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Individual- and scattered-tree influences on ultraviolet irradiance

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Abstract

Many of the potential effects of ultraviolet radiation (UVR)—damage to materials, altered herbivory of insects and activity of microbes, modified growth of vegetation, and adverse or beneficial effects on human health—are modified by the presence of trees that influence UVR exposure to various degrees. Though tree effects on total solar irradiance have been investigated often by measurements and modeling, tree influences on UVR, particularly in the ultraviolet B (UVB, 320–280 nm), differ substantially from tree influences on the rest of the solar spectrum, and thus the ratio of UVB to photosynthetically active radiation (PAR) is altered. Trees greatly reduce both UVB and PAR irradiance in their shade when they obscure both the sun and sky. Beneath dense forest canopies, relative irradiance (I_r = irradiancebeneath trees/above-canopy irradiance) for both UVB and PAR radiation may be 0.01–0.02. In the shade of a single tree, I_r on the horizontal in the PAR and total shortwave (SW) was about 0.1, whereas in the UVB and ultraviolet A (UVA, 320–400 nm), I_r was about 0.4. Conversely, where direct beam radiation came through gaps between crowns in a group of deciduous trees in winter, PAR I_r values averaged 0.95 and UVB I_r averaged only 0.41. In comparisons of minimum values of I_r on horizontal and the south-facing vertical surfaces in tree shade for UVB, UVA, SW, and PAR, where UVB I_r on the horizontal ranged from 0.22 to 0.62, depending on solar zenith angle, UVB I_r on the vertical ranged from 0.05 to 0.27. UVB I_r consistently exceeded UVA I_r on both the horizontal and vertical surfaces. PAR and SW I_r differed little between horizontal and vertical surfaces in tree shade. Modeled average I_r on the horizontal below a regular grid of ellipsoidal tree crowns was given by $I_p = 1 - m - (\theta^{0.711}/5.05)\sin(\pi m)$, where m is fraction of area covered by tree crowns and θ is solar zenith angle. The tree influences will vary with pollutants in the boundary layer, which affect scattering of UVR.

Keywords: Forests; Human health; Ozone; Plant competition; Solar radiation; Tree shade

1. Introduction

Ultraviolet radiation (UVR), particularly ultraviolet B (UVB, 320–280 nm) has many potential impacts. It affects human health (Heisler and Grant, 2000a,b), degrades various materials (Andrady et al., 1998), affects aquatic life including in freshwater ecosystems (Hader et al., 1998), directly and indirectly affects insect herbivory (Ballare et al., 1996), affects biogeochemical cycles such as those of carbon and nitrogen (Zepp et al., 1998), and affects plant community composition by altering the competitive ability of plants (Caldwell et al., 1998; Day, 2001). Little is known about the direct effects of UVB on the health of animals in natural settings, though cows, sheep, goats, dogs, and cats develop skin cancer, with sunlight strongly suggested as

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the cause (van der Leun and de Gruijl, 1993). A number of observed or suspected indirect effects of UVB radiation are caused by the effect of UVB radiation on microbes (e.g. Caldwell et al., 1998); these effects may alter effectiveness of biological pesticides, influence the potency of pathogens, affect the rate of litter decomposition, and thus also affect CO_2 sequestration. There are also complex interactions between UVR and the aerosols and photochemical smog that are important boundary layer air pollution constituents, particularly for forests in the vicinity of urban areas (Tang et al., 1998).

The potentially large impact of trees on UVR irradiance may modify all the UVR influences. The expectation that elevated UVB levels caused by reduced stratospheric ozone will continue well into the 21st century (Heisler and Grant, 2000b; Madronich et al., 1998; Weatherhead et al., 2000) is further reason to evaluate UVR levels as influenced by trees and forests.

Tree influences on UVR could be important where trees serve as overstory shelter in multicropping agriculture and in reproduction cuts in forestry silvicultural operations. This is especially true because, as shown by the measurements summarized here, trees alter the ratio of UVB to photosynthetically active radiation (PAR). This ratio is important because the effects of even ambient UVB levels on plant processes and competitive ability may be affected by the level of PAR (Caldwell et al., 1994). Differences between species in response to UVB radiation, such as have been noted for different tree species (Sullivan et al., 1996), may alter the competitive ability of different species of seedlings in the understory of a forest.

The UVR health impacts to people include basal cell carcinoma, the most common, and melanoma, the most likely to be lethal. UVR also is at least part of the cause of cataracts of the eye (Heisler and Grant, 2000b; Longstreth et al., 1998). Much of the human exposure to UVR occurs in activities such as in visits to a swimming pool, beach, or tanning salon. However, exposure also occurs routinely in outdoor environments where radiation is influenced by trees. Adverse affects of UVR are balanced to some extent by positive health effects (van der Leun and de Gruijl, 1993), which include Vitamin D production. Study results and opinions differ regarding the role and importance of UVB and Vitamin D in reducing non-cutaneous cancer incidence (Heisler and Grant, 2000b; Martinez et al., 1996). Some believe that low exposure to UVB is associated with increased risk of non-cutaneous cancers (Garland et al., 2002; Grant, 2002; Lefkowitz and Garland, 1994).

Knowledge of tree influences on UVR is needed to guide urban planning and public information and could be important in investigations of human epidemiology, including for workers in some types of agriculture such as fruit and nut production in orchards. Because UVR penetration into below-canopy spaces can differ greatly from penetration of visible radiation, the visible is not a good guide to UVR irradiance. Differences can occur partly because visible and UV differ in the diffuse fraction (F_D) of total irradiance, in the distribution of sky radiance, in reflectivity of human-made structural surfaces, and in optical properties of leaves at different wavelengths. Therefore, measurements and models of individual- and scattered-tree influences on UVR are needed.

In this paper, we give some examples of the degree to which trees influence UV irradiance by summarizing a series of our measurements that evaluated solar radiation in and near the shade of an individual tree, widely scattered trees, and a grove of trees. Comparisons are made to measurements by others. Modeling methods and results are also described briefly, so as to indicate the current status of research methodologies and research needs.

2. Methods

Irradiance measurements were made in four wavebands: total SW (2500–300 nm), PAR, ultraviolet A (UVA, 400–320 nm), and UVB. (The PAR units are more properly termed photon flux density, but we use “irradiance” for convenience in this paper.) Measurements of irradiance I with sensors at a height of 1.5 m in and near the shade of trees were referenced to above-canopy irradiance I_0 as measured on horizontal surfaces by sensors on the roof of a building or in a nearby large open space to arrive at relative irradiance, $I_r = I/I_0$. The measurements in the PAR waveband, which extends from about 700 to 400 nm and has about 75% of the sun’s energy, are pertinent to influences on plants and they also served as a surrogate for visible light measurements.

The measurements were taken on the Purdue University campus at West Lafayette, Indiana (40.5° north latitude). Below-canopy sensors were mounted close together on a tripod. For some measurements, the tripod was placed just outside the edge of the tree shade so that the shadow moved over the sensors. For other measurements, sensors were in either the sun or shade for the entire sample period. Most of the below-canopy irradiance measurements were made with sensors oriented horizontally, though some were made with sensors in a vertical orientation facing south or toward the sun.

2.1. Instrumentation

Total SW irradiance was measured using Kipp & Zonen (Bohemia, NY)[1] CM5 thermopile pyranometers. PAR irradiance was measured using LI-COR (Lincoln, NB) LI-190S silicon photodiode quantum sensors (10% response bandwidth is 702–400 nm). The aperture of these sensors is 8 mm. Most of the ultraviolet irradiance measurements were made with broadband sensors from International Light, Inc. (Newbury, MA). These were, for UVA, the SED038/UVA/W filtered silicon sensors (10% spectral response of 388–314 nm) and, for UVB, SED240/UVB/W filtered vacuum photodiode sensors (10% spectral response of 315–258 nm) (Fig. 1). Both IL sensors have 11-mm apertures. For some measurements, UVB irradiance was also measured with YES UVB-1 filtered fluorescent phosphor sensors (Yankee Environmental Systems, Inc., Turners Falls, MA) with an advertised 10% spectral response bandwidth of 317–280 nm (Fig. 1).

A data logger sampled all sensors at 5-, 10-, or 30-s intervals. Above- and below-canopy sensors were inter-compared side-by-side in the open, and the recorded sensor response was adjusted to provide equivalent response during validation measurements. Temperature response corrections (Grant, 1996) were applied to the IL UVA and UVB sensor measurements. Although the IL sensors have cosine response errors that are large relative to other sensors such as the YES UVB-1, no corrections for the cosine response errors were applied. Because of the complexity

[1] Mention of a commercial or proprietary product does not constitute endorsement by the USDA or the Forest Service.

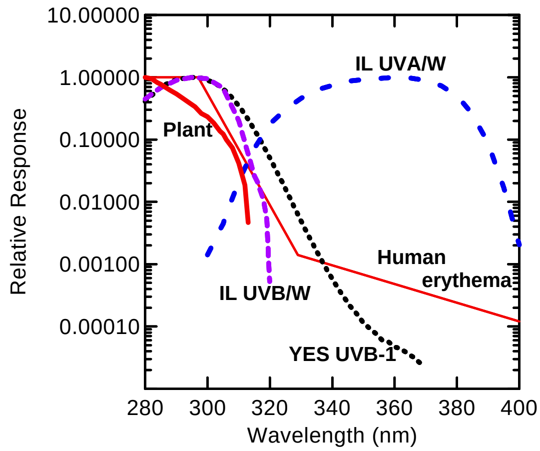

Fig. 1. Relative responses of the UV sensors (three dashed lines) compared to the CIE sunburn (human erythema) action spectrum (McKinlay and Diffey, 1987) and the generalized plant response action spectrum of Caldwell et al. (1998). Sensor response is normalized to the peak response of each instrument.

of the radiation environment in tree shade, cosine response corrections are not feasible for sensors there. Not correcting the UVB irradiance measurements for cosine response errors likely resulted in overestimates of UVB I_r. However, we believe these overestimates are small because of the diffuse UV radiation sources at below-canopy locations and the large diffuse fraction of radiation at above-canopy locations, especially at high solar zenith angles. Instruments are described in more detail elsewhere (Grant, 1997; Grant and Heisler, 1996; Grant et al., 1998).

Note that the YES UVB sensor has significantly greater reported response above 320 nm than the IL UVB sensor (Fig. 1). Because sky radiance is important as a source of irradiance below tree canopies and the F_D increases rapidly with decreasing wavelength in the ultraviolet, the IL sensor would be expected to indicate higher relative irradiance below canopy than the YES UVB-1. The action spectrum for generalized plant damage (Caldwell et al., 1998) is more similar to the IL UVB/W spectral response than to the YES UVB-1 response, which is similar to the human erythema response (Fig. 1).

Upward-facing hemispherical photographs of each measurement site were made using a Canon 7.5-mm lens. Photographs were analyzed to determine total sky obscuration due to canopies for each 5 or 10° annulus.

Analysis was done either by projecting slide photographs on grids with 5 or 10° intervals in both azimuthal and zenithal directions or by computer analysis of digital images. An area of the sky hemisphere was defined as obscured if the sky was not visible at the intersection of the azimuthal and zenithal grid lines.

2.2. Single tree

In a series of measurements near a single 17-m tall sweetgum tree (*Liquidambar styraciflua*), several different sensor configurations were used. In one, UVB, UVA, PAR, and total SW sensors on horizontal surfaces were placed near and in front of the moving tree shadow and left there until the shadow had passed over them (Grant and Heisler, 2001).

In another configuration, measurements were made with horizontal and vertical sensors in the shade of the sweetgum tree with the vertical plane sensors aligned toward the tree trunk (Fig. 2). The below-canopy measurements for both horizontal and vertical orientations were normalized by a corresponding-waveband horizontal sensor on a nearby roof. Sensors were sampled at 5- or 30-s intervals for 0.5–1.5 h at each location.

2.3. Widely scattered trees

One set of measurements included sensors for measuring UVB and PAR below deciduous campus trees that included northern red oak (*Quercus rubra*), red maple (*Acer rubrum*), white ash (*Fraxinus americana*), ginkgo (*Ginkgo biloba*), and thornless common honeylocust (*Gleditsia triacanthos* var. *inermis*) that were 10–15 m tall (Grant and Heisler, 1996). Hemispherical-view slide photos from each measurement site like those in Fig. 3 showed that the effective sky view ranged from 47 to 60%, thus these measurements represent irradiance conditions with fairly large views of the sky. The sky view percentages represent an effective sky view because they are corrected by the relative importance of the sky elevation angle zone as a radiance source for global irradiance on horizontal surfaces considering the effect of the cosine of incidence angle. Measurements were made at different points over 10 half-hour periods with International Light sensors that respond only in the UVB (Fig. 1). Skies were clear for all measurements. Comparable irradiances measured at a rural field provided an above-canopy reference. The solar zenith angle ranged from 33 to 60° during the measurements.

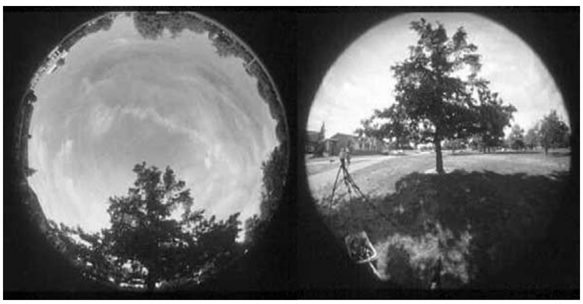

Fig. 2. Sensor's eye (hemispherical lens) views of single tree from horizontal surface in shade (left) and vertical surface (right). Adapted from Grant and Heisler (2001).

Fig. 3. Hemispherical views from position of sensors in widely scattered-tree irradiance measurements showing range of effective sky views sampled: 0.60 (left) and 0.47 (right).

2.4. Tree grove

Another environment was a park-like grove of large oak (*Quercus*) and maple (*Acer*) trees approximately 30–40 m in height (Fig. 4) and within 300 m of the reference location on a building roof (Grant and Heisler, 2001). The grove had a mean distance between trees of 13 m. Again, horizontal and vertical plane irradiance measurements were made, but vertical plane measurements in the grove were aligned to have a due south aspect since no single tree created the shade in the grove and consequently no single tree crown was obstructing the direct beam of the sun. Sky views from the horizontal sensor locations ranged from 10 to 66%. Measurements were made in July.

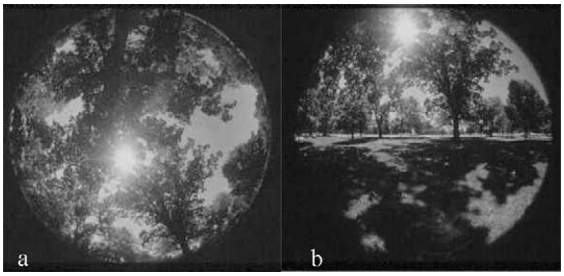

Fig. 4. Hemispherical views from a horizontal sensor position in the tree grove (a) and from a vertical sensor position (b). Adapted from Grant and Heisler (2001).

2.5. Modeling tree influences on irradiance

The geometric 3-D model described by Gao et al. (2002b) for use in a maize canopy and in an orchard (Gao et al., 2002a) was used to predict the relative irradiance of a given waveband of radiation within and below the tree canopies (Grant et al., 1998). In this model, derived from an earlier version by Norman and Welles (1983) for total solar radiation, the canopy consists of a finite number of discrete 3-D ellipsoidal crowns with foliage density ρ. The model considers attenuation of direct beam and sky radiance but not radiation reflected from other trees or buildings. The F_D was estimated using the Schippnick and Green (1982) model for UVR and the Bird (1984) model for PAR and SW.

For an array of individual plant crowns, the geometry to model the probability of a beam of radiation traveling, un-intercepted, from the beam's source (inside or outside the canopy) to any given point in the array is given by Norman and Welles (1983). We used their method for computation of the distance through vegetation within a canopy of discrete plant volumes, although we assumed all radiation sources were on a reference plane just above the canopy. The probability of radiation penetration through the canopy assumed a uniform distribution of canopy elements in the discrete sub-canopy volumes.

The probability of penetration of sky diffuse radiation is given as:

$$P_0' = \frac{\int_0^{2\pi}\int_0^{\pi/2} N(\varphi,\Theta)\mathrm{e}^{-G(\Theta)\rho S}\cos\Theta\sin\Theta\,\mathrm{d}\Theta\,\mathrm{d}\varphi}{\int_0^{2\pi}\int_0^{\pi/2} N(\varphi,\Theta)\cos\Theta\sin\Theta\,\mathrm{d}\Theta\,\mathrm{d}\varphi}, \tag{1}$$

where the anisotropic sky radiance distribution N for a given zenith angle Θ and azimuth angle φ was modeled according to Grant et al. (1996) for PAR, by Grant et al. (1997a) for UVR, and by Harrison and Coombes (1988) for SW. The term S is the path length through one or more crowns that have leaf density ρ; and G is the fraction of foliage area within the crowns projected towards the source of radiation (Θ, φ). We assumed a spherical leaf angle distribution in the foliage volume.

3. Results

3.1. Single tree

An example of results with the configuration that allowed the shade of the single-tree crown to pass over the sensors is shown in Fig. 5. In the shade, relative irradiance, I_r, in the PAR and total SW was about 0.1, whereas in the UVB and UVA, I_r was about 0.4 with the UVB higher than UVA by about 0.03. When the tree shade passed and sensors received full direct beam sun, SW and PAR I_r were slightly greater than 1.0, probably because reflection from the tree crown was greater than the sky radiance behind the tree. UVB and UVA I_r in the sun near the tree were about 0.9.

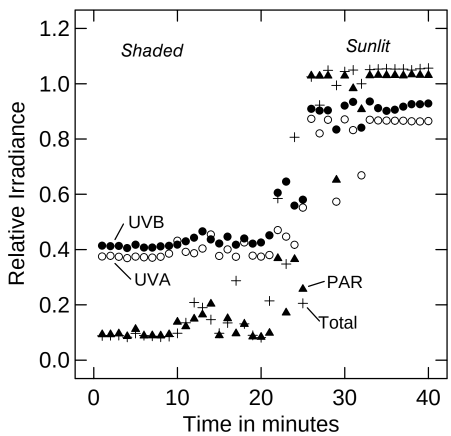

Fig. 5. Relative irradiance as tree shade moved away from sensors measuring total SW (+), PAR (▲), UVA (○), and UVB (●). Sensors were horizontal, beneath the edge of the tree crown, and had a sky view of 0.78. The solar zenith angle was about 34°. High cirrus covered 0.3 of the sky. Modified from Grant and Heisler (2001).

Although in Fig. 2 the tree crown appears to be quite visually porous, I_r values in the shade were relatively constant except when the direct beam to the sensors was near the irregular crown edge.

Thus, where only a small tree crown obscures the sun, the contrast between reduction in the PAR or SW and UVB wavelengths is pronounced. The longer wavelengths are greatly reduced, whereas UVB is reduced much less.

We compared minimum values of I_r on horizontal and the south-facing vertical surfaces in the shade for the different wavebands. The minimum values essentially exclude the effect of radiation that penetrates through the crown. Where UVB I_r on the horizontal ranged from 0.22 to 0.62, depending on solar zenith angle, UVB I_r on the vertical ranged from 0.05 to 0.27. UVB I_r consistently exceeded UVA I_r on both the horizontal and vertical surfaces. PAR and SW I_r on the horizontal were similar to values in Fig. 5, and differed little between horizontal and vertical surfaces in tree shade.

3.2. Widely scattered trees

The measurements below widely scattered trees illustrate the effect of mature deciduous trees on the PAR and UVB. Six conditions were represented: shaded and sunlit points when the tree crowns were in leaf, shaded and sunlit points after leaves had fallen and with no buildings nearby, and shaded and sunlit points after leaves had fallen and with a building wall nearby (Table 1).

Table 1 illustrates again that at points with significant view of the sky, UVB I_r can differ greatly from visible I_r. In the shade of trees in leaf, PAR I_r was only 0.16 where UVB I_r was 0.37. Conversely, at locations near in-leaf trees but out of their visible shadow (sunlit), PAR I_r was not reduced appreciably, but UVB I_r averaged only 0.61. Trees with only bare branches and twigs can cause substantial reductions in total SW irradiance (Heisler, 1985; Heisler, 1986) and similar reductions would be expected in the PAR. Indeed in leafless tree shade with no building nearby, PAR I_r was only 0.27. The UVB I_r in the shade of a leafless tree was 0.44, greater than PAR I_r, but only 0.07 more than the UVB I_r in the shade of in-leaf trees. These similar increases in shade I_r, of 0.07 in the UVB and 0.11 in the PAR with leafless trees corresponded with a 4% increase in view of the sky. I_r in the UVB differed much less between shade and sunlit points (0.24 difference with leaves on the trees and 0.16 with no leaves) than in the PAR (0.81 difference with leaves and 0.66 with leafless trees).

Reflection from a sunlit, red-brick building wall with windows led to a doubling of I_r for PAR at a tree-shaded point compared to when no wall was present, even though sky view at both points was similar (Table 1). In the UVB, the wall decreased I_r because of low UVB reflectivity of the brick surface. The brick wall and windows reflected about 0.18 of incident PAR, whereas it reflected only about 0.03 of the UVB (Grant and Heisler, 1996).

The I_r values in Table 1 are representative of tree effects, though I_r will differ with solar zenith angle

Table 1
Average UVB and PAR relative irradiance at points below a street-tree canopy (Grant and Heisler, 1996; Heisler et al., 1996)

Half-hour measurements	Number	Relative irradiance		Percent of view[a]		
		UVB	PAR	Buildings	Trees	Sky
In-leaf						
Shade	3	0.37	0.16	–	44	49
Sunlit	2	0.61	0.97	–	39	56
Out-of-leaf						
Shade	1	0.44	0.27	–	41	53
	1	0.30	0.53	23	17	56
Sunlit	2	0.60	0.94	–	36	60
	1	0.41	0.95	31	13	47

[a] View percentages (buildings + trees + sky) do not add to 100% because sky view includes a correction for the fact that the effect of a radiance source on irradiance on a horizontal surface varies with the cosine of the angle of incidence.

and F_D. Most of the in-leaf measurements were made in early September with similar solar zenith angles ranging from 48 to 57°. I_r values, particularly in the UVB, would be expected to be smaller with the smaller zenith angles of the middle of the day in midsummer, because the F_D would generally be smaller with the sun higher in the sky. The measurements were not intended to gather information representative of any particular species, because trees of several species had an impact on irradiance at each measurement site.

The difference between UVB and PAR irradiances in tree shade is apparent in Fig. 6, which shows UVB and PAR I_r as sensors become shaded over a 20-min period. The large fluctuations in PAR I_r are caused partly by the much larger importance of direct beam radiation in the PAR, which increases the difference in irradiance between points in and outside of sun flecks, though the smaller diameter of the PAR sensors may also have contributed to the PAR variability. In Fig. 6, UVB I_r in the sun is less than in Fig. 5 because sky view is greater in the Fig. 5 measurements.

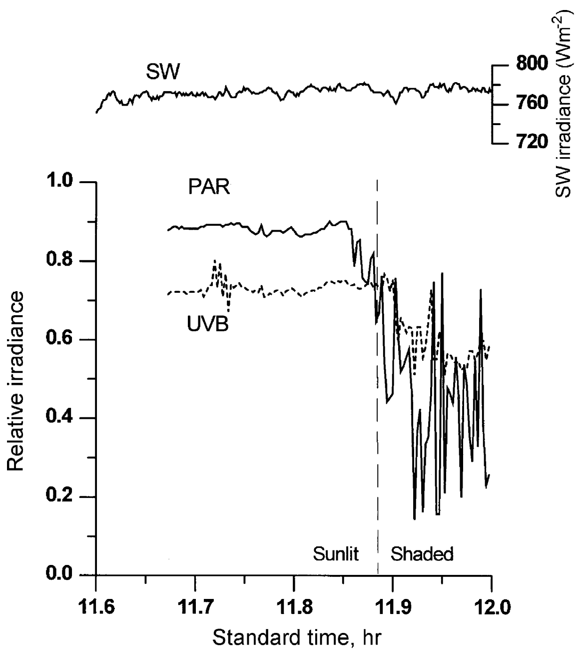

Fig. 6. Relative irradiance as tree shade moved away from sensors measuring PAR and UVB. Sensors were horizontal and had an effective sky view of 68%. The solar zenith angle was about 48°. The SW record is shown to indicate the approximate variability in above canopy irradiance. Modified from Grant and Heisler (1996).

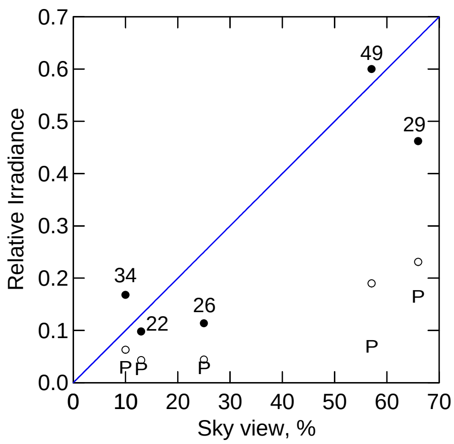

Fig. 7. Relative irradiance in the UVB (●), UVA (○), and PAR (P) in shaded spots in a grove of large broad-leafed trees. Skies were generally clear except for 10% of sky covered by high cirrus clouds. Numbers above UVB points show solar zenith angles for each measurement set. The line represents a 1:100 relationship of fractional I_r to sky view (%).

3.3. Tree grove

Our studies did not include measurements in dense forests, but Fig. 7 shows how I_r of UVB and UVA as measured by IL sensors compared to PAR I_r at points with different sky views in the tree grove. With sky views at 25% or below, though relative UVB exceeded PAR by as much as 0.14, it remained below 0.17. UVA I_r was closer to PAR I_r than to UVB I_r. For some of the measurement periods in the grove, the instrument set included a YES UVB-1 sensor (Fig. 1) that showed I_r part way between the purely UVB measured by the IL sensors and the UVA.

3.4. Modeling tree influences on irradiance

The 3-D irradiance model was tested with measurements for the sweetgum tree (Fig. 2) under the special circumstances of the assumption of very high crown density ρ, so that points in tree shade received essentially only radiation originating as sky radiance. Measured values of I_r for comparison to modeled values were derived by taking the minimum individual measurement for each sampling period (Grant and Heisler, 2000b; Grant et al., 1998). The minimum values are expected to represent the condition of little penetration through the tree crown. This comparison tests the

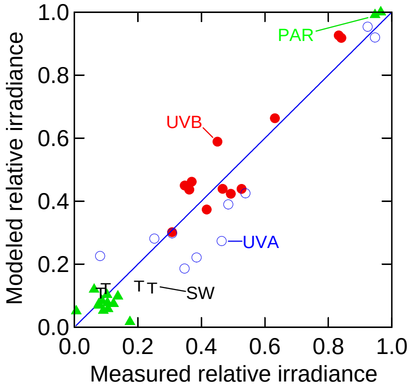

Fig. 8. Comparison of modeled to measured I_r for UVB, UVA, PAR, and total SW for both shaded and sunlit locations near the sweetgum tree.

model's ability to deal with sky diffuse radiation from outside the crown to below-canopy locations (Fig. 8). As indicated by the regression r^2, the model accounted for 95% of the variability in I_r and it predicted I_r under both sunlit and shaded conditions with a mean bias error (MBE) of less than 0.01.

Similar results were obtained using the model to predict UVB I_r in shaded and unshaded locations beneath trees of *Malus* sp. in an orchard (Gao et al., 2002a). With measured I_r ranging from 0.17 to 0.82, the MBE was 0.04. A comparison of results assuming isotropic and anisotropic sky radiance distributions showed slightly higher (by 3.6%) predicted I_r in sunlit locations with the anisotropic assumption, as expected, but the differences were small relative to general scatter in the measured and modeled values, and there was no improvement in MBE. For shaded locations, the difference in results with isotropic and anisotropic assumptions were even smaller.

4. Discussion

4.1. Factors influencing reductions of irradiance by trees

The distinction between "shade" and "sunlit" would be much less apparent if our eyes registered UVB rather than a range of wavelengths close to the PAR. The explanation for this is that the different wavebands differ in the fraction of total irradiance that originates from the sky, in the distribution of sky radiance, in optical properties of leaves at different wavelengths, and in reflectivity of nearby building surfaces.

4.1.1. Diffuse fraction

If there is a large view of the sky from points in the visible shadow, these points receive significant UVB irradiance because a large portion of UVB is from the sky and that radiance is spread widely across the entire sky (Grant et al., 1997a). This is the major explanation for differences between UVR and PAR irradiance in the vicinity of trees. Much of the time, even with clear skies, more than half of the UVB irradiance arriving on earth is from this diffuse radiation from the sky (Grant and Heisler, 1996), whereas the sky fraction of the PAR is usually less than 0.25 with clear skies. For example, with a solar zenith angle of 40°, clear skies, and moderate total column ozone level of 320 Dobson Units, the Green model (Schippnick and Green, 1982) predicts F_D in the UVB at 0.52, and the Bird (1984) model predicts PAR F_D as 0.18; at 60° solar zenith angle the comparable values are 0.72 and 0.24. High cirrus clouds increase F_D slightly, but generally cirrus has small effect on the sky radiance distribution (Grant et al., 1997b). In the measurements shown in Fig. 5, 0.3 of the sky was covered by cirrus clouds, but these probably had little effect on the F_D, and thus did not affect I_r significantly (Grant and Heisler, 2001).

4.1.2. Sky radiance distribution

The distribution of sky radiance also determines differences in relative irradiance in tree shade in the different wavebands, though radiance distribution is less important than F_D. A series of measurements with a specially designed platform that held and rotated narrow-field-of-view sensors (Grant et al., 1996) showed that most of the PAR sky radiation originates from near the sun. There is a decided dark portion in the other half of the sky away from the sun. Unlike the PAR, the UVB distribution with clear skis shows a much more even distribution across the sky (Grant et al., 1997a). The pattern for UVA is about halfway between the UVB and the PAR. For clear skies, the UVB radiance from a sector of the sky (N_{UVB}, where fN_{UVB} over all sectors equals 1.0) was best modeled using the scattering angle (ψ) between the sun and the location in the sky and the sky zenith angle (Θ) as

$N_{\mathrm{UVB}} = 0.201 + 0.020\Theta^2 + 1.48e^{-7.8\psi}$, where ψ is defined as $\cos\psi = \cos\Theta\cos\theta + \sin\Theta\sin\theta\cos\Phi$. The symbol θ represents the solar zenith angle, and Φ is the difference between the solar azimuth and the sky position azimuth angle, with angles in radians. The coefficient of determination, R^2, was 0.69. With translucent overcast skies, UVA and UVB distributions differed little from distributions with clear sky (Grant et al., 1997b).

In modeling of the effects of vegetation or other obstacles on irradiance on surfaces near them, all parts of the sky are often assumed to have equal radiance. This led to differences as large as 0.29 in modeling the SW I_r in the shadow of an individual tree (Grant, 1985). Precise characterization of anisotropy in sky radiance distributions may be less important in modeling tree influences on UVR (Section 3.4) even though F_D is large, because the UVR radiance distributions are relatively uniform.

4.1.3. Leaf optical properties

Differences in leaf reflectance may also contribute to differences between UVB and PAR I_r, particularly for sunlit points. In a study of leaves of 19 species, average PAR reflectance was 1.1–3.3 times greater than UVB reflectance (Gao et al., 1996). UVB reflectivity from the abaxial sides of the seven species measured by Yang et al. (1995) ranged from 1.0 to 5.8%; reflectivity of adaxial sides was even lower. Transmission of UVR through leaves is negligible for all tree species examined to date (Gao et al., 1996; Qi et al., 2002; Yang et al., 1995). For most broad-leaved species, about 20% of the PAR and 30% of the SW energy penetrates through an individual leaf (Gates, 1980). Of course, after the PAR or SW energy passes through several layers of leaves, it is essentially depleted. In any case, the reason that I_r in the UV was greater than I_r in the PAR and in the SW is not because more UV radiation penetrated through the leaves.

For PAR and SW, the high reflection from leaves and low sky radiance seems to explain why in these wavebands irradiance in the sun near trees can be greater than in the open (Fig. 5). The radiation added by reflection from a nearby tree can be greater than the PAR and SW sky radiance blocked by the tree. In the UVB, little radiation is reflected from the tree and considerable radiation from the sky is blocked, so the tree presence reduces UVB irradiance even for points in direct sun. Measurements of radiance from a silver maple (*Acer saccharinum*) crown normalized by sky radiance (Grant, 1997), showed negligible radiance from the tree for PAR as well as UVB and UVA. However, the radiance was measured on the side of the tree that was at 90° from the sun to tree axis, and reflection would probably be higher for the side of the tree more directly in line with the sun.

Leaf optical properties change with leaf development through the year (Qi et al., 2002). Certainly the time of leaf out and leaf fall, which varies with species, will affect tree influences on UVR irradiance. Some species such as the ashes leaf out significantly later and drop leaves earlier than most other species (Halverson et al., 1986). Tree influences will tend to be more important in the fall of the year when the annual cycle of total column ozone is at a lower point than in the spring when ozone is higher (Heisler and Grant, 2000b).

4.1.4. Ground surface and building reflectivity in the UV

Tree influences on irradiance depend on the sources of the radiance, and in many circumstances, the sources may depend largely on the reflectivity of surrounding surfaces including paving, soils, and building structures. As for leaves, many other surfaces that are good reflectors for visible radiation are poor reflectors of UV (Koller, 1965). However, there are exceptions. The high reflectivity of new fallen snow, up to 94% of incident UVB irradiance, means that eyes can experience up to 16 times greater UVB exposure with snow than with no snow on the ground (Blumthaler and Ambach, 1988), and thus tree effects in reducing irradiance in high latitudes in winter can have effects on health of humans and on other ecosystem components, such as microorganisms overwintering on vegetation surfaces.

4.2. Regional albedo effects on above-canopy irradiance

The importance of trees and forests in moderating UVB irradiance depends in part on the input of UVR above canopy. If large scale changes were made to surface albedo, UVB irradiance input might be altered by a change in the radiation that is reflected from ground-level surfaces up to the sky and then back to ground level. Such changes might occur with citywide tree planting programs such as have been undertaken in Sacramento, CA (Simpson, 1998) and some other cities. Regional UVB albedo might also be altered if roof or pavement surfaces of a sufficient portion of a city were whitened to reduce summer energy use for cooling buildings or if the ground surface of an agricultural area were lightened or darkened to influence the energy budget and consequently the thermal environment of crops. This effect could be tested by a sensitivity analysis using radiation transfer models. Though the potential for modifying incoming UVB is probably small (Heisler and Grant, 2000b), it should be examined further. A complete sensitivity analysis of albedo change effects would require consideration of the extent of areas to be altered, measured UVB albedo for the different types of lightened surfaces, inclusion of variation in ozone and aerosols, and changes in solar angles over the course of a year.

4.3. Other measurements

The few other measurements that have been made of tree influences on UVR irradiance generally agree with those in Table 1 and Figs. 5–7. For example, spectroradiometer measurements showed an essentially linear increase in average I_r with decreasing wavelength from 400 to 300 nm in the shade of five Australian trees; relative irradiance at 300 nm was almost double that at 400 nm (Parisi and Kimlin, 1999).

Where trees obscure most of the sky, reductions in UVB can be almost complete. Measurements with a personal dosimeter that responded mostly in the UVB (Diffey and Saunders, 1995) indicated that tree shade reduced the erythemal irradiance by over 98% at times. In this case, a person walking beneath a row of trees wore the dosimeter vertically at the waist. Though the details of the tree structure were not given, such large reductions in UVB probably resulted from the tree canopy being quite dense and having crowns that completely blocked the sky on the side on which the dosimeter was worn. In tropical Australia, UVB I_r with clear sky conditions and a range of solar zenith angles was reduced to an average of only 0.03 by the "dense foliage" of a fig tree, though sky view was not specified (Moise and Aynsley, 1999). Beneath complete, undisturbed canopies of a variety of tropical and in-leaf temperate deciduous forests, Brown et al. (1994) found that PAR I_r was generally greater than UVB I_r, though the UVB:PAR I_r ratio could be greater than 1, up to about 1.15 in the darkest shaded forest locations and up to about 1.65 in shaded edges of a large gap. In a closed-canopy mixed deciduous forest (described as "*Liriodendron, Quercus, and Carya*") in Maryland, UVB I_r was approximately 0.05 (Brown et al., 1994), even lower than PAR I_r. Lee and Downum (1991) found negligible UVB irradiance under dense tree canopies. Even under an oak canopy with a relatively low leaf area index of 1.7 but with an even distribution of foliage horizontally, measurements over 2 days showed UVB was attenuated to a greater extent than the PAR (Yang et al., 1993).

The measurements of vertical profiles of UVB profiles through the oak canopy by Yang et al. (1993) showed that Beer's Law explained the mean UVB, PAR, and SW penetration down into the oak forest. In this application the law was of the form $t = \exp^{-kL}$, where t is canopy transmission to a given canopy depth, L is the cumulative leaf area index from the top of the canopy down to that point, and k is an experimentally determined extinction factor that average 0.86, 0.79, and 0.64 for UVB, PAR, and SW respectively.

Although there are few measurements of the UV environment below extensive canopies of vegetation other than trees, the pattern that emerges is consistent with what is known about leaf optical properties and sky radiance in the UV. For example, the distribution of UVB I_r at points beneath sorghum did not follow the normal statistical distribution, but was skewed with the median I_r less than the mean (Grant et al., 1995). Thus, analysis of irradiance beneath similar canopies should be based on non-normal statistical methods. Brown et al. (1994) noted the same skewing in measurements made under a variety of forest canopies.

4.4. Applications

The set of algorithms used in the 3-D model (see Sections 2.5 and 3.4), with tree crowns represented by assumed 3-D ellipsoids (Gao, 1997; Grant and Heisler, 2000a), together with a contour plotting program, were used to simulate the horizontal pattern of visible (PAR) and UVB I_r below scattered crowns (Heisler and Grant, 2000a). This result suggested the potential to display patterns of I_r around trees graphically, which could have value for evaluating the

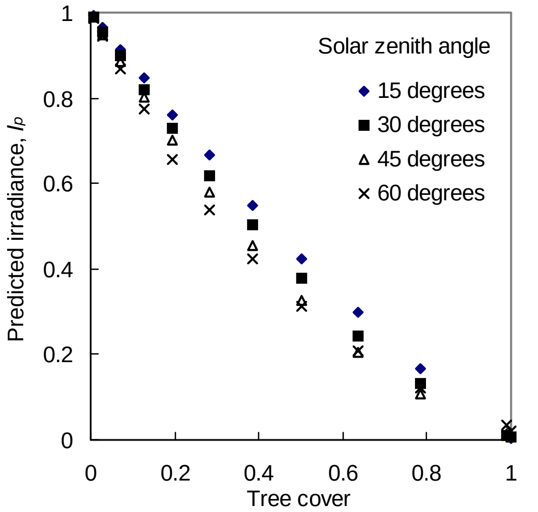

Fig. 9. Predicted mean relative irradiance under uniformly distributed tree crowns vs. tree cover fraction for at four solar zenith angles. Modified from Grant et al. (2002).

effect of UV on patterns of understory vegetation in low-density forests or on crop species in intercropping agriculture and for illustrating UV and visible shade for public education programs.

By assuming that tree cover is uniformly distributed, estimates of average UVB exposure across an understory with differing tree cover can be derived from irradiance models (Grant and Heisler, 2000a; Grant et al., 2002). Fig. 9 shows predicted average irradiance (I_p) below an area with uniformly spaced trees with varying tree cover fraction (m) for four different solar zenith angles (θ). The modeling results in Fig. 9 are fit closely ($R^2 = 0.99$) by the equation:

$$I_p = 1 - m - \left(\frac{\theta^{0.711}}{5.05}\right)\sin(\pi m). \quad (2)$$

Eq. (2) improves upon Eq. (5) in Grant et al. (2002).

4.5. Research needs

To evaluate the potential effects of UVB on agriculture, the 3-D model of tree influences on I_r in the different wavebands requires further development and application. Above-canopy irradiance as influenced by different ozone or atmospheric turbidity scenarios would be an input needed for study of tree effects on below-canopy irradiance. Ozone levels could be those predicted for the future. The model, especially with improvements such as added building effects and tree shapes other than ellipsoidal crowns might find application to human epidemiological studies, public education, and urban planning.

Longer term monitoring of irradiance below tree canopies is needed to determine if I_r is influenced by the differences in F_D that accompany changes in total column ozone and tropospheric contaminants. Aerosols reduce irradiance on horizontal surfaces, but the scattering of UV by non-absorbing aerosols may increase the UV exposure on non-horizontal surfaces.. Because of the variation in spectral reflectance of both man-made and natural surfaces, the variation in spectral response of sensors and the variation in spectral radiance across the sky, spectral irradiance measurements are needed to evaluate the wavelength distribution below canopy. Multifilter instruments (Webb, 2003) would be useful for such measurements.

Although ground-level monitoring of ozone or UVB is continually carried out at more than 150 sites around the world, this monitoring has not yielded much published information about urban to rural differences in UVB. For applications in and near urban areas, additional monitors in urban sites are needed along with analysis of existing data. The Washington, DC and Baltimore, MD area has a high density of UV monitoring stations with the possibility of urban to rural comparisons. Using, for the present, a broadband UVB sensor along with PAR and SW sensors, we have recently established a monitoring site in the City of Baltimore in collaboration with the Baltimore Ecosystem Study in the NSF Long Term Ecological Research program (Grant et al., 2000).

The potential effect of differences in tree species on UVB irradiance below their crowns has not been well quantified. This is partly because of the importance of diffuse sky radiation in determining irradiance below tree crowns, partly because of the difference in crown density with tree size and with pruning regimes, and partly because of the considerable difficulty of sampling irradiance effects of individual tree crowns when other nearby trees and buildings also have an influence, which is so much the case in the UVB. The most promising method for establishing differences in I_r by species is by using photographic methods to estimate visual crown density (Heisler, 1985, 1986). By considering path length through the crown and zenith angle of crown sectors in a photograph, the visual density estimates can yield estimates of the *G* function in Eq. (1).

5. Conclusions

The factors influencing the effect of individual trees, scattered trees, and forests on UV irradiance are known and can be modeled with a moderate degree of confidence. However, modeling methods need to be enhanced for use in evaluating UVR climatology and human exposure in epidemiological investigations and for estimating UVR levels and UVB:PAR ratios in multicrop agriculture.

Although trees do reduce exposure to UVR, differences with respect to sky diffuse radiance and reflection from leaves and human-made surfaces cause major differences in the relative amounts of visible or PAR and UVB radiation that penetrate to pedestrian levels. In visible shade where there is a significant view of the sky, reductions in UVB generally are much less than reductions of PAR. Just outside PAR shade patterns of trees where there is significant view of the sky, UVB is reduced more than PAR. Closed canopies that block the sun and sky view greatly reduce UVB exposure.

Satellite-based UVB measurements indicate that average increases in erythemal UVB owing to ozone depletion vary from negligible at the equator to about 4% in populated mid-latitude areas of the Northern Hemisphere in summer and 6% year-round in Southern Hemisphere mid-latitudes compared to the early 1970s. Large additional increases in UVB are not expected, but several decades may be required before a return to pre-1970 levels.

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