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Ultraviolet-B radiation in a row-crop canopy: an extended 1-D model

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Abstract

A decrease in stratospheric ozone may result in a serious threat to plants, since biologically active short-wavelength ultraviolet-B (UV-B 280–320 nm) radiation will increase even with a relatively small decrease in ozone. Numerous investigations have demonstrated that the effect of UV-B enhancements on plants includes reduction in grain yield, alteration in species competition, susceptibility to disease, and changes in plant structure and pigmentation. To determine the physiological effects on plants of any increases in UV-B radiation, the irradiances at the potential sensitive plant surface need to be known. A number of radiative transfer models exist but because of the importance of sky diffuse radiation to the global UV-B irradiance, models designed to estimate photosynthetically active radiation or total solar radiation may not accurately model the UV-B. This paper compares spatially and temporally averaged measurements of the UV-B canopy transmittance of a relatively dense maize canopy (sky view: 0.27°) to the estimations of two one-dimensional models differing mainly in the handling of sky radiance. The model that considered the distribution of sky radiance tended to underestimate the canopy transmittance, the model that assumed an isotropic sky radiance distribution tended to overestimate the canopy transmittance. However, the assumption concerning the sky radiance distribution accounted for only about 0.01 of the model error. Consequently, the sky radiance distribution is probably not important in modeling such dense crop canopies. The model that overestimated transmittance and had the generally larger errors, a modified Meyers model, used the assumption of uniform leaf angle distribution, whereas in the other model, designated the UVRT model, leaf angle distributions were estimated by sample measurements. Generally this model would be satisfactory in describing the statistically average UV-B irradiance conditions in the canopy. This model may also be applied to other dense plant canopies including forests.

Keywords: Ultraviolet-B; Modeling; Maize canopy

1. Introduction

A decrease in stratospheric ozone may result in a serious threat to plants, since biologically active short-wavelength ultraviolet-B (UV-B 280–320 nm) radiation will increase even with a relatively small decrease in ozone (Bojkov et al., 1998; Caldwell et al., 1998; Kerr and McElroy, 1993; Seckmeyer et al., 1994; Zerafos et al., 1995) and UV-B radiation is known to have physiological effects on plants. UV-B radiation comprises only a small portion of the solar radiation incident at the earth's surface, but has a disproportionately large photobiological effect. Experimental work has shown that various cultivars and

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species respond to UV-B in different ways (Teramura, 1983; Tevini and Teramura, 1989). Among the most commonly observed plant responses from UV-B exposure are changes in biomass and biomass allocation, flowering pattern, plant height, and leaf thickness (Bornman, 1989; Teramura and Sullivan, 1991; Tevini and Teramura, 1989). To determine the physiological effects of any increases in UV-B radiation on plants, the irradiances at the potentially sensitive plant surface need to be known. Numerical models are needed to calculate UV-B irradiance at the plant surface.

Reliable assessment of the effects of global changes in biologically active radiation requires quantitative information concerning ground-level intensities. Many models are available for estimating the potential and actual solar radiation, in particular wavelength bands for various purposes. More than 50 models for simulating radiation–vegetation interactions have been proposed in the literature (Goel, 1988; Myneni et al., 1989; Ross, 1981). However, studies of vegetation influences on the incident radiation of the total solar spectrum or the photosynthetically active radiation (PAR, 400–700 nm) wavelength band provide limited information regarding UV-B irradiance (Grant, 1991), because the major portion of UV-B irradiance at the earth's surface comes from diffuse sky radiation, not well treated in current models. As a result of the high diffuse fraction, the sky view through gaps in the canopy is the greatest single factor in defining the UV-B irradiance (Brown et al., 1994; Grant and Heisler, 1996) and the distribution of the sky radiance in those gaps may become important in estimating the irradiance.

The capability of a model to produce a statistically acceptable fit against the observations is in part a result of realistic model assumptions that fit the observed situation. The usual approach consists of solving the radiation transfer problem separately in each medium for simplified and fixed boundary conditions. Simplifying assumptions include isotropic diffuse sky radiation, a non-reflecting medium, an isotropically reflecting medium, or homogeneous density of the medium.

Radiation models describing the attenuation of radiation passing through a canopy medium are needed to define the canopy structure. These models are usually classified according to how this structure is described. A one-dimensional (1-D) model commonly assumes the canopy structure is horizontally homogeneous with foliage elements randomly dispersed in the canopy horizontal space. This kind of model has been widely applied in dense canopies and usually only requires inputs of leaf optical properties, leaf area index and angular distribution of foliage surfaces. For three-dimensional (3-D) models, the canopy structure is considered as horizontally heterogeneous with distinct plant volumes distributed in space (Gao et al., 2002).

The purpose of this paper is to evaluate the importance of the variable distribution of sky radiance on the estimation of UV-B irradiance in a crop canopy using 1-D models. This paper compares spatially and temporally averaged measurements of UV-B canopy transmittance (T_{canopy}, irradiance below canopy/irradiance above canopy) through a maize canopy to that estimated by two 1-D models with differing treatments of sky radiance.

2. Materials and methods

2.1. Modeling theory development

A newly developed 1-D model (described hereafter as the 'UVRT or UV radiation transfer model') and a modified 1-D model developed by Meyers and Paw (1987) (described hereafter as the 'MM model') were used to simulate the UV-B T_{canopy} of a maize canopy. The characteristics of the models are described below.

2.1.1. UVRT model

Incident radiation received at a horizontal plane within a canopy has two components: direct radiation not blocked or attenuated by the canopy and diffuse radiation. The diffuse components arise from three reflected (scattered) irradiance sources: the sky, foliage, and the soil. The canopy transmittance (T_{canopy}) is defined as:

$$T_{\text{canopy}} = \frac{I_{\text{t}_j}}{I_{\text{t}_0}} \quad (1)$$

where I_{t_0} is the total irradiance at the top of the canopy, in W/m^2, and I_{t_j} the transferred radiant energy at a point on a horizontal plane above layer j ($j = 0$ at ground level) within the canopy, it can be expressed by

$$I_{\text{t}_j} \downarrow = I_{\text{b}_j} \downarrow + I_{\text{d}_j} \downarrow \quad (2)$$

where $I_{t_j} \downarrow$ is transferred radiant energy from layer $j+1$ to layer j; $I_{b_j} \downarrow$ the penetrating direct radiation from layer $j+1$ to layer j; and $I_{d_j} \downarrow$ the diffuse radiation from layer $j+1$ to layer j.

The direct beam radiation above layer j ($I_{b_{j+1}}$) is defined as:

$$I_{b_j} \downarrow = I_{b_{j+1}} \downarrow \times P_{0j} \tag{3}$$

where P_{0j} is the penetration function; the fraction of the direct radiation above layer j that will not be intercepted by the leaf area δL after passing through layer $j+1$. $L=0$ at the top of the canopy and $L=$ canopy leaf area index (LAI) at the ground level.

Penetration function (the probability that a ray of radiation will not be intercepted as it passes through the canopy) P_{0j} was expressed by the classical equation for a full-cover canopy of randomly positioned leaves

$$P_{0j} = \mathrm{e}^{-G(\Omega)\times(\delta L_j/\cos\theta)} \tag{4}$$

where δL_j is the leaf area in layer j; θ the zenith angle; Ω a direction of radiation coming from zenith angle θ and azimuth φ; and $G(\Omega)$ the fraction of foliage area that is projected towards the source of radiation.

The leaf interception factor, the G function (Ross and Nilson, 1966), corresponds to the mean projection of a unit foliage area per unit volume of the canopy on the plane perpendicular to the direction Ω (the mean projection of canopy elements onto a surface normal to the direction of the projection). If the projection zenith angle is θ with azimuth angle φ, then the G function is calculated from the weighted integral of $g(\alpha, \beta)$ over the hemisphere, where α is the leaf inclination angle and β is the leaf azimuth angle.

Based on direct measurement, the leaf angle distribution (LAD) was modeled as

$$g(\alpha) = (6.4247 - 0.3754\alpha + 0.0064\alpha^2)^{-1} \tag{5}$$

The probability of penetration of sky diffuse radiation was modeled as

$$P'_{0j} = \frac{\int_0^{2\pi}\int_0^{\pi/2} N(\psi,\theta)\exp[-G(\theta)\,\delta L_j/\cos\theta]\cos\theta\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi}{\int_0^{2\pi}\int_0^{\pi/2} N(\psi,\theta)\cos\theta\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi} \tag{6}$$

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 the solar zenith angle and Φ is the difference in azimuth between the sun and the position in the sky. The sky radiance distribution $N(\psi, \theta)$ was modeled according to Grant et al. (1997) as

$$N(\psi,\theta) = 0.217 + \frac{0.038\theta^2}{\pi/2} + 0.917\mathrm{e}^{-8.9\psi} + 0.142\cos^2\psi \tag{7}$$

The downward diffuse flux above layer j (I_{d_j}) and $j+1$ ($I_{d_{j+1}}$) generating from both sky and canopy elements is

$$I_d \downarrow_j = I_d \downarrow_{j+1} [\tau(1-P'_{0j}) + P_{0j}] + I_d \uparrow_j \times [\gamma(1-P'_{0j})] + I_b \downarrow_{j+1} (1-P_{0j})\tau \tag{8}$$

and

$$I_d \downarrow_{j+1} = \frac{I_d \downarrow_j - I_d \uparrow_j [\gamma(1-P'_{0j})]}{[\tau(1-P_{0j}) + P'_{0j}]} \tag{9}$$

where $I_d \uparrow_j$ is the upward diffuse radiation above layer j, $I_{b_{j+1}}$ the direct radiation, and $I_{d_{j+1}}$ the diffuse radiation above layer j, τ the leaf transmittance, and γ is the leaf reflectance. So, the radiant transferred energy at a horizontal plane above layer j within the canopy can be expressed as

$$\mathrm{I}_{t_j} \downarrow = (I_b \downarrow_{j+1} \times P_{0j}) + I_d \downarrow_{j+1} [\tau(1-P'_{0j}) + P'_{0j}] + I_d \uparrow_j [\gamma(1-P'_{0j})] + I_b \downarrow_{j+1} (1-P_{0j})\tau \tag{10}$$

Norman (1979) states that the use of P'_{0j} in this set of equations is subjected to the restriction that the amount of leaf area within each layer is small, thereby decreasing the chance of leaf overlap. He suggests the leaf area in each layer must never be greater than 0.5 and preferably near 0.1. We assumed a leaf area of 0.1 for each layer to compute UV-B canopy transmittance in this model.

2.1.2. MM model

The MM model was modified from that of Meyers and Paw U (1987) by explicitly defining, rather than computing, the diffuse fraction.

2.1.3. Model comparison

The fundamental transport equations and method of solution in the MM model was the same as the UVRT model. In both models: (1) the fundamental transport equations and method of solution are given by Eqs. (2)–(4), (9) and (10); (2) the UV-B diffuse fraction was estimated from the green model (Green et al., 1974); (3) radiation scattering within the canopy was included; (4) scattering properties of leaf and soil were based on Grant (1993); (5) the canopy was composed of a homogeneous volume of leaf surfaces with leaf density varying only with height; and (6) the leaf azimuth distribution was assumed uniform. The differences between the two models were: (1) the sky radiance distribution was assumed to be isotropic for the MM model, but was anisotropy for the UVRT model; (2) leaf angle distribution was assumed to be spherical for the MM model, but was the actual distribution as estimated from the direct sampling measurement for the UVRT model.

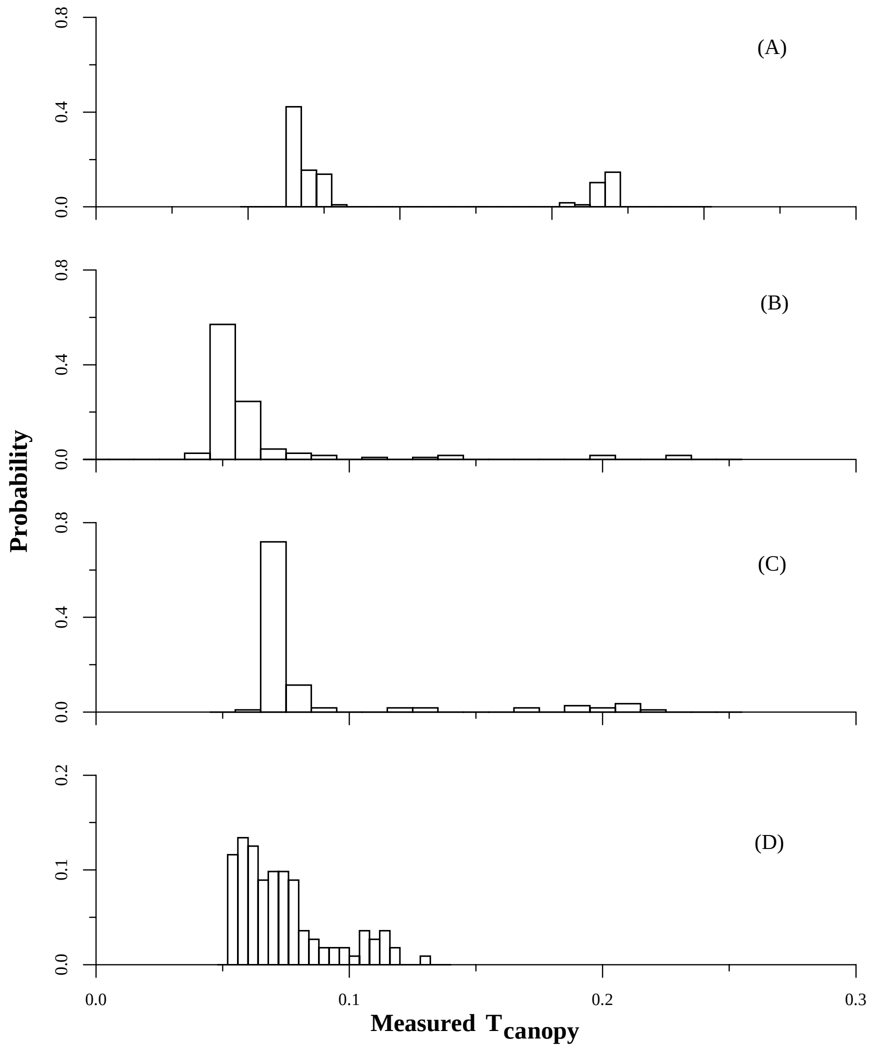

Fig. 1. Effects of maize canopy on UV-B T_{canopy} for measurement locations at the solar zenith angle 30° (A), 40° (B), 50° (C), and 60° (D), respectively.

2.2. Field experiment

The UV-B irradiance measurements were made in a maize canopy from 21 August 1995 to 24 August 1995 at the Purdue Agronomy Research Center (latitude: 40.5°, longitude: 87.5°) located in West Lafayette, IN, USA. All measurements were made under visibly clear sky conditions and stopped when clouds or haziness were seen approaching from the horizon (Table 2).

The maize (*Pioneer 3394*) in this study was planted on 5 June at the rate of 26,300 plants per acre in east–west rows 0.76 m apart. The crop was well fertilized, and a pre-emergence herbicide was applied for weed control. The soil type for this field was a dark Chalmers silty clay loam. The mean canopy height (H) was 2.6 m. The leaves at the layer of maximum leaf area index (LAI) (0.65H) were long enough to overlap.

Canopy LAI and LAD were determined directly by dimensional and orientation measurement of leaves from 20 plants selected at random (Campbell and Norman, 1989). As a result of a moderately dry period during the measurements, the crop leaves were slightly curled and more erect than normal because of plant water stress.

Hemispherical photographs of the sky hemisphere were made at all measurement locations. The photographs were analyzed for total sky obscuration using a 10° interval grid in both the azimuthal and zenithal directions. An area of the sky's hemisphere was defined as obscured by the plant tissues if the sky was not visible at the intersection of the azimuthal and zenithal grid lines. The unobstructed sky view for the locations of the measurements was not uniformly distributed with respect to zenith angle or azimuth angle.

From the experimental period, four completely clear days were chosen. Days with partial cloud cover were not selected due to errors with both the estimated spectral irradiance and sky radiance distributions. Irradiance measurements of UV-B were made using an 11 mm diameter "solar-blind" vacuum silicon photodiode sensor operated in photoconductive mode and biased by −5 V (Grant and Heisler, 1996). All measurements were temperature, dark current, and cosine response corrected. The corrected zenithal cosine error of the UV-B irradiance measurement in the open was estimated to be less than 10% for solar zenith angles of between 20° and 80° under clear sky conditions (Grant, 1996).

Measurements of the UV-B irradiance under and above the canopy were made simultaneously every 30 s and recorded on a Campbell Scientific data-logger. Runs were typically 8 m per location. The below canopy UV-B irradiance was measured using a sensor mounted on a moving platform (below the maximum leaf area density) along a 3 m rail at a height of 0.37H (H was the mean average maize height) oriented in an east–west direction between rows. The rail/platform system was described in Grant et al. (1995). Below canopy, measurements were made at seven locations along the rail at intervals of 0.4 m. The mean unobstructed sky view for the combined seven locations was 0.27° with sky view at individual locations varying from 0.24° to 0.31° (Fig. 1). Measurements from these seven locations were combined to calculate the spatially averaged median of UV-B transmittance. Each set of seven measurement locations were grouped by solar zenith angles (Table 2). Large and small solar zenith were defined as greater than, and less than, 60°. The shaded condition was defined as having canopy elements between the sun and the sensor position throughout the measurement period, but the direct radiation could go through canopies at any given instance in time due to leaf flutter.

2.2.1. Model evaluation

The UVRT model and the MM model were evaluated for their ability to estimate transmittance (T_{canopy}) for UV-B within the maize canopy. Simulations were

Table 1
Input parameters used in the UVRT models from the maize canopy measurements

Latitude (°)	40.5
Longitude (°)	87.5°
Row spacing (m)	0.76
Plant spacing (m)	0.23
Leaf area index (LAI)	3.37
Foliage density (ρ) (m^{-1})	2.58
UV-B leaf reflectance	0.063
UV-B soil reflectance	0.058
UV-B leaf transmittance	0
Subcanopy radius (X) (m)	0.45
Subcanopy radius (Y) (m)	0.42
Subcanopy radius (Z) (m)	1.30
Height of subcanopy center (m)	1.30
Height of measurements level (m)	0.88

Table 2
The background information for the sixteen measurements run in maize canopy

Date	Run number	Number of replication	Duration (min)	Solar zenith Angle (°)	Median of UV-B (T_{canopy})	S.D.	Coefficient of variation
21 August 1995	1	7	58	29	0.042	0.089	93.684
21 August 1995	2	7	58	29	0.040	0.069	89.610
23 August 1995	3	7	63	30	0.042	0.079	108.219
22 August 1995	4	5	44	30	0.039	0.005	12.821
24 August 1995	5	7	52	36	0.053	0.045	65.217
15 August 1995	6	4	44	36	0.062	0.016	24.242
23 August 1995	7	7	57	37	0.059	0.033	48.529
21 August 1995	8	7	60	39	0.052	0.021	39.623
22 August 1995	9	7	60	39	0.052	0.073	90.123
23 August 1995	10	7	59	40	0.045	0.007	14.894
21 August 1995	11	7	58	43	0.049	0.003	6.123
24 August 1995	12	7	56	46	0.057	0.028	40.580
23 August 1995	13	7	58	50	0.055	0.005	9.091
24 August 1995	14	7	57	51	0.074	0.036	41.860
21 August 1995	15	7	58	52	0.057	0.011	18.644
22 August 1995	16	7	57	53	0.077	0.039	42.391
21 August 1995	17	7	57	59	0.077	0.014	17.722
24 August 1995	18	6	50	63	0.059	0.006	10.169
23 August 1995	19	7	58	64	0.072	0.018	23.684
23 August 1995	20	3	30	71	0.129	0.07	48.276

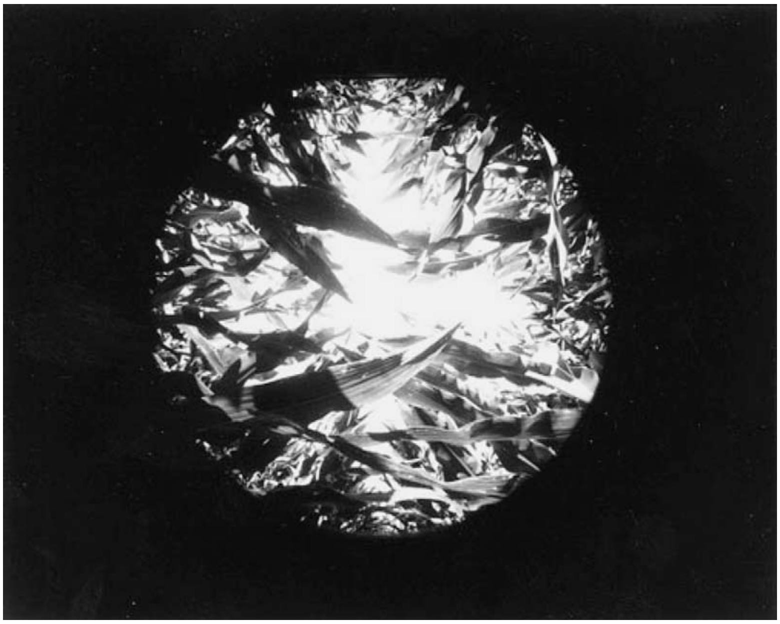

Fig. 2. Hemispherical photograph of a measurement site. The center of the photograph represents the zenith. Distance from the center toward the edge is linearly related to the zenith angle.

run and compared against 4 days on which measurements were made. Table 1 summarizes the model input parameters for the evaluation. Table 2 summarizes conditions during the measurement periods used to validate the models.

The T_{canopy} model error (the difference between estimated and median measured T_{canopy}) for each model was evaluated relative to the root mean squared error (RMSE: the magnitude of an individual error value), and mean bias error (MBE: the signed difference between estimated and measured values) (Davies et al., 1984).

The median above canopy irradiance of each time period was used for comparison to the modeled UV-B canopy transmittance, to avoid confusion resulting from the typical skewed probability distribution of the instantaneous canopy. Grant et al. (1995) found that the probability distribution of UV-B irradiance under a dense *Sorghum* canopy was positively skewed (a predominance of low irradiance with occasional high irradiance sunfleck events), with the median irradiance less than the mean. Skewing in UV-B measurements was also found by Brown et al. (1994) for dense forests.

In the UVRT model, three estimated values of three layers were selected for comparison to measurements since the true height of the canopy is hard to determine. The highest layer in defined range gave the highest values, while the lowest layer gave the lowest value.

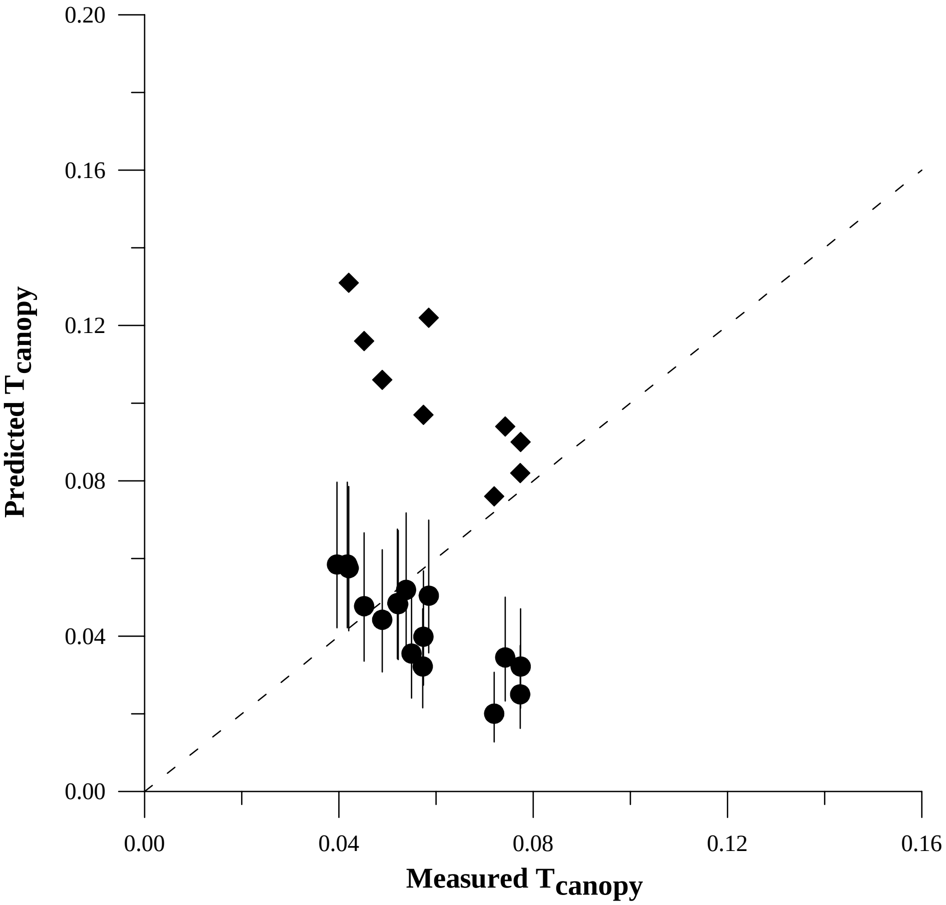

Fig. 3. Accuracy of T_{canopy} models. The estimated T_{canopy} values using the MM (◆) and UVRT model (●) are indicated. Vertical bars represent the values estimated assuming ±0.1 LAI. The dotted line is a 1:1 line.

3. Results and discussions

3.1. Measurements

The measurement locations included both sunlit and shaded positions in the canopy. Since the sunlit fraction penetrating the defined leaf angle distribution canopy varies by solar zenith angle, analysis was performed after classifying the measurements by solar zenith angle (Table 2). The irradiance at a shaded location consists of sky diffuse and canopy-scattered radiation. The irradiance at sunlit locations includes those components found in shade locations as well as direct beam radiation. The higher irradiance CV (coefficient of variation) values at low solar zenith angle were due to temporal variability of irradiance because of sunflecks when the direct to diffuse radiation ratio was high (Table 2). The direct radiation profoundly influenced average canopy transmittance values. Greater solar zenith angles result in an increased diffuse fraction of UV-B irradiance and decreased influence of sunlit conditions on the measurement.

The analysis of the T_{canopy} probability distributions indicated that one or two peaks in T_{canopy} were found in the analyses of individual runs (Fig. 2). Observation at the time of the measurements showed that the transmittance associated with the two peaks correlated with sunlit and shaded conditions. The magnitude of T_{canopy} depended more on the probability of the diffuse

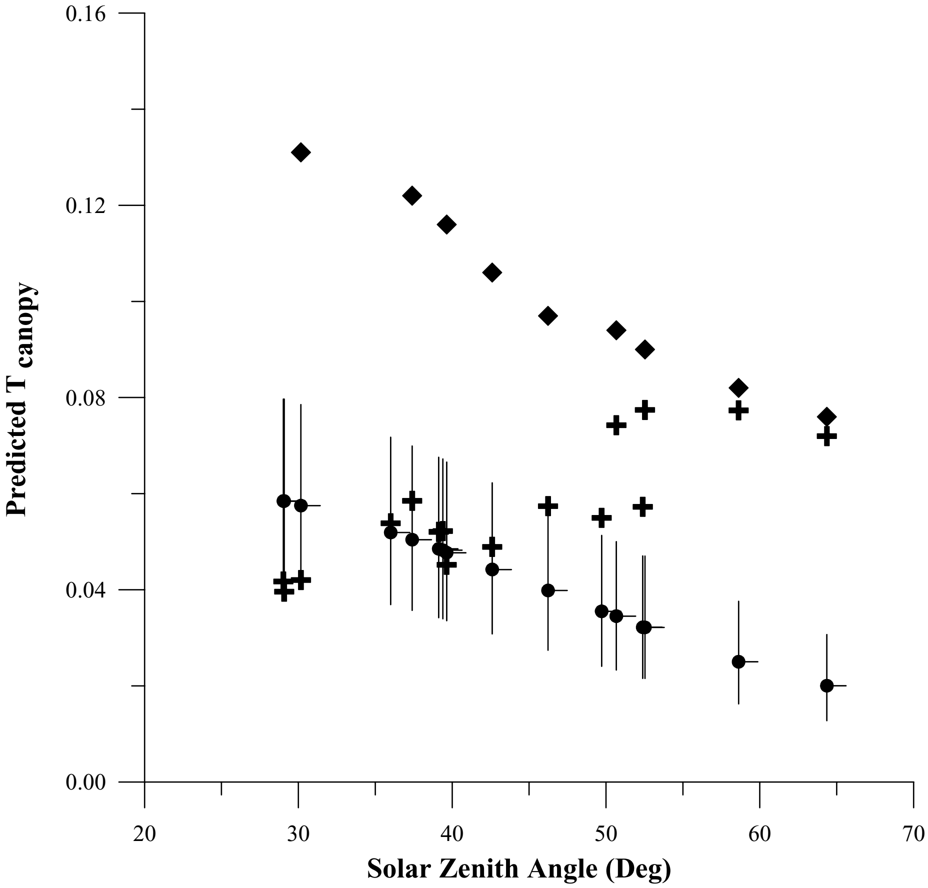

Fig. 4. Variability of T_{canopy} with solar zenith angle. Filled circles (●) represent T from UVRT model, filled diamonds (◆) represent T_{canopy} from MM model, and crosses (✚) represent the measured T_{canopy}. Vertical bars represent the values estimated assuming ±0.1 LAI.

peak. T_{canopy} value had less effect on the variation of T_{canopy} than on the probability of the direct beam peak.

Although the reported median measured T_{canopy} is a spatial average, all measurement locations were in the middle of rows (not randomly distributed under the canopy). Therefore, the distribution of sky view found in this study could not represent the "real" canopy condition exactly. Consequently, the median measured T_{canopy} was probably higher than the true median condition for the whole canopy. Furthermore, T_{canopy} increased with increasing solar zenith angle because with high zenith angles the azimuth angle of the sun became parallel to the row directions, which caused more direct beam penetration down the row.

3.2. Model evaluation

3.2.1. UVRT model

The agreement between measured and estimated T_{canopy} by the UVRT model was generally good with most modeled values underestimating the median measured values (Fig. 3). The UVRT model had a maximum error of 0.052, an MBE of 0.012 and a RMSE of 0.026. In general, T_{canopy} was estimated with greater accuracy at lower zenith angles than at higher zenith angles for the UVRT model (Fig. 4) because measured values increased with zenith angle owing to row orientation becoming parallel to direct solar beams, whereas estimated values decreased with increasing zenith angle because of increased interception of the assumed homogeneous canopy. Thus,

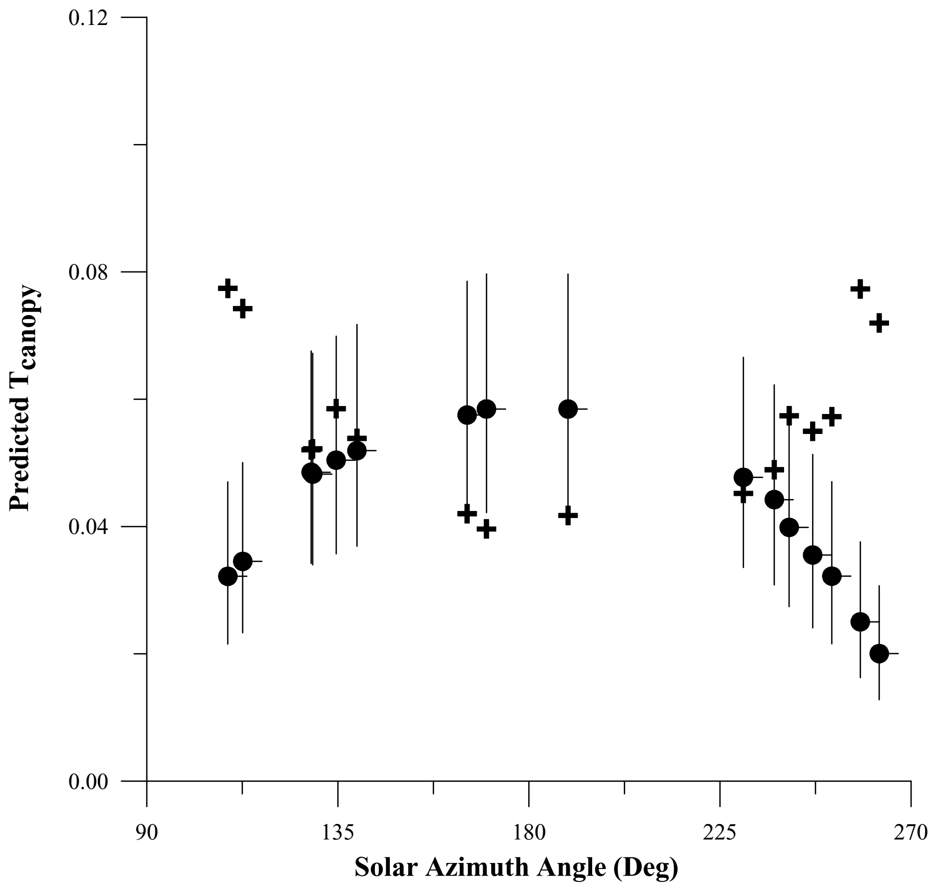

Fig. 5. Variability of UVRT estimated T_{canopy} (●) and the measured T_{canopy} values (✚) with solar azimuth angle.

the homogeneous canopy assumption is a limitation of 1-D models, especially in a high LAI canopy.

The influence of the sky radiance distributions on the UVRT model was evaluated. Results showed about a 0.01 change in transmittance (approximately 20% of the measured transmittance) when the sky distribution was changed from anisotropic to isotropic. The small absolute change in transmittance due to the sky distribution was because the view of the sky in the maize canopy was very small. The measurements represented averages including sunlit and shaded areas along the measurement rail, which made the variation in the irradiance measurements relatively large (Fig. 3).

3.2.2. MM model

The MM estimations overestimated the measured UV-B T_{canopy} by as much as 0.09 (Fig. 3). MM estimations tended to parallel the UVRT estimation but they were offset by about 0.06–0.07. The model had an MBE of 0.050 and RMSE of 0.058. The estimation errors decreased with increasing zenith angle because, as with the MM model, estimated values decreased increasing solar zenith angle as measured values increased (Fig. 4). Thus, at high solar zenith angles this model was better at estimating T_{canopy} than the UVRT model (Fig. 5).

The isotropic sky radiance distribution assumption in the MM model probably caused an overestimation of only 0.01. The impact of the sky-radiance distribution assumption for modeling the UV-B in a canopy is certainly dependent on the sky view. An anisotropic sky radiance assumption improved the accuracy of a 3-D model of UV-B irradiance by 0.04 in an orchard where the sky view averaged 0.59° (Gao et al., 2002). The assumption of spherical leaf angle distribution and homogeneous horizontal canopy leaf density used in the MM model may have produced some bias compared to UVRT model that used leaf angle distribution estimated by sampling.

4. Conclusions

The UV-B T_{canopy} of a maize canopy was modeled using two one-dimensional models. The UVRT model had less than one-half the MBE and RMSE of the MM model. Typically the UVRT model, which used an estimated actual leaf angle distribution and considered the distribution of sky radiance, somewhat underestimated the UV-B T_{canopy}, while the MM model, which assumed a spherical leaf angle distribution and an isotropic sky radiance, overestimated the UV-B T_{canopy}.

Much of the apparent model error was likely due to the assumption of homogeneity in the horizontal canopy leaf density. To better represent the modeled average canopy transmittance, measurements should be made using moving point sensors or a sensor network. Analysis of the errors due to model assumptions of sky radiance distribution points out that an isotropic sky radiance distribution assumption accounted for only about 0.01 of the difference between 1-D model estimations and measurements for this maize canopy with mean sky view of 0.27°. Consequently, the sky radiance distribution is probably not important in modeling such dense crop canopies even with the high diffuse fraction in UV-B over-the-canopy irradiance. A larger portion of the error in the traditional 1-D MM model was likely caused by the assumption of spherical leaf angle distribution. If a more random measurement system had been used, averaged measured T_{canopy} would probably have been lower and the MM model errors probably would have been greater because all of the MM estimations were high, whereas UVRT error probably would have been less.

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