Urban tree influences on ultraviolet irradiance

Gordon M. Heisler*[a], Richard H. Grant**[b], and Wei Gao***[c]
[a]Northeastern Research Station, USDA Forest Service; [b]Department of Agronomy, Purdue University;
[c]USDA UV-B Radiation Monitoring and Research Program

ABSTRACT

Many of the effects of ultraviolet radiation (UVR) on people and their environment--damage to various materials, survival of insects and microbial pathogens, growth of vegetation, and adverse or beneficial effects on human health—are modified by the presence of trees. Human epidemiological investigations generally consider exposure as given by indices of UVR irradiance on horizontal surfaces in the open. Though many people are exposed to UVR while reclining at a beach or swimming pool, thus experiencing irradiance on essentially horizontal surfaces in the open, exposure to UVR during daily routines in urban areas may also be important in affecting human health. Tree influences on UVR irradiance, particularly in the UVB, can differ substantially from influences on the visible portion of the solar spectrum. Trees greatly reduce UVB irradiance in their shade when they obscure both the sun and sky. Where trees obscure the sun but leave much of the sky in view, UVB irradiance will be greater than suggested by the visible shadow. In small sunny areas near trees that block much of the sky from view, UVB irradiance is reduced substantially, whereas visible irradiance may be nearly as great or slightly greater than in the open.

Key Words. Air pollution, human health, ozone, skin cancer, solar radiation, urban environments, urban trees

1. INTRODUCTION

Ultraviolet radiation (UVR), particularly ultraviolet B (UVB, 320 to 280 nm) has many potential impacts on people and their environment in urban areas[1]. It affects human health, degrades various materials, affects health and habitat of animals on land and in water, affects survival of pests and effectiveness of pesticides, influences the potency of pathogens, affects biogeochemical cycles such as those of carbon and nitrogen[2], and affects plant community composition by altering the competitive ability of plants[3]. Also, there are complex interactions between UVR and the aerosols and photochemical smog that are important boundary layer air pollution constituents, particularly in urban areas[4]. Trees have potentially large impacts on UVR irradiance, and thus on all these UVR influences. Hence, knowledge of tree influences on UVR is needed to guide urban planning and public information. Because UVR penetration into below-canopy spaces can differ greatly from penetration of visible radiation, the visible is often not a good guide to UVR irradiance. Therefore, measurements and models of tree influences on UVR are needed.

The most important effect of UVR is probably its role in human health. Much of the human exposure to UV occurs in activities such as in visits to a swimming pool, beach, or tanning salon. However, exposure also occurs routinely in urban environments where radiation is influenced by the structure of buildings and trees. Thus, the relative importance of tree influences on UVR then depends in part upon the importance of the routine exposure in environments that have or could have tree cover. The most common skin cancer, basal cell carcinoma; cataracts of the eye; and immune deficiencies have been attributed to cumulative UVR exposure[1,5]. Tree influences may be most important in relation to influences on eye diseases, as one does not need to be at a beach wearing scanty attire to get eyes exposed to UVR.

Some reports suggest that cutaneous melanoma (CM) is related to intermittent extreme sun exposure[6-8] rather than to cumulative exposure over long time periods. This is consistent with the fact that melanoma incidence tends to be higher in

* gheisler@fs.fed.us; phone 1 315 448-3214; fax 1 315 448-3216; http://www.fs.fed.us/ne/syracuse/index.html; Northeastern Research Station, USDA Forest Service, c/o SUNY College of Environmental Science and Forestry, 5 Moon Library, Syracuse, NY 13210; **rgrant@Purdue.edu, phone 1 765 494-8048; fax 1-765 496-2926; http://shadow.agry.purdue.edu/; Department of Agronomy, Purdue University, 1150 Lily Life Sciences Bldg., West Lafayette, IN 47907-1150; ***wgao@nrel.colostate.edu; phone 1 970-491-3609; fax 1 970-491-3601; http://uvb.nrel.colostate.edu/UVB/home_page.html; USDA UV-B Radiation Monitoring and Research Program; Cooperative Institute for Research in the Environment; Colorado State University; Fort Collins, CO 80523

indoor workers than in outdoor workers[9]. Also, high exposure to the sun in childhood and early youth seem positively correlated with CM incidence[7], particularly if people suffered blistering sunburns in childhood or adolescence. This suggests that cumulative exposure in urban settings may be of little importance for CM. A few cases of severe sunburn might easily be acquired in occasional visits to high UV environments such as a beach. On the other hand, features such as tree shade for children's play areas, which could reduce UVB sufficiently to prevent sunburn, may be beneficial.

Adverse affects of UVR are balanced to some extent by positive health effects, which include vitamin D production. Some diseases are alleviated by moderate UVB exposure[10]. Study results and opinions differ regarding the role and importance of UVB and vitamin D in reducing non-cutaneous cancer incidence[1,11]. There is a school of thought in the literature that expounds the belief that low exposure to UVB is associated with increased risk of non-cutaneous cancers[12-17]. Reduced vitamin-D production with lower UVB in northern climates, or as a result of air pollution over cities, has been suggested as the cause of the increased risk of the non-cutaneous cancers. If the effect of air pollution on UVR contributes to non-cutaneous cancer, then large amounts of tree cover in residential neighborhoods might also contribute, depending upon the amount of UVR reduction that trees cause.

Many public education programs strive to increase awareness of the dangers of UVR, often urging people to take precautions to avoid excess exposure by seeking shade. A recent example of such programs is the "Choose Your Cover" initiative of the Centers for Disease Control (http://www.cdc.gov/ChooseYourCover). Public information brochures from the U.S. Environmental Protection Agency[18] make similar recommendations. In the United States, it has been suggested in the popular press[19] that tree-shaded spaces be used to prevent excessive UVB exposure. Authorities in Australia have issued similar recommendations[20]. Such programs would benefit from accurate information on UVR irradiance in shade of trees, as well as in shade of structures in urban environments. The expectation that elevated UVB levels caused by reduced stratospheric ozone will continue well into the 21st century[1,21,22] is further reason to evaluate UVR levels as influenced by trees and buildings.

It seems simple enough that where we see the shade of trees, there will be some protection from UVB. However, there can be significant differences between reductions of the visible portion of the solar spectrum (that is, the shade pattern we see) and reductions of UV by trees and other structures in urban areas. 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 urban structural surfaces, and in optical properties of leaves at different wavelengths. Relative reductions of UV radiation and visible radiation in shade can be surprisingly different, and the UVB irradiance is sometimes reduced more and sometimes less than visible wavelengths.

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, street trees, and a grove of trees. 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 short-wave (SW, 2500 to 320 nm), photosynthetically active radiation (PAR), ultraviolet A (UVA, 400 to 280 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_o 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, $I_r = I/I_o$. 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) CM5 thermopile pyranometers. PAR irradiance was measured using LI-COR (Lincoln, NB) LI-190S silicon photodiode quantum sensors (10% response bandwidth is 702 to 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 to 314 nm) and, for UVB, SED240/UVB/W filtered vacuum photodiode sensors (10% spectral response of 315 to 258 nm) (Fig. 1). Both IL sensors have 11-mm apertures. The IL UVB/W spectral response is similar to the action spectrum for generalized plant damage[3]. 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 to 280 nm (Fig. 1).

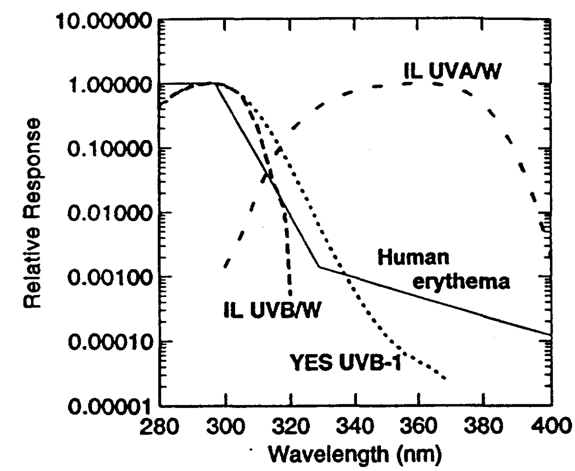

Figure 1. Relative responses of the UV sensors compared to the CIE sunburn (erythema) action spectrum. Sensor response is normalized to the peak response of each instrument.

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[23] 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 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[24-26].

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.

Upward-facing hemispherical photographs of each measurement site were made using a Canon 7.5-mm lens. Photographs were analyzed using grids with 5 or 10° intervals in both azimuthal and zenithal directions to determine total sky obscuration due to canopies for each 5 or 10° annulus. 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[27].

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. 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 to 1.5 hr at each location.

2.3 Street trees

One set of measurements included sensors for measuring UVB and PAR below deciduous campus trees that included red oak (*Quercus rubra*), red maple (*Acer rubrum*), white ash (*Fraxinus americana*), ginko (*Ginkgo biloba*), and thornless honeylocust (*Gleditsia triacanthos* var. *inermis*) that were 10 to 15 m tall and spaced approximately like street trees typical of older suburban neighborhoods. Hemispherical-view slide photos from each measurement site like those in Figure 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.

Figure 2. Sensor's eye (hemispherical lens) views of single tree from horizontal surface in shade (left) and vertical surface (right).

2.4 Tree grove

The second environment was a park-like grove of large oak (*Quercus*) and maple (*Acer*) trees approximately 30 to 40 m in height (Fig. 4) and within 300 m of the reference location on a building roof. 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.

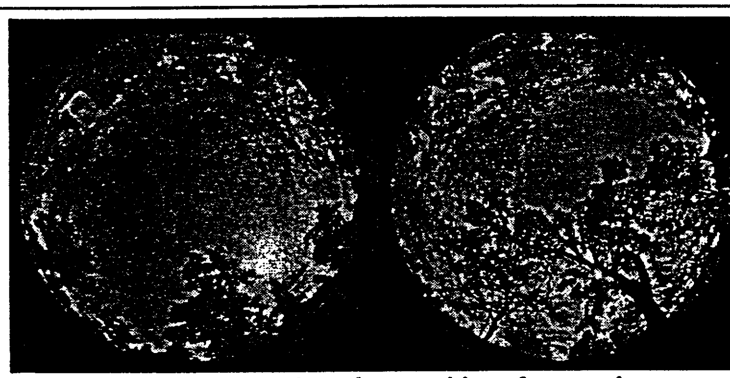

Figure 3. Hemispherical views from position of sensors in street tree irradiance measurements showing range of effective sky views sampled, 0.63 (left) and 0.43 (right).

2.5 Modeling tree influences on irradiance

The geometric 3-D model described in these proceedings by Gao et al.[28] for use in a maize canopy was used to predict the relative irradiance of a given waveband of radiation within and below the tree canopies[25]. In this model 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[29] model for UVR and the Bird[30] model for PAR and SW.

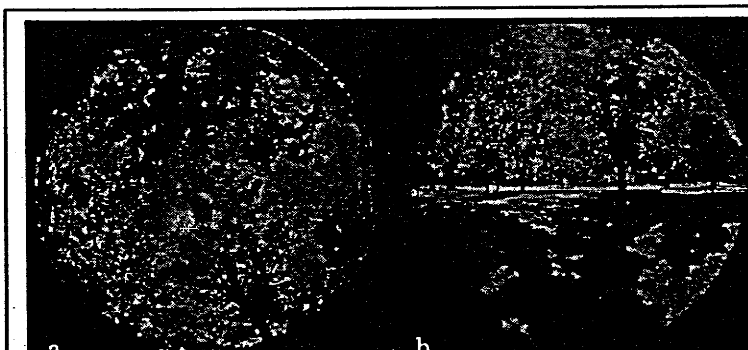

Figure 4. Hemispherical views from a horizontal sensor position in the tree grove (a) and from a vertical sensor position (b).

For an array of individual plant crowns, the geometry to model the probability of a beam of radiation traveling, unintercepted, from the beam's source (inside or outside the canopy) to any given point in the array is given by Norman and Welles[31]. 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:

$$P_o' = \frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} N(\varphi,\theta)e^{-G(\theta)\rho S}\cos\theta\sin\theta d\theta d\varphi}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} N(\varphi,\theta)\cos\theta\sin\theta d\theta d\varphi} \qquad [1]$$

where the anisotropic sky radiance distribution N for a given zenith angle θ and azimuth angle φ was modeled according to Grant et al.[32] for PAR, by Grant et al.[33] for UVR, and by Harrison and Coombes[34] 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 Figure 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. 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, with the UVB I_r being slightly greater than UVA I_r. Although in Figure 3 the tree crown appears to be quite visually porous, I_r values in the shade were relatively constant except when the direct beams to the sensors were near the irregular crown edge.

Thus, where only a small tree crown obscures the sun, the contrast between reductions in the visible 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 Figure 5, and differed little between horizontal and vertical surfaces.

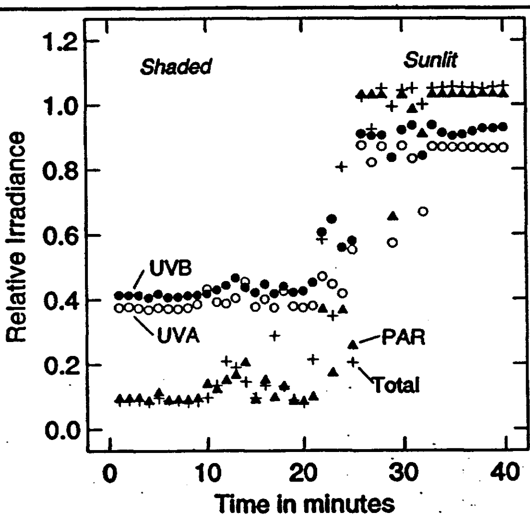

Figure 5. Relative irradiance as tree shade moved away from sensors measuring total SW (+), PAR (Δ), UVA (∘), and UVB (•). Sensors were horizontal, beneath the edge of the tree crown, and had a sky view of 0.78. The solar zenith angle was about 34 degrees. High cirrus covered 0.3 of the sky.

3.2 Street trees

The measurements below street 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[35,36] 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).

Table 1.--Average UVB and PAR relative irradiance at points below a street-tree canopy [24,37].

Half-hour measurements		Relative irradiance		Percent of view[a]		
	Number	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 percent 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.

Reflection from a sunlit building wall, which happened to be red brick with windows and made up 23% of the view, led to greater I_r for PAR at a tree-shaded point than when no wall was present, even though sky view at both points was similar. In the UVB, the wall decreased I_r because of low reflectivity in the UVB by 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[24].

The I_r values in Table 1 are representative of tree effects, though I_r will differ with solar zenith angle 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 important point of the measurements is the comparison between the UVB and the PAR. People can see the PAR radiation and make judgments about the impact of sunlight.

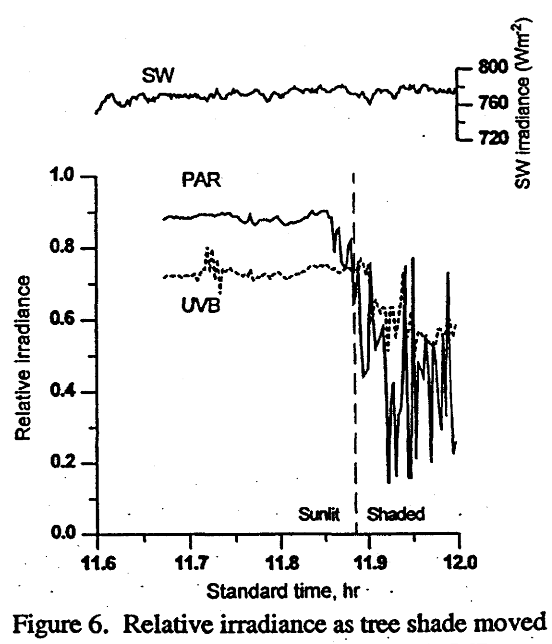

Figure 6. Relative irradiance as tree shade moved away from sensors measuring PAR and UVB. Sensors were horizontal and had an effective sky view of 68%. The solar zenith angle was about 48 degrees. The SW record is shown to indicate the approximate variability in above canopy irradiance.

The difference between UVB and PAR irradiances in tree shade is apparent in Figure 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 sunflecks, though the smaller diameter of the PAR sensors may also have contributed to the PAR variability. In Figure 6, UVB I_r in the sun is less than in Figure 5 because sky view is greater in the Figure 5 measurements.

3.3 Tree grove

Below a closed, dense forest canopy, UVB I_r can be reduced to low levels. In a closed-canopy mixed deciduous forest (described as "*Liriodendron, Quercus, and Carya*") in Maryland, UVB I_r was approximately 0.05 [38], even lower than PAR I_r. Lee and Downum[39] found negligible UVB irradiance under dense tree canopies. Our studies did not include measurements in dense forests, but Figure 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.

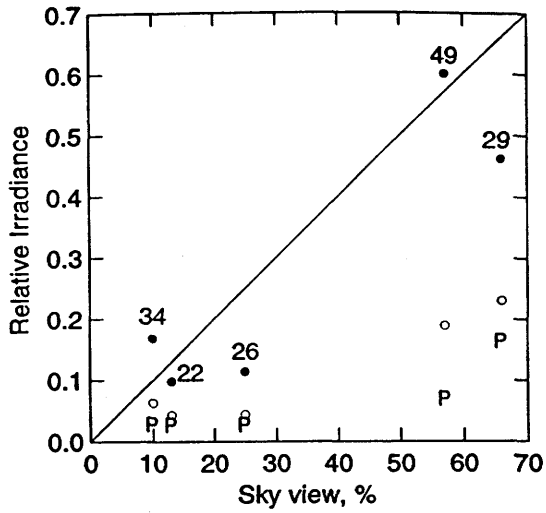

Figure 7. Relative irradiance in the UVB (•), UVA (o), and PAR (P) in shaded spots in a grove of large broad-leafed trees. Skies were generally clear except for 10% of sky covered by high cirrus clouds. Numbers above UVB points show solar zenith angles for each measurement set. The line represents a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

3.4 Modeling tree influences on irradiance

The 3D 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[25,40]. The minimum values are expected to represent the condition of little penetration through the tree crown. This comparison tests the 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 of less than 0.01.

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 urban structural surfaces.

4.1.1 Diffuse fraction

High diffuse fraction in the UVR is the major explanation for differences between UVR and PAR irradiance in the vicinity of trees. Much of the time, more than half of the UVB irradiance arriving on earth is from this diffuse radiation from the sky [24], 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[29] predicts F_D in the UVB at 0.52, and the Bird model[30] model predicts PAR F_D as 0.18; at 60° the comparable values are 0.72 and 0.24.

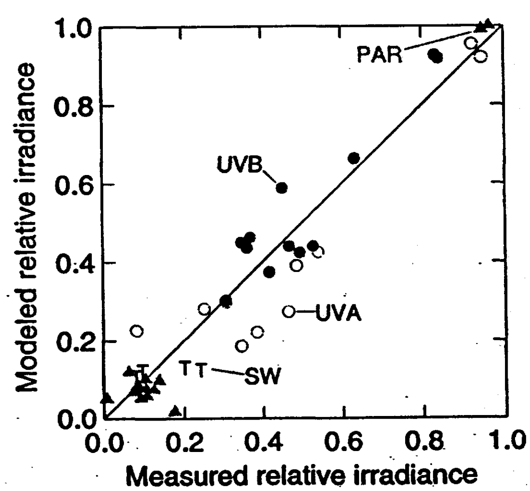

Figure 8. Comparison of modeled to measured I_r for UVB, UVA, PAR and total SW for both shaded and sunlit locations near the sweetgum tree.

4.1.2 Sky radiance distribution

Both the amount and distribution of sky radiance are important in determining irradiance in tree shade in the different wavebands. A series of measurements with a specially designed platform that held and rotated narrow-field-of-view sensors[33] showed that most of the

PAR sky radiation originates from near the sun[32]. There is a decided dark portion in the other half of the sky away from the sun. Unlike the PAR, the UVB distribution shows a much more even distribution across the sky. The pattern for UVA is about halfway between the UVB and the PAR. 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[33]. High cirrus clouds increase F_D slightly, but generally cirrus has small effect on the sky radiance distribution[41]. In the measurements shown in Figure 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[27].

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. However, this leads to errors even for modeling of the SW in the shadow of a tree[42]. Models of radiance distributions have been developed for the UVB and UVA with clear skies[33], for the UVA and UVB with translucent overcast skies[41], for UVR and PAR with overcast skies[43], and for PAR with clear skies[32]. For example, 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 $N_{UVB}=0.201 + 0.020\Theta^2 + 1.48e^{-7.8\psi}$, 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.

4.1.3 Leaf optical properties

Differences in sky F_D are primarily responsible for the differences between UVB and PAR I_r, particularly for sunlit points, though differences in leaf reflectance may also contribute. In a study of leaves of 19 species, average PAR reflectance was 1.1 to 3.3 times greater than UVB reflectance[44]. UVB reflectivity from the bottom sides of the seven species measured by Yang et al.[45] ranged from 1.0 to 5.8%; reflectivity of top sides was even lower. Transmission of ultraviolet radiation through leaves is negligible for nearly every tree species[44,45]. For most broad-leaved species, about 20% of the PAR and 30% of the SW energy penetrates through an individual leaf[46]. 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 not because more UV radiation penetrated through the leaves.

The high reflection from leaves and low sky radiance of PAR and SW 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[26], 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. Because reflectivity from crowns has implications for modeling irradiance in urban locations, it needs more study.

Leaf optical properties may change with leaf development through the year. 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[47]. 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[1].

4.1.4 UV reflectivity of urban surfaces

Tree influences on irradiance depend on the sources of the radiance, and in urban areas the sources may depend largely on reflectivity of building and paving surfaces. As for leaves, many other surfaces that are good reflectors for visible radiation are poor reflectors of UV[48]. 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[49], and thus tree effects in reducing irradiance in high latitudes in winter can have health effects.

One suggestion for making buildings more energy efficient and cities cooler is to increase the albedo of a large proportion of building and paved surfaces in a city[50,51] by organized programs for painting or otherwise covering them with light-colored materials. Although reflectivity in the UVB is less than in the visible, whitened wall or paving surfaces may significantly increase UVB irradiance on pedestrians and also increase UVB loads on vegetation in a similar fashion as snow increases UVB irradiance, although admittedly not quite so dramatically as for snow. For example, if we assume that radiation to the eyes is primarily from the ground[49], a doubling of surface albedo in the UVB could double UVB radiation into the eyes of pedestrians. Measured UVB reflectivities are not available for most of the materials that are proposed for lightening urban surfaces, but it is reasonable to assume that an increase in asphalt albedo for total solar radiation of 0.25 (or to about 0.36 for dark asphalt), as proposed by Rosenfeld et al.[51], might be accompanied by a doubling in UVB albedo from 0.055 to 0.11[1].

Most clean metals free from tarnish and oxide reflect between 30 and 55% of incident radiation in the middle of the UVB band at 300 nm; however, such materials will usually not remain clean in outdoor environments[48]. For 300-nm radiation, reflection from glass is less than 10% with incidence angles up to about 70°, where it increases very rapidly to nearly 100% reflectivity at near grazing incidence. This means that with high incidence angles, reflection from glass-walled buildings could nearly double the UVB irradiance on a person standing near the building. Water is similar to glass, but with reflectivity just a few percentage points higher at low incidence angles when the sun is nearly perpendicular to the surface, but high reflectivity at high incidence angles.

4.2 Tree influences on above-canopy irradiance

An apparently unstudied effect of urban trees is the potential effect on regional ground surface albedo with a large-scale change in tree cover. Citywide tree planting programs have been undertaken in some locations, such as Sacramento, CA[52] that might significantly lower albedo. Conversely, if roof or pavement surfaces of a sufficient portion of a city were whitened to increase the general UVB reflectivity of the landscape, UVB irradiance at ground level might be increased by an increase in the radiation that is reflected from ground-level surfaces up to the sky and then back to ground level. This effect could be tested by a sensitivity analysis using radiation transfer models. Though the potential for modifying incoming UVB is probably small[1], it should be examined further. A complete sensitivity analysis of light-surfaces program effects would require consideration of the extent of areas to be lightened, measured UVB albedo for the different types of lightened surfaces, inclusion of variation in ozone and urban aerosols, and changes in solar angles over the course of a year.

4.3 Other measurements

There have been few other measurements of the UV environment in urban areas. The few other studies have results generally in agreement with those in Table 1 and Figures 5, 6, and 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[53].

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[54] 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 detail of the tree structure was 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 that 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[55]. This was a greater reduction than provided in seven other urban shade structures that ranged from a school grandstand to a concrete walkway cover.

Beneath complete, undisturbed canopies of a variety of tropical and in-leaf temperate deciduous forests, Brown et al.[38] found that PAR I_r was greater than UVB I_r. This might be expected from the low transmittance of UVB radiation through leaves. In "disturbed" canopies and gaps, the same study showed that UVB I_r was more than PAR I_r.

Measurements over 2 days of the radiation environment under an oak canopy with a relatively low leaf area index (area of leaf surface per area of ground surface) of 1.7 showed UVB was attenuated to a greater extent than the PAR[56]. Beer's Law explained the mean UVB penetration through 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.

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[57]. Thus, analysis of irradiance beneath similar canopies should be based on non-normal statistical methods. Brown et al.[38] 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 three-dimensional ellipsoids[40,58], together with a contour plotting program, was used to simulate the horizontal pattern of visible (PAR) and UVB I_r below scattered crowns[59]. This result suggested the potential to display patterns of I_r around trees graphically, which could have value in public education programs. A "shade UV Index" based on modeled UV irradiance below tree crowns has been proposed to indicate the benefit of tree shade and the limits of that benefit [60]. Such an index might be coupled with the 3D illustrations for public education.

By assuming that tree cover is uniformly distributed and that the people are moving randomly around the neigborhood, estimates of average UVB exposure across urban neighborhoods with differing tree cover can be derived from irradiance models[40]. Initial estimates including trees but not buildings and assuming a solar zenith angle of 30°indicate that for a mid-latitude city, average UVB I_r ranges from 0.33 in single-family residential neighborhoods, which have 53% tree cover, to about 0.60 in parks and neighborhoods of multiple family dwellings, which have 27 to 29% tree cover. Average tree cover in urban areas ranges from 4% in Wyoming cities to 55% in Georgia. Considering buildings would probably significantly affect the predicted I_r estimates for residential neighborhoods, as would considering the actual tree locations rather than assuming uniformity of distribution.

Exposure to UVB is involved in both synthesis and breakdown of vitamin-D by a complex series of photochemical reactions[16,17,61]. These reactions regulate the production of vitamin-D so that toxic levels are not reached[62]. Only low levels of UVB exposure, far less than one MED (minimum erythemal dose), are needed in the synthesis process[62]. This suggests that tree shade in urban areas would not greatly limit vitamin-D production, or that tree shade might not limit it at all.

Because tree shade reduces heat stress on people, trees as a UV protective feature tend to be self-enforcing because people seek it out to keep cool under the sunniest conditions. This self-enforcing aspect is important because, judging by continued high incidence rates for skin cancer, people often do not take precautions to avoid excessive sun.

4.5 Research needs

For purposes of epidemiological studies, public education, and urban planning, the 3D 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 could be an input to study the effect on below-canopy irradiance. Ozone levels could be those predicted for the future. The model currently simulates trees only as ellipsoidal shapes; other tree shapes and buildings need to be added. Enhancing the model to simulate walk throughs, such as provided by a human thermal-comfort model by Bruse[63] would permit estimation of UVR exposure for people perambulating in various urban environments. A user-friendly format would enhance model utility. For public education, output with trees and buildings shown as 3D graphical images would be useful. Ideally, a future model would include applications to vertical surfaces or surfaces of maximum irradiance.

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, which could be important for human exposure in complex urban environments. 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 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. 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[64].

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. It is surprisingly difficult to find isolated urban trees growing away from other obstacles that can be used to measure single-tree influences for model validation. Except for crown size and shape, differences between species in irradiance effects will be largely due to differences in visual density. The literature shows little consistent trend in visual density or apparent irradiance reductions for different species[65] because measurement methods differ and the definition of crown edge differs from study to study. Thornless honeylocust (*Gleditsia triacanthos*), a species that is widely planted in urban areas in the United States, stands out for its relatively consistent low crown density of about 30%. The most promising method for establishing differences in I_r by species is by using photographic methods to estimate visual crown density[35,36]. 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 Equation 1.

5. CONCLUSIONS

The factors influencing the effect of urban 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 over an urban area so that the information might contribute to such purposes as evaluation of human exposure to UVR for epidemiological investigations. Ideally there should be interaction between studies of tree influences on UV irradiance and epidemiology, because epidemiology requires information on human exposure and studies of tree influences on UVR require knowledge of the possible importance of the question of tree influences. In spite of considerable research and some major advances, medical science has yet to fully define the levels and regimes of UV exposure that cause health problems versus health benefits. For example, the effect on health of equal total dosages at different intensities seems not well defined.

Tree effects have been quantified for a few conditions. Although trees do reduce exposure to UVB, differences with respect to sky diffuse radiance and reflection from leaves and urban surfaces cause major differences in the relative amounts of visible 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 in visible levels. Just outside visible shade patterns of trees where there is significant view of the sky, UVB is reduced more than visible. Closed canopies that block the sun and sky view of a person greatly reduce UVB exposure. Thus, for the purposes of public education, people could be told that as a rule of thumb, if they are in a dense forest with the crowns of trees close together, they need not be concerned about excess UVB radiation exposure, but if they are in the shade of a single moderate-sized tree with a crown that starts above head high, UVB will be reduced by only about half.

Additional UV radiation monitoring in urban areas would enhance possibilities for public education and research on UV radiation. Few cities have UVB monitoring in place.

Satellite-based UVB measurements indicate 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 1970's. Large additional increases in UVB are not expected, but several decades may be required before a return to pre-1970 levels. Research is needed to determine the relationship between average human exposure to UVB in particular urban areas and the satellite-derived averages for latitude zones.

ACKNOWLEDGMENTS

Dr. James R. Simpson, Dr. James R. Slusser, and Dr. Melanie Wetzel provided helpful review comments on earlier manuscripts on which this paper is based. William King assisted with radiation measurements. Sue Sisinni provided graphics support. Charles D. Canham of the Institute of Ecosystem Studies made available software for analyzing hemispherical photographs. This research was partially funded by the USDA Forest Service's Northern Global Climate Change Program.

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Ultraviolet Ground- and Space-based Measurements, Models, and Effects

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30 July–1 August 2001
San Diego, USA

Sponsored and Published by
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Please use the following format to cite material from this book:

Author(s), "Title of paper," in *Ultraviolet Ground- and Space-based Measurements, Models, and Effects*, James R. Slusser, Jay R. Herman, Wei Gao, Editors, Proceedings of SPIE Vol. 4482, page numbers (2002).

ISSN 0277-786X
ISBN 0-8194-4196-1

Published by
SPIE—The International Society for Optical Engineering
P.O. Box 10, Bellingham, Washington 98227-0010 USA
Telephone 1 360/676-3290 (Pacific Time) • Fax 1 360/647-1445
http://www.spie.org/

Printed in the United States of America.