

**A Geometric UV-B Radiation Transfer Model Applied  
to Agricultural Vegetation Canopies**

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**Acknowledgments.** This study was supported by the USDA Forest Service Northern Global Change Research Program (Agreement 23-793), USDA (Agreement 98-34263-6888 and 99-34263-8566), NASA (Contract number NCC5-288) and Purdue University Agricultural Experiment Station.

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**ABSTRACT**

The stratospheric ozone decrease has prompted renewed efforts in assessing the potential damage to plant and animal life due to enhanced levels of solar Ultraviolet-B (UV-B, 280-320 nm) radiation. The object of this study was to develop and evaluate an analytical model to predict the UV-B radiation loading on potentially sensitive surfaces as influenced by vegetation. The UV-B irradiance measurements were made in a widely-spaced orchard and in a closely-spaced maize crop during cloud-free days. Solar zenith angles ranged from 20° to 80°. The sky view was typically 0.59 for the orchard and 0.28 for the maize canopy. Measured and predicted values of UV-B canopy transmittance generally agreed very well. The model can serve as a much-needed tool to examine UV-B loading of people and other life in and below tree and other vegetation canopies.

There has been growing concern about the possible impact of depletion of the ozone layer because

the stratospheric ozone column is the primary attenuator of solar ultraviolet -B radiation (UV-B region, between 280 and 320 nm). A decrease in this ozone column would lead to increases in UV-B reaching the earth's surface. The most important wavelengths for assessment of potential plant damage due to increased UV radiation are in the UV-B band (Caldwell 1971, 1998; Madronich et al., 1998). The effect of UV-B enhancements on plants includes reduction in 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 species show sensitivity to present levels of UV-B radiation while others are apparently unaffected by rather massive UV enhancements (Becwar et al., 1982). This issue is complicated further by 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 radiation.

Many radiative transfer models for the short-wave wavelength band have been developed and used to understand and predict of 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) (deWit, 1965; Monsi and Saeki, 1953; Cowan, 1968). But many important canopies 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.

Prediction of the UV-B irradiance on potentially sensitive surfaces requires knowledge of

UV-B radiation distribution in 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 the canopy is not closed (found in “open canopy”). Open canopies typically have large discontinuities that give large views of the sky and its diffuse radiation (a large portion of the total UV-B irradiance) and that also provide paths for the transmission of direct radiation under the appropriate sun angle. The 1-D models assume a homogeneous canopy and cannot simulate an open canopy where there is large spatial variation in leaf area in the horizontal plane, anisotropic scattering, and important anisotropic distributions of the incident radiation at the canopy top as is the case with UV sky radiance distributions. Obviously, an advanced 3-D radiation model which considers anisotropic sky radiance penetrating through heterogeneous canopies (such as row crops before canopy closure) is needed to evaluate UV-B radiation loading in many plant canopies. Such a 3-D model is most useful for canopies that contain dense grouping of leaves within subcanopies that are widely separated. When dimensionality increases in radiation models, more canopy structure information is needed.

This paper describes a 3-D UV Radiation Transfer (UVRT) model that can be used to calculate canopy transmittance ( $T_{\text{canopy}}$ , irradiance below canopy/irradiance above canopy) for any location within or below an open vegetation canopy. This paper presents both the development of the 3-D UVRT Model and an assessment of the model accuracy using irradiance measurements made in an orchard (*Malus sp.*) and a maize (*Zea Mays*) canopies.

## **2. Materials and Methods**

## 2.1 The Theory of UV Radiation Transfer Model

The 3-D UVRT model was developed to predict UV-B canopy transmittance ( $T_{\text{canopy}}$ ) 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 with the individual plants regarded as discrete scattering volumes of ellipsoidal shape.

The model inputs include the atmospheric ozone column thickness, aerosol optical depth, and the solar zenith and azimuth angles. The portioning of radiation into diffuse sky and direct beam is done by incorporating the UV-B irradiance functions of Schippnick and Green (1982) into the "front end" of the model. The diffuse sky radiation can be treated as either a uniform or non-uniform sky distribution that is a function of the solar zenith angle (Grant et al., 1996).

### 2.1.1 3-D UVRT Model

The 3-D UVRT model includes attenuation of direct beam and sky diffuse radiation. The amount of foliage is characterized by a foliage density  $\rho$ , defined as the foliage area per unit volume containing the foliage.

The canopy transmittance ( $T_{\text{canopy}}$ ) can be modeled using:

$$T_{\text{canopy}} = \frac{I_t}{I_{t0}} \quad (1)$$

where:

$I_{t0}$ : the known total radiation at the top of canopy

$I_t$ : the transferred radiant energy through the canopy to some depth in the canopy

The transferred radiant energy can be expressed by

$$I_t = (I_{b0} \times P_0) + (I_{d0} \times P_0') \quad (2)$$

where:

$I_{b0}$ : the known direct radiation at the top of canopy

$I_{d0}$ : the diffuse radiation at the top of canopy

$P_0$ : direct beam penetrating function (the probability that a ray will pass through the canopy unintercepted)

$P_0'$ : sky diffuse radiation penetrating function.

In an array of individual crowns, 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 is given by (Norman and Welles, 1983):

$$P_0 = e^{[-G(\Omega) \times \rho S]} \quad (3)$$

where:

$\Omega$ : a direction of radiation coming from (zenith angle  $\theta$  and azimuth  $\varphi$ )

$G(\Omega)$ : the fraction of foliage area that is projected towards the source of radiation. It can be called the G-function or projection coefficient

$\rho$ : foliage density (foliage area per unit canopy volume)

$S$ : the distance through the canopy that the ray must pass.

Computation of  $S$  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 sun and sensor,  $S_1$  as the distance between sun and one intersection point,  $S_2$  as the distance between sun and another intersection point ( $S_2 > S_1$ ), the three cases are: 1)  $S_0 > S_2$ , the sensor is under the canopy and  $S = S_2 - S_1$ , 2)  $S_2 > S_0 > S_1$ , the sensor is within the canopy, and  $S = S_0 - S_1$ , and 3)  $S_0 > S_1$ , the sensor is in front of the canopy, and  $S = 0$ .

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

$$P_0' = \frac{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} N(\psi, \theta) \exp[-G(\theta)\rho S] \cos\theta \sin\theta d\theta d\phi}{\int_0^{2\pi} \int_0^{\frac{\pi}{2}} N(\psi, \theta) \cos\theta \sin\theta d\theta d\phi} \quad (4)$$

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

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

and the isotropic sky radiance was defined as  $N(\psi, \theta) = 1/\pi$ . This approach differed from the Norman and Welles (1983) model which assumed an isotropic sky by explicitly defining the sky radiance. The input information used in the model for both the orchard and maize canopies can be found in Table 1.

## 2.2 Measurements

The accuracy of the 3-D UVRT model in predicting the UV-B irradiance on sunlit and

shaded surfaces in agricultural canopies was determined by comparing model predictions with irradiance measurements in an orchard and in a maize field. The UV-B irradiance measurements were made in the orchard from 9 Sep. to 10 Oct. 1994 and in a maize canopy from 29 July to 31 July 1995 at West Lafayette, Indiana, USA (40.5°N latitude).

The apple orchard, located at the Purdue Horticultural Research Farm, consisted of similar-sized 11- year-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 based on Charles-Edwards (1976). The leaf angle distribution was assumed to be spherical within each tree crown.

The maize canopy (*Pioneer 3394*) was located at the Purdue Agronomy Research Center. The maize was planted on June 5, 1995 at the rate of 26,300 plants per acre in east-west rows 0.76 m apart. The foliage density, canopy LAI (leaf area index) and LAD (leaf angle distribution) were determined by direct measurements of 20 plants using the method described by Daughtry (1990) and Perry (1988).

The dimensions of the simulated canopies were determined by direct measurements of plant height, width, and row spacing. Since both the orchard and maize canopies were planted in E-W 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 the Z coordinate.

Hemispherical photographs of each measurement site were made using a Canon 7.5 mm lens. Sky obscuration due to the vegetation canopy 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.

The UV-B irradiance measurements above and in both canopies were made using SED 240/UV-B/W sensors (International Light, Newbury, Mass., USA) which are 11-mm-diameter “solar-blind” vacuum silicon photodiode sensors operated in photoconductive mode and biased by -5 V (Grant, 1996). All measurements were made under visibly clear sky conditions and stopped when clouds or haziness were seen approaching from the horizon. Irradiance measurements were made every 30 seconds.

The measurement height was 0.3 H (H was the mean height of plants) at both sunlit and shaded locations in the apple orchard and 0.45 H at shaded locations in the maize canopy. A shaded location was defined as having canopy biomass between the sun and the sensor position throughout the measurement period, but direct beam radiation could go through canopies creating sunflecks at any given instance in time. Above canopy measurements for the maize were made over the maize canopy, and for the orchard they were made at the Purdue Agronomy Research Center weather station which was within 10 km of the orchard.

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

The canopy UV-B transmittance was calculated from the simultaneous above- and

below-canopy UV-B irradiance measurements. Since the ratio of UV-B irradiance within canopy to that above the canopy was of primary interest in this study, all UV-B sensors were intercompared and differences in the responses adjusted accordingly prior to calculating the canopy transmittance. For purposes of model evaluation, the measured irradiances above-canopy and within-canopy were averaged over 30 minute measurement periods.

### **3. Results and Discussion**

#### **3.1 Measurement**

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

The UV-B irradiance attenuation within the canopy decreased with increasing sky view. In sunlit locations, attenuation of UV-B irradiance was caused by reduction in the penetration of diffuse radiation. In shaded locations, both direct beam and sky diffuse were attenuated. The reduction of UV-B irradiance varied less between sunlit and shaded conditions at higher solar zenith angles than at low solar zenith angles. The analysis of the  $T_{\text{canopy}}$  probability distribution for maize canopy frequently showed two peaks of measured  $T_{\text{canopy}}$  (Fig. 2), corresponding to sunlit and

shaded conditions (Grant, 1999). The  $T_{\text{canopy}}$  associated with periods of shaded (and primarily only diffuse radiation) was 0.07 in the maize canopy (Fig. 2). In the orchard we only set our sensors either in sunlit condition or shaded condition and consequently each measurement period had only one peak  $T_{\text{canopy}}$  value corresponding to either direct and diffuse radiation penetration or only diffuse radiation penetration.

### 3.2 Model Accuracy

The accuracy of the model was evaluated by comparing the prediction of the model to the measured UV-B  $T_{\text{canopy}}$  in both sunlit and shaded locations in the orchard and shaded locations in the maize canopy (Fig. 3). The mean predicted  $T_{\text{canopy}}$  values were 0.57 and 0.12 while the mean observed values were 0.61 and 0.15 for orchard and maize canopy respectively. The mean bias error (MBE) of the model was similar for the orchard and maize canopies (0.038 for the orchard and 0.033 for the maize). The root mean squared error (RMSE) was greater for the orchard than the maize canopy (0.082 for orchard and 0.061 for maize). The model predictions were generally slightly higher than measured partly because of  $T_{\text{canopy}}$  variability caused by sun flecks. Comparisons between a predicted and measured value must, however, consider the probability distribution of  $T_{\text{canopy}}$  from which the median value was derived (Fig. 2). The difference between predicted and measured UV-B  $T_{\text{canopy}}$  in the maize canopy was partly due to measurements being made only between rows--which did not represent the real “mean” maize field. The distances between those dense subcanopies should be bigger like the space between each plant. The complexity of the model is probably only justified for widely-separated plants such as is common in young stands of many crops and tree stands. The UV-B  $T_{\text{canopy}}$  prediction error ( $T_{\text{predicted}} - T_{\text{measured}}$ ) for the orchard was

smaller at small solar zenith angle and tended to increase as the solar zenith angle increased (Fig. 4). This was probably partly due to the decreasing ratio of direct beam to diffuse sky radiation with increasing solar zenith angle and partly due to difficulty in correcting for the sensor cosine response error which increases with increasing solar zenith angle.

### **3.3 Isotropic/anisotropic sky radiance comparison**

Most canopy radiation models assume an isotropic sky radiance distribution. Isotropic diffuse radiation specifies a sky hemisphere of constant brightness. Actually the radiation from the sky is never truly isotropic even for completely overcast or completely cloud-free conditions (Hutchison et al., 1980, Grant et al, 1996; Grant et al., 1997; Grant and Heisler 1997). To determine the importance of the sky radiance distribution on the prediction of the below-canopy irradiance, the UV-B  $T_{\text{canopy}}$  was predicted: 1) assuming an anisotropic sky radiance distribution (ANI UVRT model) and 2) assuming an isotropic sky radiance (ISO UVRT model). Results showed greater predicted penetration into the canopy from an anisotropic sky than an isotropic sky (Fig. 5). The mean difference in penetration was about 3.6% at sunlit locations but the difference was smaller at shaded locations, which agreed with the work of Hutchison et al. (1980). This is reasonable since the greatest intensity of sky radiation occurs near the solar disk (Fig. 6), and the locations in the shade typically are shaded because a plant crown obscures a sector of sky including the solar disk and the surrounding sky. Thus obstruction of the circumsolar region minimizes the differences between the anisotropic sky radiance and an assumed isotropic sky radiance (Grant et al., 1996). While the difference between the predicted irradiance in the sunlit location based on the isotropy of the sky radiance distribution was small, the predicted values assuming an anisotropic sky

condition were closer to the measured irradiance than those assuming an isotropic sky condition in this study. The difference between predicted UV-B  $T_{\text{canopy}}$  values due to the assumed sky radiance distribution increased with increased UV-B  $T_{\text{canopy}}$  through canopies in sunlit condition and decreased in shaded condition .

The canopy sky view is the greatest single factor in defining the UV-B irradiance (Brown, et al. 1994). Clearly, the sky view 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 predicted  $T_{\text{canopy}}$  due to the choice of modeled sky radiance distribution became more positive with increased sky view for shaded points and more negative with sunlit points. The differences actually increased for both sunlit and shaded in an absolute sense (Fig. 7). This difference in affect of sky view is a result of the anisotropic sky distribution under cloud-free skies reported by Grant et al. (1996). When the solar disk is obscured by the crown, the location is shaded, and the arc of sky obstructed by the crown (the circumsolar region) has relatively high radiance and decreasing the fraction of sky obstructed increases the relative sky radiance received on a location to values above that of the isotropic sky (Fig. 6). Conversely, when the solar disk is not obstructed, the location is sunlit, and the arc of sky obstructed by the crown has relatively low radiance and decreasing the fraction of sky obstructed decreases the relative sky radiance received on a location to values above that of the isotropic sky (Fig. 6).

#### **4. Conclusions**

A 3-Dimensional model was developed to predict the UV-B irradiance for horizontal

surfaces in open canopies. Tests of the model accuracy were made using field measurements in an open canopy apple orchard and in a closed canopy of maize for cloudless sky conditions. Measured and predicted values of UV-B canopy transmittance generally agreed very well. The largest differences between measured and modeled UV-B  $T_{\text{canopy}}$  occurred at high solar zenith angles. This was partly due to the decreasing ratio of direct beam to diffuse sky radiation with increasing solar zenith angle. The sky radiance distribution (isotropic/anisotropic) did not strongly influence the model prediction accuracy, though the predicted values assuming an anisotropic sky condition were closer to the measured irradiance. The influence of sky conditions on difference in canopy transmittance in the sunlit and shaded locations was not as important as having direct Sun light or not on the measurement locations. The greatest difference in UV-B canopy transmittance 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. 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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**Fig. 1a.** Hemispherical photograph of a measurement site in the orchard. The center of the photograph represents the zenith. Distance from the center toward the edge is linearly related to the

zenith angle.

**Fig. 1b.** Hemispherical photograph of a measurement site in maize canopy. The center of the photograph represents the zenith. Distance from the center toward the edge is linearly related to the zenith angle.

**Fig. 2.** Effects of maize canopy on UV-B  $T_{\text{canopy}}$  for different measurement locations. A represents  $T_{\text{canopy}}$  for only shaded location while B, C represent  $T_{\text{canopy}}$  for both sunlit and shaded locations

**Fig. 3.** Accuracy of 3-D UVRT  $T_{\text{canopy}}$  model. The predicted  $T_{\text{canopy}}$  values for orchard (open circles) and for maize field (open squares) are indicated. The solid line has a slope of one and the dotted line is linear regression of predicted  $T_{\text{canopy}}$  on measured  $T_{\text{canopy}}$ .

**Fig. 4.** Errors of predicted to measured  $T_{\text{canopy}}$  with solar zenith angle in orchard measurement area.

**Fig. 5.** Comparison of predicted  $T_{\text{canopy}}$  with different sky radiance distribution and measured  $T_{\text{canopy}}$  with solar zenith angle in one sunlit measurement area of orchard. The predicted  $T_{\text{canopy}}$  assuming an isotropic sky (open triangles) and an anisotropic sky (filled triangles) and measured  $T_{\text{canopy}}$  (crosses) are indicated.

**Fig. 6.** Effect of sky obstruction on relative reduction in sky radiance along the principal plane of

the sun. For this example, the sun is located at  $30^\circ$  zenith angle. All values of sky radiance have been reduced to a normalized value of 1 corresponding to the radiance of the isotropic sky (dashed line).

**Fig. 7.** Difference in predicted  $T_{\text{canopy}}$  between assumed isotropic and anisotropic sky radiance distribution with sky view fraction. The sunlit and shaded measurement locations area indicated by the open and filled circles respectively.

**Fig. 1a.** Hemispherical photograph of a measurement site in the orchard. The center of the photograph represents the zenith. Distance from the center toward the edge is linearly related to the zenith angle.

Fig. 1b. Hemispherical photograph of a measurement site in maize canopy. The center of the photograph represents the zenith. Distance from the center toward the edge is linearly related to the zenith angle.

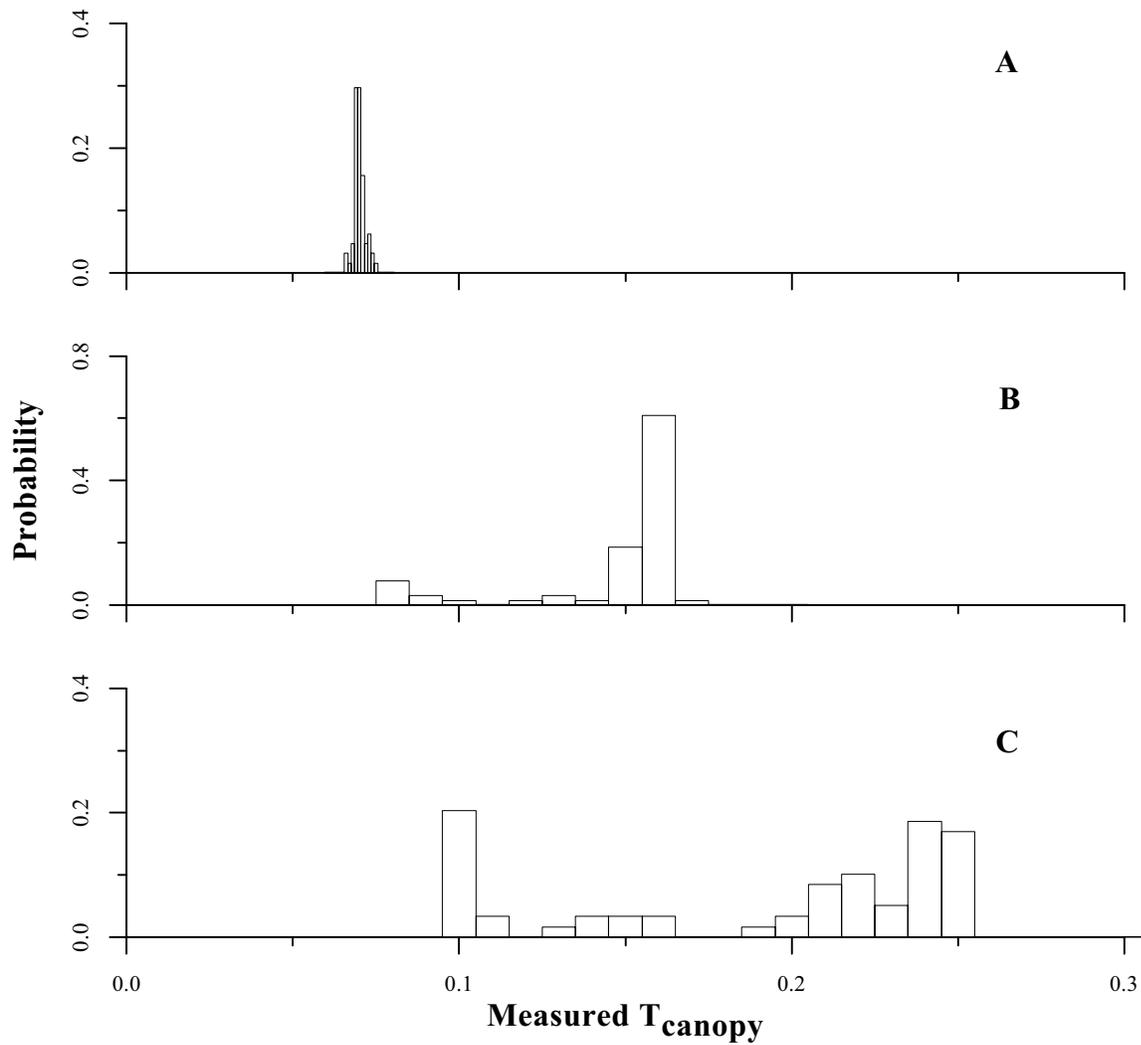


Fig. 2. Effects of maize canopy on UV-B  $T_{\text{canopy}}$  for different measurement locations. A represents  $T_{\text{canopy}}$  for only shaded location while B, C represent  $T_{\text{canopy}}$  for both sunlit and shaded locations

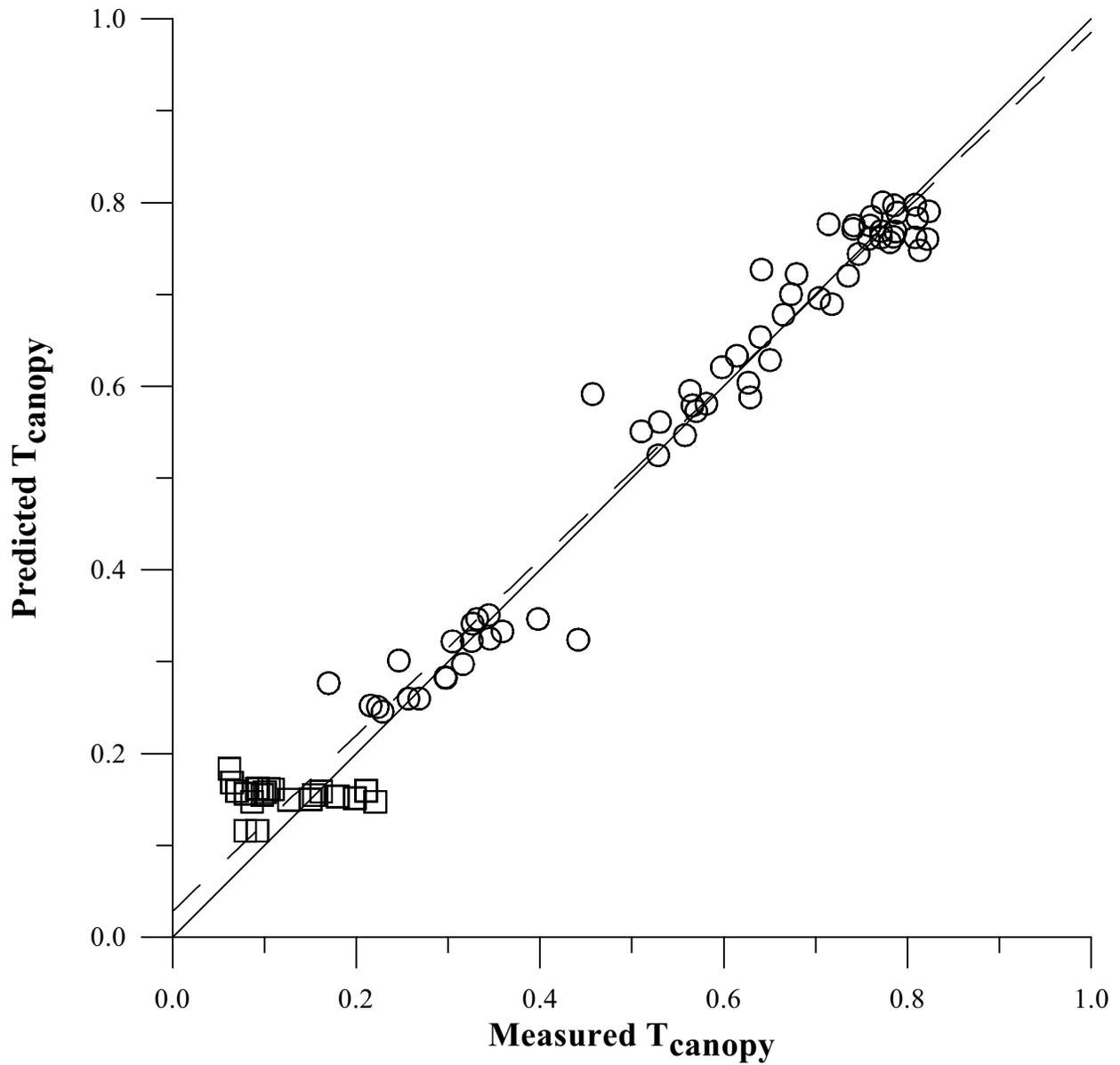


Fig. 3. Accuracy of 3-D UVRT  $T_{\text{canopy}}$  model. The predicted  $T_{\text{canopy}}$  values for orchard (open circles) and for maize field (open squares) are indicated. The solid line has a slope of one and the dotted line is linear regression of predicted  $T_{\text{canopy}}$  on measured  $T_{\text{canopy}}$ .

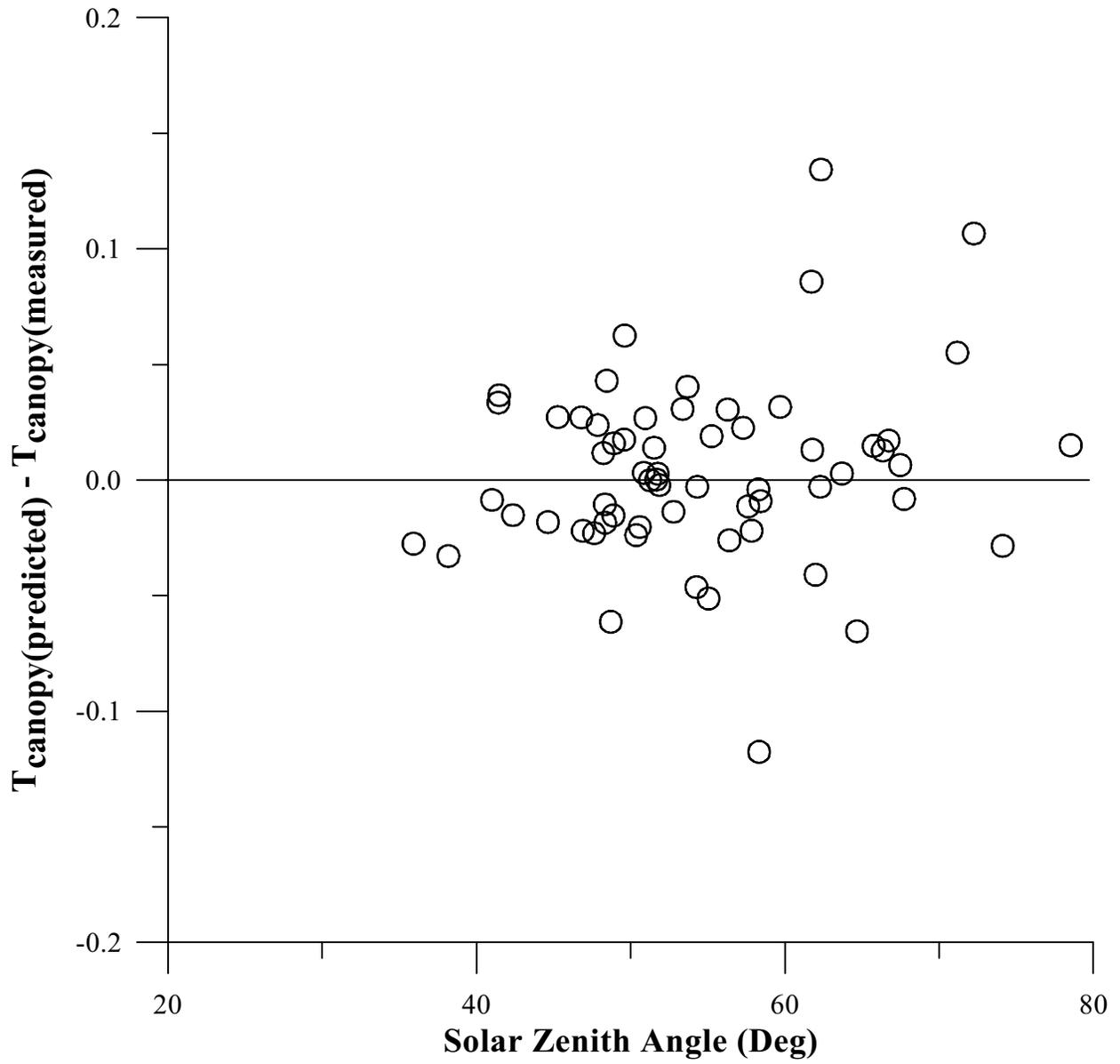


Fig. 4. Errors of predicted to measured  $T_{\text{canopy}}$  with solar zenith angle in the orchard measurement area.

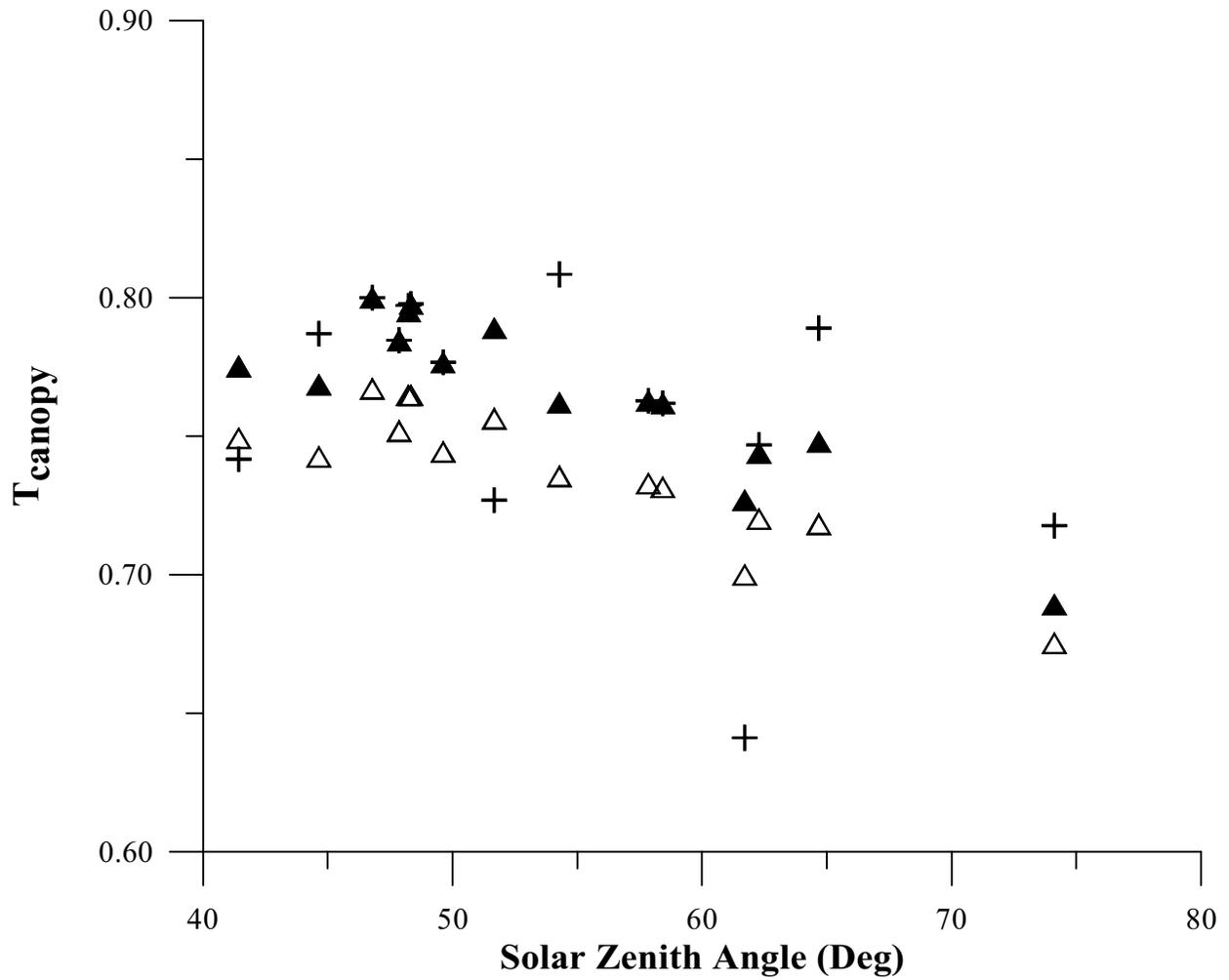


Fig. 5. Comparison of predicted  $T_{\text{canopy}}$  with different sky radiance distribution and measured  $T_{\text{canopy}}$  with solar zenith angle in one sunlit measurement area of orchard. The predicted  $T_{\text{canopy}}$  assuming an isotropic sky (open triangles) and an anisotropic sky (filled triangles) and measured  $T_{\text{canopy}}$  (crosses) are indicated.

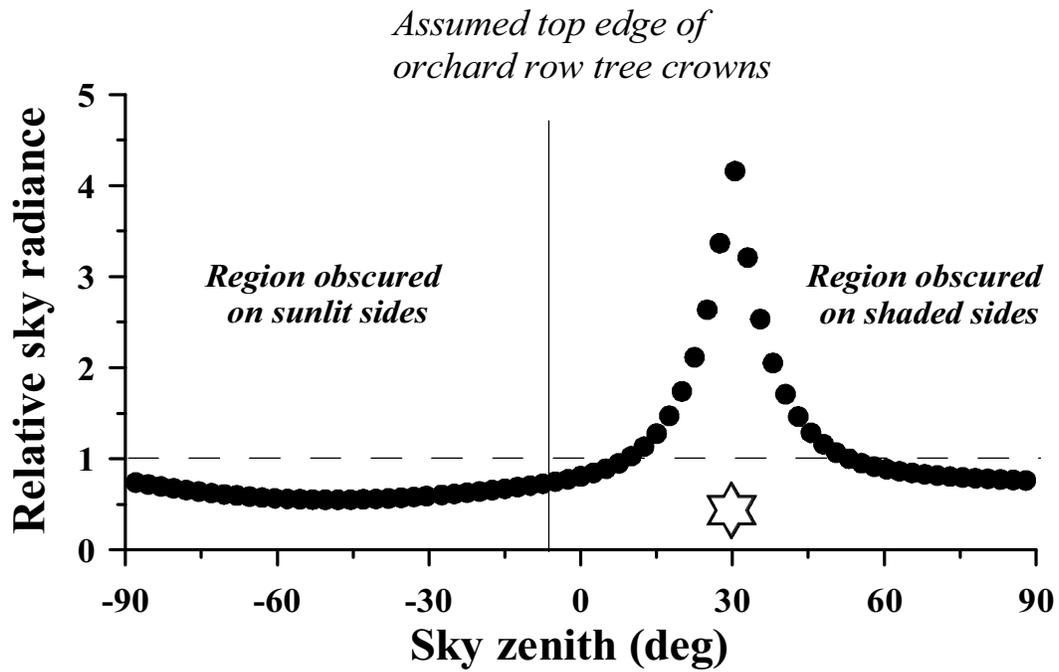


Fig. 6. Effect of sky obstruction on relative reduction in sky radiance along the principal plane of the sun. For this example, the sun is located at  $30^\circ$  zenith angle. All values of sky radiance have been reduced to a normalized value of 1 corresponding to the radiance of the isotropic sky (dashed line).

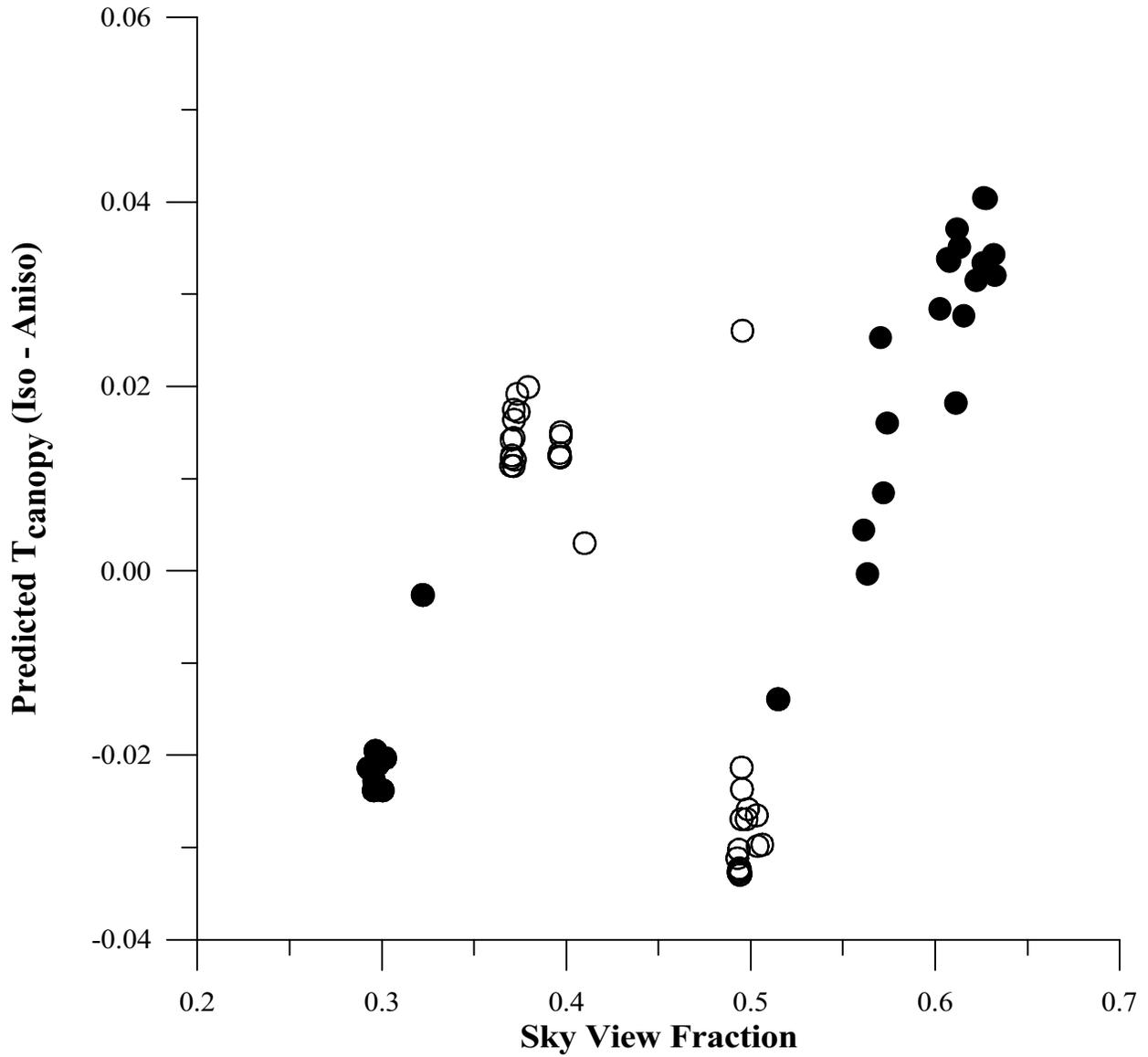


Fig. 7. Difference in predicted  $T_{\text{canopy}}$  between assumed isotropic and anisotropic sky radiance distribution with sky view fraction. The sunlit and shaded measurement locations area indicated by the open and filled circles respectively.

Table 1. Input parameters used in the UVRT models from the canopy measurements of orchard

Quantity	Maize	Orchard
Latitude	40.5°	40.5°
Longitude	87.5°	87.5°
Row spacing	0.76 m	5.5 m
Plant spacing	0.23 m	3.35 m
Foliage Density ( $\rho$ )	2.87 m <sup>-1</sup>	1.8 m <sup>-1</sup>
Subcanopy radius (X)	0.47 m	1.68 m
Subcanopy radius (Y)	0.44 m	1.22 m
Subcanopy radius (Z)	1.00 m	1.82 m
Height of subcanopy center	1.00 m	2.28 m
Height of measurements level	0.80 m	1.20 m