV-B radiation would more accurately simulate the effects of stratospheric O_3 depletion (Caldwell et al., 1983). However, the constant daily addition system for supplemental UV-B radiation was a simpler and less expensive method for determining the relative sensitivity of plants to the combined effects of increased solar UV-B radiation and O_3 under field conditions. The cost of materials for a chamber and lamp bank was approximately $3000. In addition, it should be noted that the same lamp configuration and chamber design could be used with a proportional-control supplemental UV-B radiation system, and the data characterizing the chamber environment would still be applicable.

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