A Geometric Ultraviolet-B Radiation Transfer Model Applied to Vegetation Canopies

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ABSTRACT

The decrease in stratospheric ozone (O_3) has prompted continued efforts to assess the potential damage to plant and animal life due to enhanced levels of solar ultraviolet (UV)-B (280–320 nm) radiation. The objective of this study was to develop and evaluate an analytical model to simulate the UV-B irradiance loading on horizontal below-canopy surfaces, as influenced by vegetation. The UV-B irradiance above canopy and transmitted to below-canopy points was measured in a widely spaced orchard and in a closely spaced maize (*Zea mays* L.) crop during cloud-free days, with solar zenith angle ranging from 20° to 80°. The sky view fraction was typically 0.59 for the orchard and 0.28 for the maize canopy. Transmitted irradiance fractions were simulated and compared to measured fractions. Measured and simulated values of UV-B canopy transmittance generally agreed well both for points in locations shaded by plant crowns and for points below the top of the canopy that were not shaded. The model had mean bias errors of 0.04 and 0.03 for the orchard and maize canopies respectively, and the root mean squared error of the model was 0.08 for orchard and 0.06 for maize. The model can serve as a much-needed tool to examine UV-B irradiance loading of organisms below tree canopies and of sensitive plant surfaces in and below tree and vegetation canopies.

There has been growing concern about the possible impact of ozone layer depletion because the stratospheric ozone column is one of the primary attenuators of solar ultraviolet (UV)-B radiation (280–320 nm). A decrease in this ozone column would lead to increases in UV-B irradiances reaching the earth's surface. The most important wavelengths for assessing potential plant damage due to increased UV radiation are in the UV-B band (Caldwell, 1971; Caldwell et al., 1998; Madronich et al., 1998). The effect of UV-B enhancements on plants includes reduction in grain yield, alteration in species competition, decrease in photosynthetic activity, susceptibility to disease, and changes in plant structure and pigmentation (Tevini and Teramura, 1989; Bornman 1989; Teramura and Sullivan, 1991). Some plant species show sensitivity to present levels of UV-B irradiance while others are apparently unaffected by rather massive UV enhancements (Becwar et al., 1982). To make matters more complicated, there are reports of equally large response differences among cultivars of a species (Biggs et al., 1981; Teramura and Murali, 1986). About two-thirds of some 300 species and cultivars tested appear to be susceptible to damage from increased UV-B irradiance.

Many radiative transfer models for the shortwave band have been developed and used to understand and simulate the radiation environment of vegetative canopies. Smith (1983), Goel (1988), and Myneni et al. (1989) have reviewed these models and studies. Most of these radiative transfer models apply to homogeneous canopies of a large horizontal extent and are one-dimensional (1-D) models (deWit, 1965; Monsi and Saeki, 1953; Cowan, 1968). Many important canopies, however, are extremely variable spatially and cannot be treated by 1-D models. For instance, tree canopies often have large natural openings between crowns, incomplete row crops have big spaces between rows of vegetation, and urban scenes are complex three-dimensional (3-D) arrangements of trees and buildings.

Simulation of UV-B irradiance above and in canopies differs from total shortwave or photosynthetically active radiation in that the fraction of global irradiance received as diffuse irradiance from the sky is much larger, frequently exceeding 50% for midlatitudes during much of the day. Consequently, particular effort must be made in the modeling treatment of the sky-diffuse irradiance. Simulation of the UV-B irradiance on surfaces below or in the canopy also requires detailed knowledge of UV-B irradiance penetration of the direct and diffuse irradiance through the canopy. Surfaces of potentially UV-B-sensitive plant parts (like young leaves and inflorescences) are frequently present in canopies before canopy closure or in the higher part of the canopy where it is relatively open. Open canopies typically have large discontinuities that give large views of the sky and its diffuse irradiance (a large portion of the total UV-B irradiance) and that also provide paths for the transmission of direct irradiance under the appropriate sun angle. The 1-D models assume a homogeneous canopy that cannot simulate an open canopy where there is large spatial variation in leaf area in the horizontal plane and important anisotropic distributions of the incident irradiance at the canopy top as is the case with UV sky radiance distributions. An advanced 3-D radiation model that considers anisotropic sky radiance penetrating through heterogeneous canopies (such as row crops before canopy closure) is needed to evaluate UV-B irradiance loading in many plant canopies. Such a 3-D model is most useful for canopies that contain dense grouping of leaves within subcanopies, or crowns, that are widely separated. When dimensionality increases in radiation models, more canopy structure information is needed as input to the model.

This paper describes the testing of a 3-D UV radiation transfer (UVRT) model that can be used to calculate canopy transmittance (T_{canopy}, irradiance below canopy/

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Abbreviations: 1-D, one dimensional; 3-D, three dimensional; MBE, mean bias error; RMSE, root mean squared error; T_{canopy}, canopy transmittance; UV, ultraviolet; UVRT, ultraviolet radiation transfer.

irradiance above canopy) for horizontal surfaces located within or below an open vegetation canopy. This paper presents both the development of the 3-D UVRT model and an assessment of its accuracy using transmittance measurements made in an orchard (*Malus* sp.) and maize (*Zea mays* L.) canopy. Although the model cannot simulate irradiance on nonhorizontal surfaces of plant parts, the point of interest could be located within plant crowns to simulate irradiance on sensitive parts, such as flowers or fruits that are produced within crowns. Assessments of UV-B irradiance received by a crop could be made by running the model for a set of representative locations of sensitive plant parts within or on the surface of a typical crown.

MATERIALS AND METHODS

The Theory of Ultraviolet Radiation Transfer Model

The 3-D UVRT model was developed to simulate UV-B T_{canopy} within and below vegetation canopies. The model assesses the UV-B irradiance below canopies given initial sky conditions and canopy composition and structure. In this model, the canopy consists of a finite number of 3-D geometrical bodies (plants), with the individual bodies, or crowns, regarded as discrete scattering volumes of ellipsoidal shape located in an *X*, *Y*, and *Z* Cartesian coordinate space. The crowns are modeled such that *X* radii may differ from *Y* radii at a given *Z*, that is, the crowns are not simple ellipsoids of revolution. This differs from 1-D models, which assume that plant canopies consist of horizontally uniform layers.

The model inputs describing the atmospheric conditions include the atmospheric ozone column thickness, aerosol optical depth, relative humidity, atmospheric pressure, surface albedo, and the solar zenith and azimuth angles. The sky-diffuse irradiance can be treated as either a uniform or nonuniform sky distribution that is a function of the solar zenith angle (Grant and Heisler, 1996).

Three-Dimensional Ultraviolet Radiation Transfer Model

The 3-D UVRT model includes transmittance of direct beam and sky-diffuse irradiance in the canopy. The amount of foliage is characterized by a foliage density ρ, defined as the foliage area per unit volume containing the foliage.

The T_{canopy} is defined as:

$$T_{canopy} = I_t/I_{t0} \quad [1]$$

where I_{t0} is the total irradiance at the top of the canopy, in W/m^2, and I_t is the total irradiance transmitted to some depth in the canopy, in W/m^2.

Table 1. Input parameters used in the ultraviolet radiation transfer (UVRT) models from the canopy measurements.

Quantity	Maize	Orchard
Latitude, degrees	40.5	40.5
Longitude, degrees	87.5	87.5
Row spacing, m	0.76	5.5
Plant spacing, m	0.23	3.35
Foliage density (ρ), m^{-1}	2.87	1.8
Subcanopy radius (*X*), m	0.47	1.68
Subcanopy radius (*Y*), m	0.44	1.22
Subcanopy radius (*Z*), m	1.00	1.82
Height of subcanopy center, m	1.00	2.28
Height of measurements level, m	0.80	1.20

The modeled I_t is estimated by:

$$It = (I_{b0} \times P_0) + (I_{d0} \times P'_0) \quad [2]$$

where I_{b0} is the direct irradiance at the top of the canopy, in W/m^2; I_{d0} is the sky-diffuse irradiance at the top of the canopy, in W/m^2; P_0 the direct beam irradiance–penetrating function (the probability that a ray will pass through the canopy unintercepted); and P'_0 is the sky diffuse irradiance–penetrating function.

The values of I_{t0}, I_{b0}, and I_{d0} in Eq. [1] and [2] are modeled using the clear-sky Schippnick and Green (1982) model using the mean solar zenith of the measurement period and assuming an albedo of 0.02, a low aerosol rural atmosphere amount, and atmospheric pressure and relative humidity derived from measurements made at the Purdue University Airport (8 km away) for the hour of radiation measurements. Column ozone over the region was extracted from the database of the METEOR3 Total Ozone Mapping Spectrometer (TOMS) for 1994 measurement periods (C. Long, personal communication, 1996) and was assumed a constant 320 DU for the 1995 measurement periods because there were no TOMS ozone measurements being made at that time.

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 of subcanopies of homogeneous density (P_0) in Eq. [2] is given by (Norman and Welles, 1983):

$$P_0 = e^{[-G(\theta,\varphi)\rho S(\theta,\varphi)]} \quad [3]$$

where θ is the zenith angle, in degrees; φ is the azimuth angle, in degrees; G(θ,φ) is the fraction of foliage area that is projected towards (θ,φ) (called the G-function or projection coefficient); ρ is the foliage density (foliage area per unit canopy volume); and S(θ,φ) is the distance through the canopy that the ray must pass.

The computation of S in Eq. [3] was based on the equations of Norman and Welles (1983) although all sources were assumed to be on a reference plane just above the canopy to simplify the three cases of S determination: sensor under the canopy, sensor in the canopy, and sensor above or away from the canopy. Defining S_0 as the distance between the sun's position on the reference plane and the sensor, S_1 as the distance between the sun and one point of intersection with the canopy, S_2 as the distance between the sun on the reference plane and another intersection point ($S_2 > S_1$), the three cases are: (i) $S_0 > S_2$, the sensor is under the canopy, and $S = S_2 - S_1$; (ii) $S_2 > S_0 > S_1$, the sensor is within the canopy, and $S = S_0 - S_1$; and (iii) $S_0 > S_1$, the sensor is above or in front of the canopy, and $S = 0$. S was computed based on the mean *X* and *Y* spacing of the crowns; the *X*, *Y*, and *Z* dimensions of the individual plant crowns; and the *X*, *Y*, and *Z* coordinates of the measurement location. The crown spacing, dimensions, and densities for the maize and orchard canopy used in the model evaluation reported here are indicated in Table 1.

The probability of penetration of sky-diffuse irradiance (P'_0) in Eq. [2] is given as:

$$P'_0 = \frac{\int_0^{2\pi}\int_0^{\pi/2} N(\psi,\theta)\exp[-G(\theta)\rho S(\theta,\varphi)]\cos\theta d\theta d\varphi}{\int_o^{2\pi}\int_0^{\pi/2} N(\psi,\theta)\cos\theta\sin\theta d\theta d\varphi} \quad [4]$$

where ψ is the scattering angle between the sun and the location in the sky, and it can be defined as $\cos\psi = \cos\theta\cos\Theta + \sin\theta\sin\Theta\cos\Phi$, where Θ is solar zenith angle and Φ is the difference in azimuth between the sun and the position in the sky. $N(\psi,\theta)$ is the clear-sky anisotropic sky radiance distribution and was modeled according to Grant et al. (1997a, 1997b) as:

$$N(\psi,\theta) = 0.217 + \frac{0.038\theta^2}{\pi/2} + 0.917e^{-8.9\psi} + 0.142\cos^2\psi \quad [5]$$

and the isotropic sky radiance was defined as $N(\psi,\theta) = 1/\pi$. This approach differs from the Norman and Welles (1983) model by explicitly defining the sky radiance, which was deemed necessary due to the typically high diffuse fraction of the global irradiance in the UV-B waveband (Schippnick and Green, 1982).

Measurements

The accuracy of the 3-D UVRT model in simulating the UV-B irradiance on *sunlit* and *shaded* surfaces in vegetation canopies was determined by comparing model simulations with irradiance measurements in two different canopies. Measurements of UV-B irradiance were made in the orchard from 9 Sept. to 10 Oct. 1994 and in a maize canopy from 29 July to 31 July 1995 at West Lafayette, IN (40.5° N lat).

The apple (*Malus* sp.) orchard, located at the Purdue Horticultural Research Farm, consisted of similarly sized 11-yr-old trees ('Redchief Apple') in a hedgerow system. The trees were spaced at 3.4 m within the row, and the rows were 5.5 m apart. The trees had a mean height of 4.2 m, with some shoots extending to about 4.5 m. No foliage occurred below about 0.46 m above ground level. The foliage density was estimated according to Charles-Edwards (1976). The leaf angle distribution was assumed to be spherical within each tree crown, setting G at a constant 0.5.

The maize canopy ('Pioneer 3394') was located at the Purdue Agronomy Research Center. The maize was planted on 5 June 1995 at the rate of 65 000 plants ha^{-1} in east-west rows 0.76-m apart. The foliage density and canopy leaf area index (LAI) and leaf angle distribution (LAD) were determined by direct measurements using the method described by Daughtry (1990) and Perry et al. (1988), and G was computed using those measurements.

The canopies were simulated as individual plants (with uniform crown density) based on direct measurements of plant height, width, and row spacing. Because both the orchard and maize canopies were planted in east-west rows, the coordinate system had the $+X$ direction along the row toward the east and the $+Y$ direction toward the north in the 3-D UVRT model. The vertical dimension was designated as the Z coordinate.

The sky view fraction at each measurement location was determined by analysis of hemispherical photographs taken using a Canon short focal length 7.5-mm lens. Sky obscuration by the vegetation canopy (including stalks, branches, and trunks) was determined by analyzing the photographs using a 10° interval grid in both azimuthal and zenithal directions. An area of the sky hemisphere was defined as obscured if the sky was not visible at the intersection of the 10° interval azimuthal and zenithal grid lines.

Above and within the canopy, UV-B irradiance was measured using SED 240/UV-B/W sensors (International Light, Newbury, MA), which are 11-mm-diam. *solar-blind* vacuum silicon photodiode sensors operated in a photoconductive mode and biased by −5 V (Grant, 1996). Because the ratio of UV-B irradiance within the canopy to that above the canopy was of primary interest in this study, all UV-B sensors were intercompared at Purdue Agronomy Research Center before each day of measurement. Measured differences from the intercomparison in the responses under the clear morning sky were used to adjust the within-canopy measurements before calculating the T_{canopy}. All measurements were made under visibly clear-sky conditions and terminated when clouds or haziness were seen approaching from the horizon. Irradiance measurements were made every 30 s and averaged over 30 min.

Within-canopy measurements were made at a height of $0.3H$ (where H was the mean height of plants) at both sunlit and shaded locations in the apple orchard and $0.45H$ at shaded locations in the maize canopy. A shaded location was defined as that having canopy biomass between the sun and the sensor position throughout the measurement period except for small sunflecks on the sensors. A sunlit location was defined as one having direct-beam irradiance going through the canopy for the duration of the measurement period. Above-canopy irradiance measurements for the maize experiment were made above the canopy within 2 m of the location where the under-canopy measurements were made while above-canopy measurements for the orchard were measured at the Purdue Agronomy Research Center weather station, which was within 10 km of the orchard. Because measurements were made only with clear-sky conditions, it is a reasonable assumption that irradiance was equal at the orchard and Research Center locations.

Irradiance measurements were corrected for sensor temperature calibration, dark current, and cosine response according to Grant (1996). The cosine correction was not applied to the total UV-B irradiance but only to the estimated direct component of the measured irradiance (I_{bt}/I_t), as calculated by the model of Schippnick and Green (1982).

For purposes of model evaluation, the measured above- and within-canopy irradiances were averaged over 30-min measurement periods. The measured UV-B T_{canopy} was calculated from the mean corrected simultaneous above- and below-canopy UV-B irradiance measurements using Eq. [1]. Leaves in both canopies were regarded as blackbodies. The accuracy of the T_{canopy} model (Eq. [2]) was evaluated by the mean bias error (MBE) and the root mean squared error (RMSE), with low values indicating greater model accuracy. The MBE of the model for n pairs of modeled and measured values describes the systematic model error and was defined as:

$$\text{MBE} = \frac{1}{n}\sum[T_{canopy}(\text{simulated}) - T_{canopy}(\text{measured})] \quad [6]$$

and the RMSE of the model for n pairs of modeled and measured values described the random model error and was defined as:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum[T_{canopy}(\text{simulated}) - T_{canopy}(\text{measured})]^2} \quad [7]$$

RESULTS AND DISCUSSION

Measurement

Ultraviolet-B irradiance was measured within and above the orchard in 62 measurement periods, with solar zenith angle ranging from 40° to 80° while in the maize field, there were 20 measurement periods, with solar zenith angle ranging from 20° to 70°. Within-canopy measurements in the orchard were in both predominantly sunlit (36 measurement periods) and shaded (26 measurement periods) locations. Analysis of the hemispherical photographs showed that the average sky view fraction in the orchard was 0.59, with individual locations varying from 0.52 to 0.65 (Fig. 1, left). The average sky view fraction for the maize canopy was 0.31 (Fig. 1,

Fig. 1. Hemispherical photograph of a measurement site in the (left) orchard and (right) maize canopy. The centers of the photographs represent the zenith. Distance from the center toward the edge is linearly related to the zenith angle.

right), with all within-canopy measurements in shaded locations.

In sunlit and shaded locations, transmittance of UV-B irradiance was limited by the penetration of sky-diffuse irradiance. The penetration of above-canopy UV-B irradiance differed less between sunlit and shaded locations at higher solar zenith angles than at low solar zenith angles because increased solar zenith angle corresponds with increased diffuse fraction. Although the measurements made in the maize canopy were classified to be in shaded locations, the canopy had significant gaps, producing direct-beam UV-B irradiance penetration through the canopy and resulting in sunflecks crossing the generally shaded location over the course of the individual measurement period. The analysis of the T_{canopy} probability distribution for the maize canopy frequently demonstrated two peaks of measured T_{canopy} (Fig. 2), showing the occurrence of these sunflecks in the otherwise shaded environment (Grant, 1999). The T_{canopy} associated with periods of shade (and primarily only diffuse irradiance) was 0.07 in the maize canopy (Fig. 2). Similar problems with sunflecks were not found in the orchard. Because the crown density of individual trees within the orchard was high, penetration of UV-B irradiance through the crown was generally very small, resulting in few sunflecks at the chosen shaded locations over the period of measurement. Consequently, setting our sensors either in sunlit or shaded locations resulted in only one peak T_{canopy} value corresponding to direct and diffuse irradiance penetration at the sunlit locations or mostly diffuse with little direct irradiance penetration at the shaded locations.

Model Accuracy

The accuracy of the model was evaluated by comparing the simulated T_{canopy} to the measured values in both sunlit and shaded locations in the orchard and shaded locations in the maize canopy (Fig. 3). For the orchard canopy, the mean ratio of simulated T_{canopy} values to measured values was 0.98 while for the maize canopy, the mean ratio of simulated T_{canopy} values to measured values was 0.88. The MBE of the model was similar for the orchard and maize canopies (0.04 for the orchard and 0.03 for the maize). The RMSE was greater for the orchard than the maize canopy (0.08 for the orchard and 0.06 for the maize). Comparisons between a simulated and measured value must, however, consider the probability distribution of T_{canopy} from which the median value was derived (Fig. 2). Because the model assumed uniform density crowns within the maize canopy, the simulated value represents a mean simulation in penetration while measurements show either sunlit or shaded conditions whose average value would, with sufficient replication across the whole canopy, give a measure comparable to the model simulation. Because we were seeking to determine the accuracy of the model using relatively short periods of measurements under a wide range of solar zenith angles in distinct shaded or sunlit locations rather than by long periods of measurements and having to assess whether sufficient measurements had been made to account for the variability in sunflecks in a given canopy, the inclusion of sunflecks at the shaded locations biased the measurements upward. Therefore, the difference between simulated and measured UV-B T_{canopy} in the maize canopy was partly due to measurements being made only between rows, which did not represent the real *mean* maize field. In addition, the simulation model assumed perfectly uniform leaf angle distribution and foliage density with respect to azimuth angle, whereas in the real field, both leaf angle distribution and foliage density were variable. Because sunflecks were essentially nonexistent in the shade of

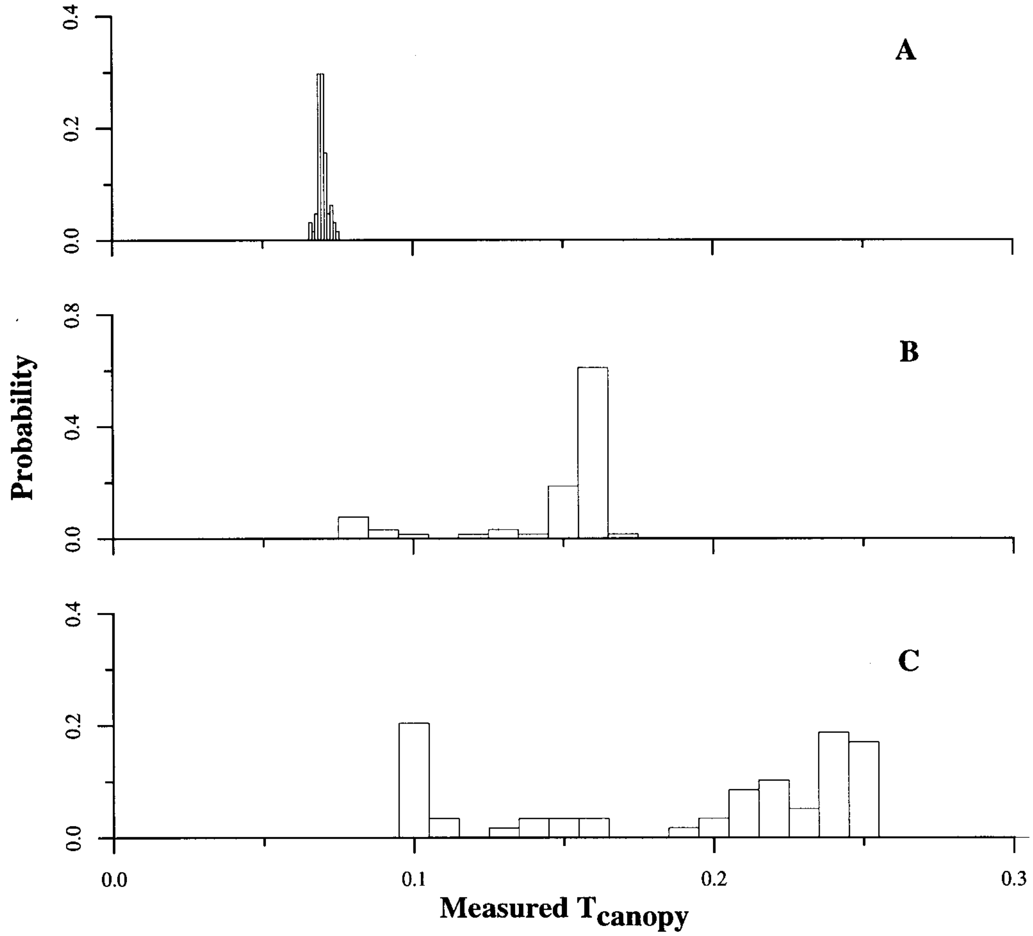

Fig. 2. Variability in ultraviolet (UV)-B canopy transmittance (T_{canopy}) for different measurement locations in the maize canopy. A represents the probability distribution of individual T_{canopy} measurements over the course of a measurement period for a location without sunflecks while B and C represent the probability distributions for individual T_{canopy} measurements at locations with sunflecks. The intervals of T_{canopy} were 0.001 for A and 0.01 for B and C.

the crown in the orchard but common in the maize canopy, the model performed better in the orchard canopy than in the maize canopy.

The geometric complexity of the model is probably only justified for widely separated plants where the gaps between plants greatly exceeds the gaps within the crown of the individual plants, such as is common in young stands of many crops and tree stands. The UV-B T_{canopy} simulation error ($T_{simulated} - T_{measured}$) for the orchard was smaller at small solar zenith angles and tended to increase as the solar zenith angle increased (Fig. 4). This increase in error was probably partly due to (i) the decreasing ratio of direct-beam to sky-diffuse irradiance with increasing solar zenith angles causing increased importance of the distribution of diffuse irradiance (Grant et al., 1997b), (ii) the difficulty in correcting for the sensor cosine response error at high-incidence angle, and (iii) the decreasing signal-noise ratio resulting from decreasing UV-B irradiance with increasing solar zenith angle.

Isotropic and Anisotropic Sky Radiance Comparison

The diffuse irradiance from the sky is never truly isotropic, or constant in radiance across the entire sky hemisphere, but varies in radiance in accordance with molecular and aerosol-scattering theory (Hutchison et al., 1980; Grant and Heisler, 1996, 1997; Grant et al., 1997a). However, this variation is not necessarily important in modeling solar irradiance above canopies. For shortwave irradiance, the diffuse fraction of the global irradiance is typically small, obviating the need for detailed descriptions and treatment of the sky-diffuse irradiance. These models typically assume an isotropic sky radiance distribution, one where the radiance is constant across the entire sky hemisphere. In the UV-B, the diffuse fraction is commonly >50% of the global irradiance. This suggests that the sky-diffuse irradiance should be treated more carefully in any modeling effort. To determine the importance of the sky radiance distribution on the simulation of below-canopy irradiance, the UV-B T_{canopy} was simulated assuming an anisotropic sky radiance distribution (ANI-UVRT model) and an isotropic sky radiance (ISO-UVRT model). A comparison of the simulated T_{canopy} resulting from these two assumptions showed greater simulated penetration into the canopy from an anisotropic sky compared with an isotropic sky (Fig. 5). The mean difference in penetration due to the assumption of sky radiance distribution was about 3.6% at sunlit locations and less than that at shaded

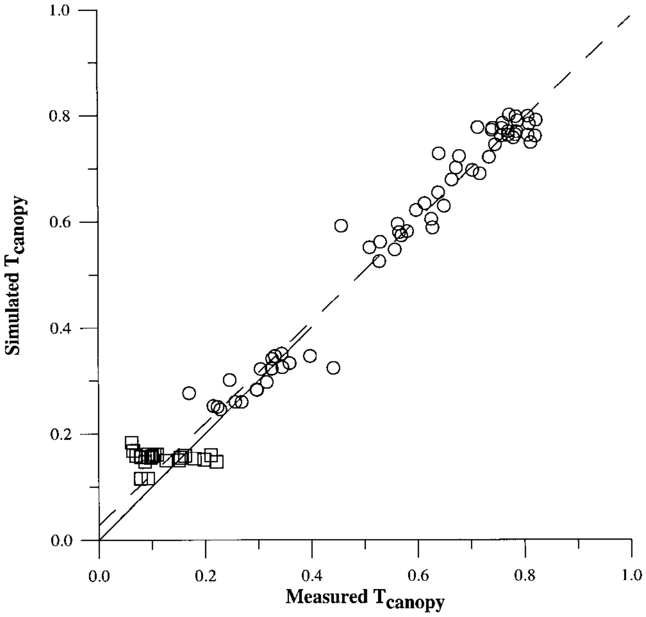

Fig. 3. Accuracy of three-dimensional (3-D) ultraviolet radiation transfer (UVRT) canopy transmittance (T_{canopy}) model. The simulated T_{canopy} values for the orchard (open circles) and maize canopy (open squares) are indicated. The solid line has a slope of 1, and the dotted line is a linear regression of simulated T_{canopy} on measured T_{canopy}.

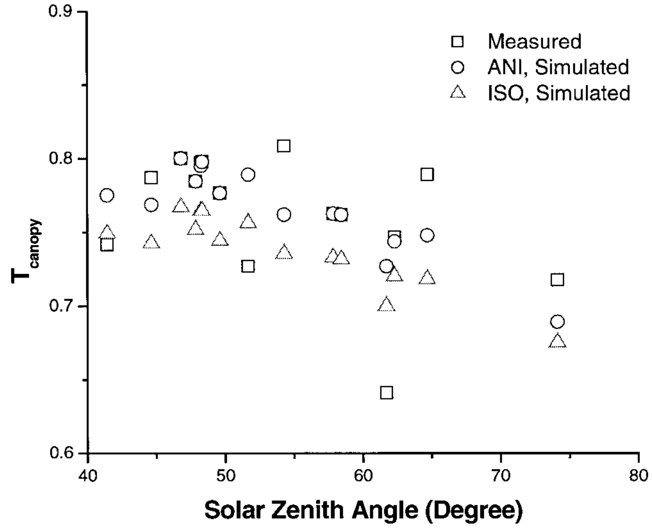

Fig. 5. Comparison of simulated canopy transmittance (T_{canopy}) with different sky radiance distribution and measured T_{canopy} with solar zenith angle in *sunlit* locations in the orchard canopy. The simulated T_{canopy}, assuming an isotropic (open triangles) and anisotropic (open circles) sky and measured T_{canopy} (open squares).

locations, in agreement with the work of Hutchison et al. (1980). In sunlit locations, the portion of the sky obscured by the trees tends to have less radiance than estimated using the isotropic sky radiance distribution (note relative radiance at angles away from the solar disk in Fig. 6), resulting in greater penetration of above-canopy irradiance than simulated using the isotropic sky distribution (Fig. 5). The difference between simulated UV-B T_{canopy} values due to the assumed sky radiance distribution increased with increased UV-B T_{canopy} through canopies in sunlit locations and decreased in shaded locations.

The canopy sky view fraction is the greatest single factor in defining the UV-B irradiance (Brown et al., 1994). Clearly, the sky view fraction should be important in the UV-B because of the typically high diffuse fraction and the anisotropy of the UV-B sky radiance distribution. Differences in the simulated T_{canopy} due to the choice of simulated sky radiance distribution became more positive [T_{canopy}(ISO) > T_{canopy}(ANI)] with increased sky view fraction for shaded locations and more negative [T_{canopy}(ISO) < T_{canopy}(ANI)] at sunlit locations. The differences between the simulated T_{canopy} values increased for both sunlit and shaded locations (Fig. 7)

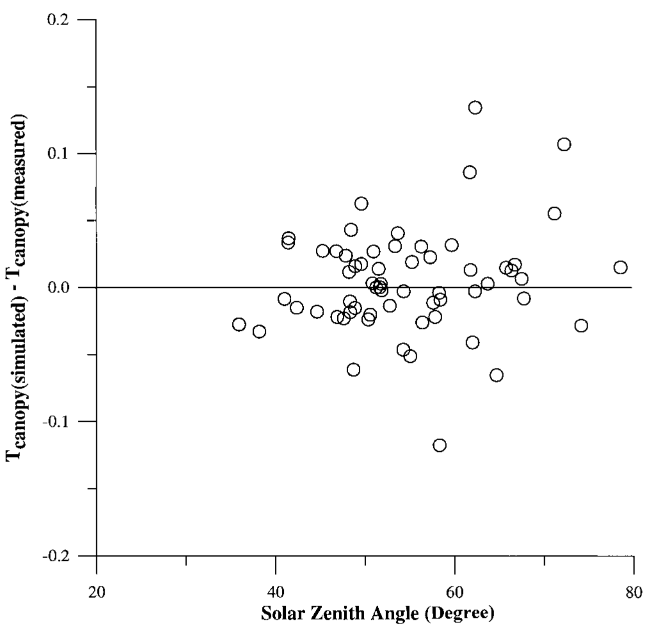

Fig. 4. Errors of simulated to measured canopy transmittance (T_{canopy}) with solar zenith angle in orchard measurement area.

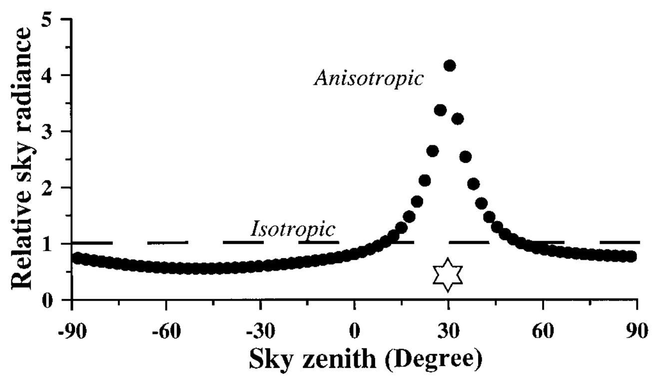

Fig. 6. Effect of sky radiance assumptions on the distribution of sky radiance along the vertical plane between the sensor and the sun. The effect of sky obstruction on simulated isotropic and anisotropic irradiance differences at *sunlit* locations (sky zenith angles away from the sun location), where the isotropic sky radiance is greater than the anisotropic sky radiance, is opposite that of sky obstruction at *shaded* locations (obstruction of the solar disk) where the anisotropic sky radiance exceeds the isotropic radiance. For this example, the sun is located at 30° zenith angle. All values of sky radiance have been normalized to an isotropic sky radiance values so that the value of 1 corresponds to the radiance of the isotropic sky (dashed line).

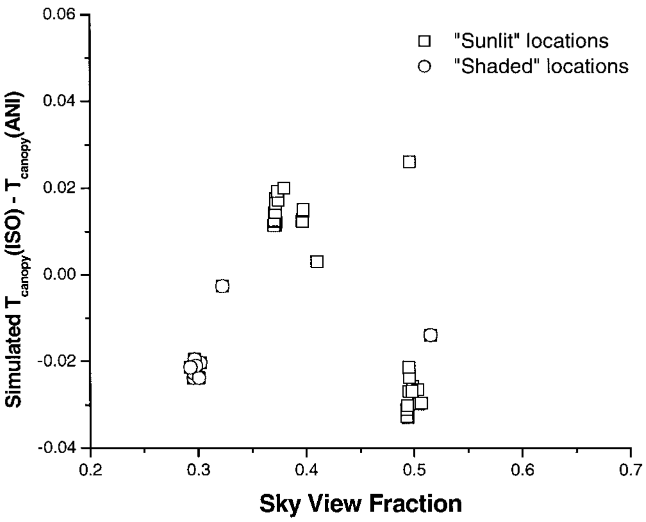

Fig. 7. Difference in simulated canopy transmittance (T_{canopy}) between assumed isotropic and anisotropic sky radiance distribution with sky view fraction. The *sunlit* and *shaded* measurement locations are indicated by the open squares and open circles, respectively.

and are in agreement with Grant and Heisler (1996). In shaded locations, the trees are obscuring portions of the sky that have greater radiance in the anisotropic model than in the isotropic model (Fig. 6). Consequently, we would expect the simulated T_{canopy} to be greater using the isotropic model than the anisotropic model, and this is confirmed by the analysis (Fig. 7). In sunlit locations, the trees are obscuring portions of the sky that have less radiance in the anisotropic sky than in the isotropic sky (Fig. 6). Therefore, we expect that the differences in the simulated irradiance using an isotropic or anisotropic sky radiance distribution would be opposite that found for the shaded locations. This is indeed what was found (Fig. 7).

The assumption concerning the sky radiance distribution affected the accuracy of the simulated T_{canopy} (Fig. 5). The measured values had MBEs of 0.0028 and 0.026 and RMSEs of 0.035 and 0.034 for the simulated T_{canopy} with the anisotropic and isotropic assumption, respectively, at the sunlit locations in the orchard canopy. This indicates that it is better to use the anisotropic sky radiance assumption in our modeling the UV-B penetration in open canopies. The performance of the anisotropic sky radiance model to a solar zenith angle of 80° is encouraging because the sky radiance distribution was developed using only solar zenith angles of $<65°$.

CONCLUSIONS

A 3-D model was developed to simulate the UV-B irradiance for horizontal surfaces in open canopies. Tests of the model accuracy were made using field measurements in an open canopy of apple orchard and in a closed canopy of maize for cloudless sky conditions. Measured and simulated values of UV-B T_{canopy} generally agreed well. The model had MBEs of 0.04 and 0.03 for the orchard and maize canopies, respectively, and RMSEs of 0.08 and 0.06 for orchard and maize, respectively. The model performed better in the orchard canopy than in the maize canopy. The largest differences between measured and simulated UV-B T_{canopy} occurred at large solar zenith angles. This was partly due to the decreasing ratio of direct-beam to sky-diffuse irradiance with increasing solar zenith angle. The diffuse sky radiance distribution (isotropic and anisotropic) did not strongly influence the model simulation accuracy though the simulated values assuming an anisotropic sky condition were closer to the measured irradiance. The influence of sky conditions on the difference in T_{canopy} in the sunlit and shaded locations was not as important as having direct sunlight or not on the measurement locations. The greatest difference in UV-B T_{canopy} was between sunlit and shaded locations. This model can be used to assess the UV-B irradiance below dispersed canopies (agricultural crops, orchards, and trees in urban areas) given initial sky conditions and canopy composition and structure where the individual crown can be described as an ellipsoid. The source code and document of the model can be obtained by contacting the authors. Sky radiance distributions for use in the model are available for clear and overcast conditions. Additional testing would be needed to determine the applicability of the model for partly cloudy conditions.

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