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CANOPY RADIATIVE TRANSFER MODELS FOR SPHERICAL AND KNOWN LEAF INCLINATION ANGLE DISTRIBUTIONS: A TEST IN AN OAK–HICKORY FOREST

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SUMMARY

(1) Two canopy radiative transfer models were tested against solar radiation measurements made in an oak–hickory forest. One model assumes that the distribution of leaf inclination angles is spherical (Norman 1979). The other model uses measurements of the distribution of leaf inclination angles to simulate the radiation regime within the canopy (de Wit 1965).

(2) Vertical profiles of downward directed insolation components computed with Norman's model are in better agreement with measured values than are those computed with de Wit's model. Insolation flux densities computed with both models, however, underestimate total incoming shortwave radiation and its components direct and diffuse shortwave radiation, total photosynthetically active (PAR) and near infrared radiation (NIR). This underestimation results primarily from clumping of the foliage, which enhances the penetration of direct and diffuse radiation into the canopy and minimizes the conversion of beam to scattered diffuse radiation.

(3) Although observed leaf inclination angles are different from a spherical leaf inclination distribution these differences do not account for differences between simulated and measured fluxes of solar radiation. This is because the leaf orientation function (G) computed with observed leaf angles is greater than the G-function for a spherical canopy, which should lead to an overestimation in beam penetration. Possible errors in the optical parameters are also not a factor since most of these parameters were measured directly and because the agreement between measured and simulated diffuse shortwave radiation, which is affected by optical parameters, is relatively good.

(4) Canopy reflectivities of PAR are overestimated by a factor of three. This is because deep penetration of insolation reduces the amount of light that is intercepted and scattered upward in the upper canopy. De Wit's model estimates shortwave reflectivity reasonably well. However, this is an artifact of compensating errors.

INTRODUCTION

One aim of forest ecophysiological research is to extend physiological relationships developed for individual leaves to entire canopies. For light-driven processes, such as canopy photosynthesis and stomatal mechanics, accurate canopy radiative transfer models must be used to make this extension.

Many theoretically-sound, canopy radiative transfer or phytoactinometric models are available in the literature. Most notable are those of de Wit (1965), Monteith (1965), Ross & Nilson (1966), Anderson (1966), Cowan (1968), Idso & de Wit (1970), Nilson (1971), Lemeur (1973), Norman & Jarvis (1975) and Norman (1979). Most of these models, however, have been developed for uniform crop canopies. Forest canopies, on the other

hand, are structurally more heterogeneous than agricultural crop canopies. This structural heterogeneity is the combined result of random establishment and survival of trees, the mixed-species composition of forest canopies, the clumping of foliage in forest stands (Norman & Jarvis 1975; Oker-Blom & Kellomaki 1983) and the vertical variation in leaf inclination angles inside forest stands (Baldocchi *et al.* 1984a).

Phytoactinometric models developed for agricultural crops can be applied in forest stands if the limitations of these models are known. Unfortunately, few canopy radiative transfer models have been tested independently in forest canopies (Miller 1969; Lemeur, Gietl & Hager 1979).

Because of the lack of a general canopy radiative transfer model for deciduous canopies, Jarvis & Leverenz (1983) recently advocated using Norman's (1979, 1980, 1982) canopy radiative transfer model. Norman's model is attractive for this purpose because it is general, yet theoretically sound. Norman's model owes its generality to the assumption that the distribution of leaf inclination angles is spherical and the spatial distribution of foliage elements is random. This is a good assumption in crops such as soybeans, corn and wheat (Lemeur 1973; Lemeur & Blad 1974). The validity of this assumption in a deciduous forest, however, is questionable.

The canopy radiative transfer model of de Wit (1965) is also a likely candidate for usage in a deciduous forest. De Wit's model is attractive because it improves upon the pioneering work of Monsi & Saeki (1953) by accounting for the distribution of leaf inclination angles and considers first order scattering. The derivation of this model is based on the assumption that leaves are randomly distributed in space and have no preferred azimuthal orientation.

Concepts from Norman's and de Wit's phytoactinometric models are often incorporated into stand productivity models (de Wit 1965; Norman 1980), canopy mass and energy exchange models (Norman 1979; Goudriaan 1979) and canopy reflectance models (Kimes, Ranson & Smith 1980). Norman's and de Wit's models should, therefore, be tested before they are applied in a deciduous forest. Here we present a test of Norman's (1979) and de Wit's (1965) canopy radiative transfer models against solar radiation measurements made in a fully-leafed oak–hickory forest.

THEORY

The downward flux density of solar radiation inside a vegetated canopy consists of direct, diffuse and downward scattered radiation. The direct and diffuse radiation originate from the solar disk and sky, respectively. The scattered radiation is generated from intercepted radiation that is reflected or transmitted.

Norman's radiative transfer model

The penetration of direct radiation into a canopy is a function of earth–sun geometry and distribution of leaf inclination angles. Norman (1979) uses the theory developed by Ross & Nilson (1966) and Anderson (1966) to estimate the penetration of this radiation.

For a discrete layer of known leaf area index (Δf), the fraction of beam penetration (I_b) is:

$$I_b = \exp(-G\,\Delta f/\sin(\beta)) \tag{1}$$

where β is the solar elevation angle and G is the leaf orientation function. For a canopy

whose leaves are assumed to have a leaf inclination angle distribution that is spherical, G equals 0·5 (Norman 1979).

Diffuse radiation at the canopy–atmosphere interface is assumed to emanate from an isotropic sky. The fractional penetration of this diffuse radiation (I_d) into a layer of known leaf area is computed as:

$$I_d = \int_0^{\pi/2} \exp[-G\,\Delta f/\sin(\beta)]\,\sin(\beta)\cos(\beta)\,d\beta \tag{2}$$

Equation (2) is integrated only over solar elevation angle classes since azimuthal symmetry is assumed.

Scattered radiation is generated within the canopy via the transmission and reflection of insolation by the canopy elements and the reflection of insolation by the ground. Upward and downward scattered components are computed using an iterative technique developed by Norman, Miller & Tanner (1971):

$$A(j+1) = R_i/R_o = \frac{[(\tau(1-I_d)+I_d)^2 - (\rho(1-I_d))^2]\,A(j) + \rho(1-I_d)}{1-\rho(1-I_d)\,A(j)} \tag{3}$$

where τ is transmissivity, ρ is reflectivity, j is the index of the layer number and R_i and R_o are the incoming and outgoing flux densities of diffuse radiation, respectively. The first iteration is initiated by setting $A(j=1)$ equal to the reflected flux density of insolation at the ground surface. Convergence usually occurs after two to three iterations. Scattering is treated separately for the photosynthetically active (PAR) and near infrared (NIR) radiation wavebands since the optical properties of the leaves are different for these wavebands (Ross 1976, 1981).

de Wit's canopy radiative transfer model

De Wit's model accounts for the geometrical relationship between the foliage elements and the incoming light rays. The flux density of light intercepted by a leaf is proportional to the sine of the angle between the leaf and the light rays ($\sin(\alpha)$):

$$\sin(\alpha) = A + B\sin(\Delta\gamma) \tag{4}$$

where $A = \sin(\beta)\cos(\theta_L)$, $B = \cos(\beta)$, $\sin(\theta_L)$, θ_L is the leaf inclination angle and $\Delta\gamma$ is the difference between the leaf and light azimuth angle. From this relationship, de Wit derived the light distribution function (L) which is defined as the probability that a light ray is intercepted by a leaf:

$$L(\sin(\alpha)) = (B\cos(\Delta\gamma) - A((\pi/2)+\Delta\gamma))\,W; \quad \text{if } \Delta\gamma < Q \tag{5}$$

$$L(\sin(\alpha)) = (B(2\cos(Q) - \cos(\Delta\gamma)) - A(2Q + (\pi/2) - \Delta\gamma))\,W; \quad \text{if } \Delta\gamma >= Q, \tag{6}$$

where $Q = \sin^{-1}(A/B)$ if $\beta < \theta_L$ and $Q = -\pi/2$ if $\beta >= \theta_L$ and $W = (2B\cos(Q) - 2AQ)^{-1}$.

The fractional penetration of beam radiation (I_b) is a function of the mean projection of one unit of leaf area in the direction of the light ($O_p(\beta)$), which is computed by weighting $L(\sin(\alpha))$ with the leaf inclination frequency distribution. I_b is computed using a form of the binomial relationship developed by Monsi & Saeki (1953). This relationship is expressed as:

$$I_b(f) = \left(1 - s\frac{O_p(\beta)}{\sin(\beta)}\right)^{(f/s)} \tag{7}$$

where f is the cumulative plant area and s is the canopy density factor, which ranges

between zero and one. De Wit (1965) states that $s = 0{\cdot}1$ is a good estimate for most canopies.

The fractional penetration of diffuse radiation (I_d) is computed by integrating eqn (7) over the hemisphere of the sky:

$$I_d = 2\int_0^{\pi/2}\left(1 - s\frac{O_p(\beta)}{\sin(\beta)}\right)^{(f/s)}\cos(\beta)\sin(\beta)\,d\beta \tag{8}$$

Equation (8) is derived on the assumption that diffuse radiation emanates from the hemisphere of a sky with uniform brightness.

Insolation incident on a leaf is either absorbed or scattered. De Wit (1965) considers only first order scattering, by assuming that half of the scattered radiation in directed upward and half is directed downward. Ninety per cent of the insolation reaching the soil surface is assumed to be absorbed. The other 10% is assumed to be scattered upward and absorbed by the foliage or reflected out of the canopy.

MATERIALS AND METHODS

Modelling parameters

Biomass and environmental data used to drive the models were obtained from an oak–hickory forest (Quercus and Carya sp.) located near Oak Ridge, Tennessee (lat. 35°57′30″N; long. 84°17′15″W; altitude 365 m above msl).

The forest is uneven-aged and has a mean height of 21·5 m. The leaf area index (LAI) and silhouette woody biomass index (WBI) are 4·9 and 0·6, respectively. Thus, the plant area index (PAI) is 5·5. The mean leaf inclination angle is about 40° above crown closure and is about 10° below crown closure. Canopy architectural measurements were made along twenty-two vertical transects in the area where radiation measurements were made. Further details concerning the architecture of this canopy are reported in Hutchison *et al.* (1984).

Norman's model uses the above-canopy flux densities of photosynthetically active (PAR) and near infrared radiation (NIR) and the beam fractions of PAR and NIR to compute vertical profiles of insolation components. PAR was measured above the canopy with a quantum sensor (Lambda Instru. Co., Lincoln, Nebr., model LI-190S). PAR was converted from quantum units to energy units using a conversion factor of 4·6 μEinstein $m^{-2}\ s^{-1}$ $(W\ m^{-2})^{-1}$ (McCree 1972). NIR was determined by taking the difference between incoming shortwave radiation (R_g) and PAR, where R_g was measured with a pyranometer (Kipp & Zonen, Delft, Holland, model CM-5). The beam fractions of PAR (PAR(beam)) and NIR (NIR(beam)) were computed from measurements of total and direct shortwave radiation:

$$\text{PAR(beam)} = {\cdot}83\ S/R_g \tag{9a}$$

$$\text{NIR(beam)} = 1{\cdot}18\ S/R_g \tag{9b}$$

where S is direct shortwave radiation. Direct shortwave radiation was computed as the difference of total and diffuse shortwave radiation, where diffuse shortwave radiation was measured with an Eppley pyranometer (model 8-48A, Newport, RI) equipped with a shadow band. The conversion factors in eqns (9a) and (9b) were derived on the assumption that PAR/R_g is 0·43 and 0·52 for the direct and diffuse components, respectively, and NIR/R_g is 0·57 and 0·48 for these two components (Ross 1981).

TABLE 1. Transmissivities (τ), reflectivities (ρ) and scattering coefficients (ω) used to compute vertical profiles of solar radiation components

Variable	Waveband	Element	Value	Reference
ρ	PAR	*Quercus alba*	0·11	
ρ	NIR	*Quercus alba*	0·43	
ρ	R_g	*Quercus alba*	0·30	Birkebak & Birkebak (1964)
ρ	PAR	forest floor	0·033	
ρ	NIR	forest floor	0·023	
ρ	R_g	forest floor	0·056	
τ	PAR	*Quercus alba*	0·16	
τ	NIR	*Quercus alba*	0·26	
τ	R_g	*Quercus alba*	0·22	Birkebak & Birkebak (1964)
ω	PAR	*Quercus alba*	0·27	
ω	R_g	*Quercus alba*	0·52	Birkebak & Birkebak (1964)
ω	PAR	forest floor	0·10	de Wit (1965)
ω	R_g	forest floor	0·10	de Wit (1965)

Norman (1979) recommends that eqns (1) and (2) be computed with Δf less than 0·5. We used Δf equal 0·28 to conform with this recommendation.

De Wit's model requires measurements of direct and diffuse PAR or R_g incident to the canopy–atmosphere interface to compute the radiation regime within the canopy. We used s equal 0·1, as recommended by de Wit (1965), to compute the penetration of direct and diffuse radiation. The leaf and light distribution functions were computed using nine angle classes distributed between 5 and 85°.

Reflectivities (ρ), transmissivities (τ) and scattering coefficients (ω) of the leaves and reflectivities of the forest floor used to compute scattered radiation are presented in Table 1. Leaf reflectivities and transmissivities in the PAR waveband were measured on the top and bottom of leaves of *Quercus alba* with a spectroradiometer (LI-COR model 1800, Lambda Instru. Co., Lincoln, Nebr.). It was not possible to measure reflectivities and transmissivities for NIR waveband. NIR reflectivities and transmissivities were computed using known ratios of PAR/R_g and NIR/R_g (Ross 1981) and shortwave radiation reflectivities and transmissivities reported by Birkebak & Birkebak (1964) for *Q. alba*:

$$\rho(\text{NIR}) = (\rho(R_g) - (\text{PAR}/R_g)\,\rho(\text{PAR}))/(\text{NIR}/R_g) \quad (10a)$$

$$\tau(\text{NIR}) = (\tau(R_g) - (\text{PAR}/R_g)\,\tau(\text{PAR}))/(\text{NIR}/R_g) \quad (10b)$$

Forest floor reflectivities in the PAR and NIR wavebands were measured directly to integrate the effects of detritus and soil. The measurements were made with upward and downward facing PAR and R_g sensors mounted on a moving tram (the tram system is described below). The tram used for this measurement was positioned 1 m above the forest floor. The ground reflectivities reported here are much lower than values reported for bare soil by Monteith (1973) since litter was present on the forest floor.

Data used to compare model computations with observed values were obtained on 30 September 1981. The sky was relatively clear; the daily integrated total of shortwave radiation was 18·2 MJ m^{-2}. The forest was still fully-leafed at this late date, allowing the canopy to be representative of the phenological condition observed between late spring and early autumn (see Baldocchi *et al.* 1984b). Measurements of the radiation components were made with instruments described above. These measurements had an accuracy of about ±5%.

Vertical profiles of solar radiation components were measured at five levels inside the canopy and at one level above the canopy. The instruments were mounted on trams that

traversed through the canopy. The tram system was employed to account for spatial variability in the radiation regime within the canopy and to reduce sampling error (see Reifsnyder, Furnival & Horowitz 1971; Norman & Jarvis 1974). The tram system traversed a horizontal transect of 30 m, an adequate distance in view of the work of Norman & Jarvis (1974). The trams tranversed through the canopy at a rate of 0·6 m min^{-1}. Instruments were sampled three times per minute, resulting in measurements being made every 0·20 m along the transect. Further details regarding the description of the tram system and measurement procedures are presented in Baldocchi *et al.* (1984a, b).

Analysis procedure

Measured and calculated vertical profiles of solar radiation components, compared below, represent the downward flux density of insolation passing through a horizontal surface. Daily means computed from hourly values obtained between 08.00 and 17.00 h were used to compare model predictions with observations. This approach integrates the effect of the diurnal variation in the sun's position. Thus, any bias which may occur from the position of the sun coinciding with an anomalous gap in the canopy is minimized. Differences between measured and simulated irradiance flux densities were tested for significance with a paired *t*-test computed on 5% level of probability. The paired *t*-tests and 95% confidence levels were computed using hourly data.

The frequency distribution of leaf inclination angles in this oak–hickory forest varies with height (Baldocchi *et al.* 1984a; Hutchison *et al.* 1984). Since de Wit's model has no provision for altering $O_p(\beta)$ with height we computed $O_p(\beta)$ using the distribution of leaf inclination angles from the upper canopy. This assumption is reasonable since this distribution is applicable for 65% of the canopy foliage, which, depending on the solar elevation, intercepts between 85 and 100% of incoming beam radiation. The pyranometer at PAI = 1·3 malfunctioned occasionally. Since the attenuation of R_g is exponential in this forest (Baldocchi *et al.* 1984a), the Beer–Bouguer relationship and an attenuation coefficient of 0·5 was used to estimate R_g.

RESULTS

Total shortwave radiation

Measured and simulated vertical profiles of mean daily shortwave radiation (R_g) are presented in Fig. 1 and are compared in Fig. 2. Simulated values computed with Norman's and de Wit's models significantly underestimate measured values throughout the canopy. Values of R_g computed with Norman's model are in closer agreement with observed values than are those computed with de Wit's model. Computations of R_g using Norman's model underestimate observed values by 25–50 W m^{-2}, whereas those computed with de Wit's model underestimate measured values by 50–75 W m^{-2}.

Direct shortwave radiation

Measured and simulated vertical profiles of direct shortwave radiation (S) profiles are presented in Fig. 3 and are compared in Fig. 4. These figures show that simulated S values significantly underestimate measured values by about 20–40 W m^{-2} in the lower canopy (PAI > 3·9). In the upper canopy (PAI = 1·3) simulated values underestimated estimated flux densities by about 40 W m^{-2}. Values of S computed with Norman's model (eqn 1) are nearly identical with computations from de Wit's model (eqn 7), which incorporates the frequency distribution of leaf inclination angles.

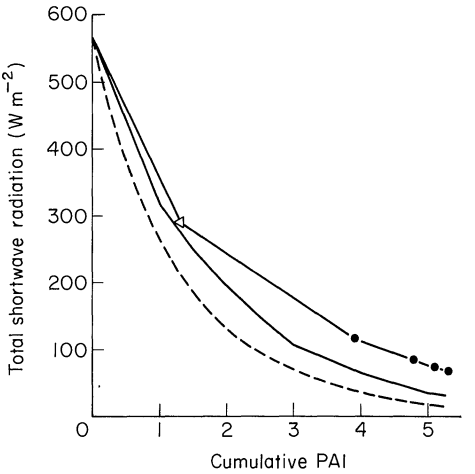

FIG. 1. Calculated (modelled) and measured mean daily vertical profiles of downward directed total shortwave radiation. (——), Norman's model; (– – – –), de Wit's model; (—●—), measured; (—△—), estimated.

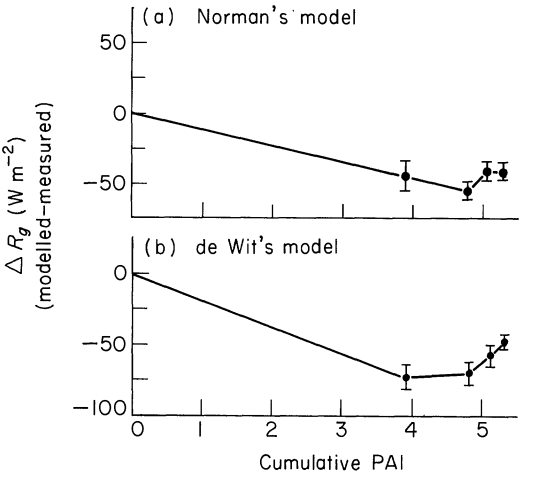

FIG. 2. Comparison of calculated and measured vertical profiles of total shortwave radiation (R_g). The error bars represent the standard error of the differences. (a) Calculated vertical profiles of R_g were computed with the model of Norman (1979); (b) Calculated vertical profiles of R_g were computed with the model of de Wit (1965).

Diffuse shortwave radiation

Mean daily vertical profiles of measured and simulated diffuse shortwave radiation (D) are presented in Fig. 5 and are compared in Fig. 6. Here, the agreement between measured values of D and those calculated with Norman's model is reasonable. Simulated values overestimate measured by only 20 W m^{-2} in the upper canopy (PAI $<$ 1·3) and underestimate them by about 10 W m^{-2} in the lower canopy (PAI $>$ 3·9) (Fig. 6a). De Wit's model, on the other hand, underestimates D by about 25–50 W m^{-2} throughout the canopy (Fig. 6b).

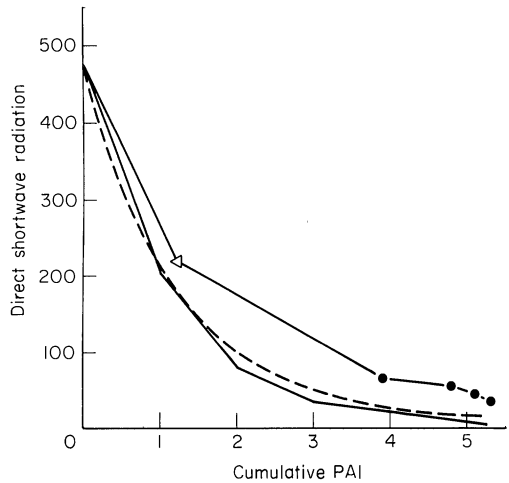

FIG. 3. Calculated and measured mean daily vertical profiles of incoming direct shortwave radiation. (——), Norman's model; (– – – –), de Wit's model; (—●—), measured; (—△—), estimated.

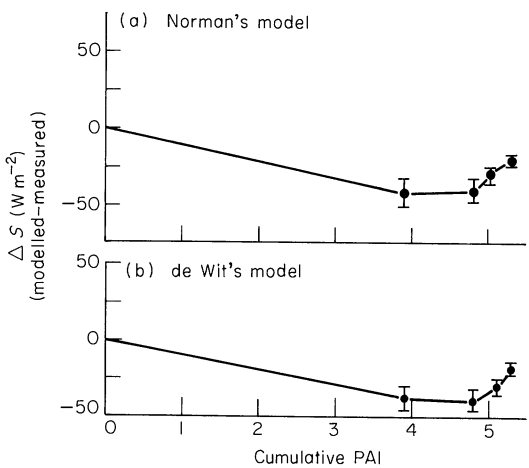

FIG. 4. Comparison of calculated and measured vertical profiles of direct shortwave radiation (S). The error bars represent the standard error of the differences. (a) Calculated vertical profiles of S were computed with the model of Norman (1979); (b) Calculated vertical profiles of S were computed with the model of de Wit (1965).

Figure 5 also shows that the shape of the observed and simulated profiles is strikingly different. Values of D simulated with Norman's model initially increase with depth into the crown, then decrease, whereas those computed with de Wit's model decrease rapidly with depth. The observed profile, on the other hand, decreases with depth throughout the canopy at a relatively slow rate.

Photosynthetically active radiation

Mean daily vertical profiles of simulated and measured total PAR, direct plus diffuse components, are presented in Fig. 7 and are compared in Fig. 8. In the upper canopy,

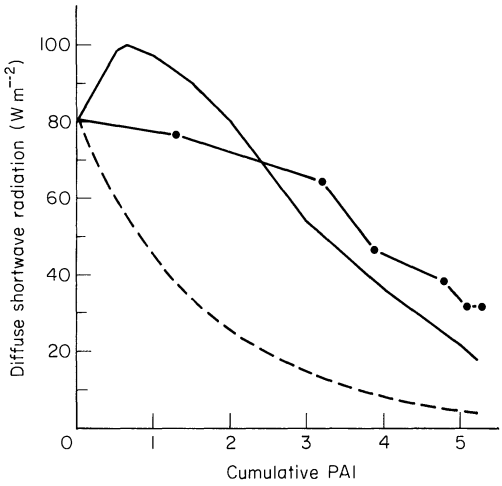

FIG. 5. Calculated and measured mean daily vertical profiles of downward-directed diffuse shortwave radiation (*D*). (——), Norman's model; (– – – –), de Wit's model; (—●—), measured.

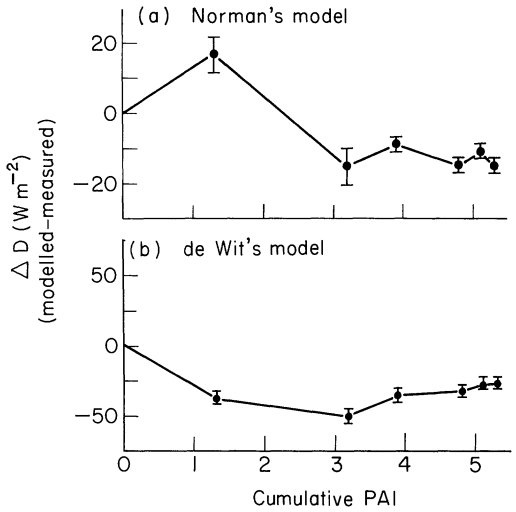

FIG. 6. Comparison of calculated and measured vertical profiles of downward directed diffuse shortwave radiation (*D*). The error bars represent the standard error of the differences. (a) Calculated vertical profiles of *D* were computed with the model of Norman (1979); (b) Calculated vertical profiles of *D* were computed with the model of de Wit (1965).

simulated values underestimate measured by about 50–65 W m^{-2}, with PAR values computed with Norman's model being in better agreement with observed values. In the lower canopy, both models underestimate measured values by only 10–20 W m^{-2}.

Near infrared radiation

Simulated and measured profiles of total NIR computed with Norman's model are presented and compared in Fig. 9. This figure shows that simulated NIR underestimates measured values by 20–40 W m^{-2}.

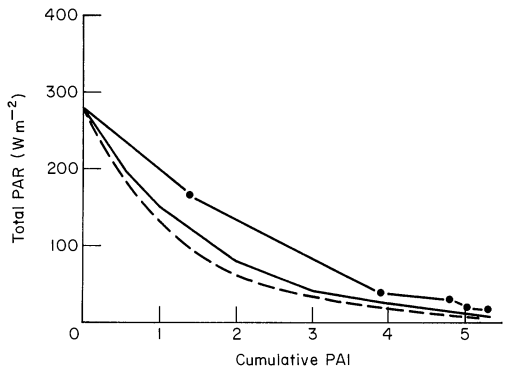

FIG. 7. Calculated and measured mean daily vertical profiles of downward direct total photosynthetically active radiation (PAR). (——), Norman's model; (– – – –), de Wit's model; (—●—), measured.

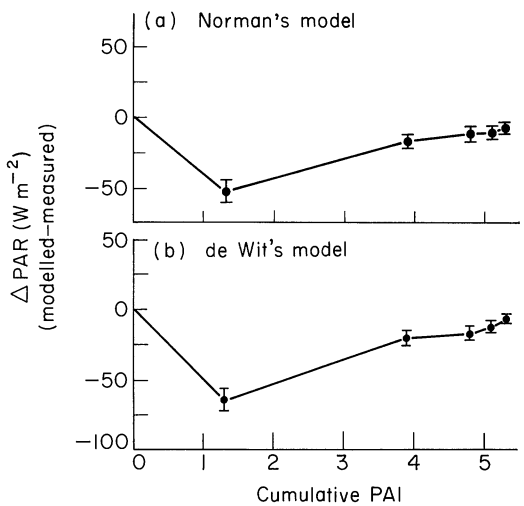

FIG. 8. Comparison of calculated and measured vertical profiles of downward directed photosynthetically active radiation (PAR). The error bars represent the standard error of the differences. (a) Calculated vertical profiles of PAR were computed with the model of Norman (1979); (b) Calculated vertical profiles of PAR were computed with the model of de Wit (1965).

Canopy reflectivity

Figure 10 compares measured and simulated canopy reflectivity values for PAR and R_g, respectively. Simulated values of PAR reflectance overestimate measured values by a factor of three (Fig. 10a). Shortwave reflectance, computed with de Wit's model agrees reasonably well with measured values while those values computed with Norman's model overestimate measured values by about 30%.

DISCUSSION

Reasons for the differences between computed and measured S values, shown in Fig. 3, can be identified by examining the beam penetration theory. According to eqn (1), beam penetration is a function of leaf orientation and solar elevation. The leaf orientation

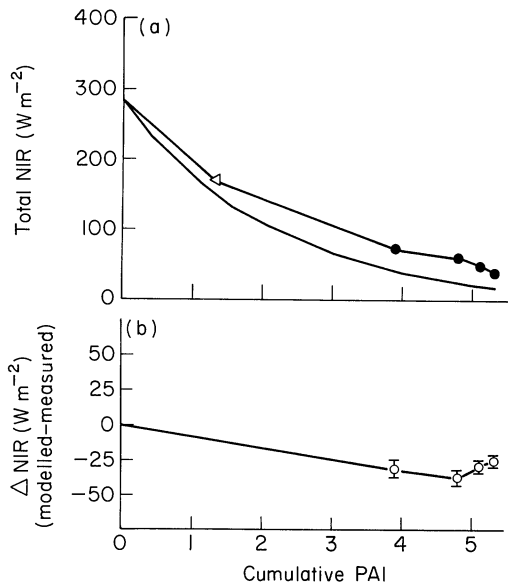

FIG. 9. (a) Calculated and measured mean daily vertical profiles of near infrared radiation (NIR). (b) Comparison of calculated and measured NIR. The error bars represent the standard error of the differences. (——), Norman's model; (—●—), measured; (—△—), estimated.

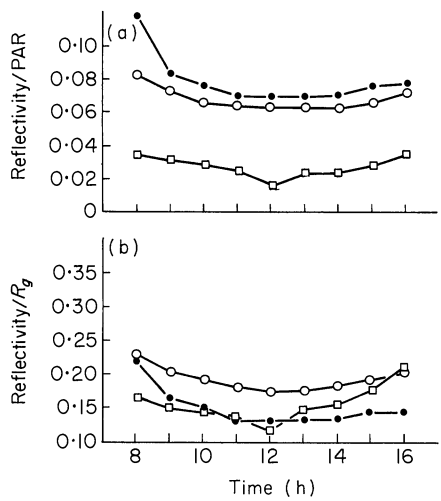

FIG. 10. (a) A comparison of calculated and measured reflectivities of photosynthetically active radiation. (b) A comparison of calculated and measured reflectivities of shortwave radiation. (O——O), Norman's model; (●——●), de Wit's model; (□——□), measured.

function (G) is defined as the mean projection of a unit foliage area in the direction of the solar beam (Ross 1976). For a canopy with a spherical leaf distribution, G equals 0·5 and is independent of solar elevation. Theoretically G is expressed as:

$$G(\beta, \phi) = \frac{1}{2\pi} \int_0^{\pi/2} d\phi_L \int_0^{\pi/2} g(\phi_L, \theta_L) \, |\cos(nn_L)| \, \sin(\theta_L) \, d\theta \qquad (11)$$

where $g(\theta_L, \phi_L)$ is the distribution function of the foliage area orientation, and ϕ_L is the leaf azimuth angle. The term $\cos(nn_L)$ is the direction cosine between the leaf's normal and the incident beam. It is expressed as:

$$\cos(nn_L) = \cos(\beta)\cos(\theta_L) + \sin(\beta)\sin(\theta_L)\cos(\phi - \phi_L) \qquad (12)$$

The observed differences presented in Fig. 3 can be explained in terms of leaf inclination angles only if the G-function for this canopy is less than that for a spherical canopy.

Values of G were computed using actual stand structure data with a technique developed by Lemeur (1973). These computations were based on the assumption that the azimuthal distribution of the leaves is symmetrical, a reasonable assumption for closed canopies (de Wit 1965; Lemeur 1973; Ross 1981).

Table 2 presents G-function values for portions of the canopy above and below crown closure. Below crown closure, the daily mean G-function is 0·61, whereas above crown closure it is 0·57. Since these measured G-values exceed the value for a spherical canopy, these data suggest that the actual leaf inclination angle distribution cannot explain the differences between measured vertical profiles of direct shortwave radiation and those computed with Norman's model.

Inspection of eqn (7) reveals that several possibilities can account for de Wit's model underestimating S, and subsequently R_g. These possibilities include errors in the estimation of the canopy density factor, s, and O_p.

It is possible to discount the possibility that the underestimation of S is due to an incorrect parameterization of s. De Wit (1965) states that the penetration of S increases as s decreases, but that beam penetration increases little as s decreases from 0·2 to 0·0. Based on these arguments a further reduction in s will not improve the de Wit's model since the calculated vertical profile of S already underestimates the measured profile.

Possible errors in the estimation of O_p also do not account for the observed differences in S. This is because values of S computed from actual stand data (where mean θ_L equals 40°) and for the spherical case (where mean θ_L equals 60°) agree within 5 W m^{-2}. This agreement suggests that the computation of S is relatively insensitive to errors in the measurement of the frequency distribution of leaf inclination angles if the distribution is not extreme, e.g. planophile or erectophile.

An alternative explanation for measured values of S being greater than simulated values is that the foliage in this canopy is clumped. Clumping enhances the penetration of beam

TABLE 2. Computations of the leaf orientation function (G) using leaf angle inclination data from an oak-hickory forest

Hour	Solar elevation		Leaf orientation function Below crown-closure	Above crown-closure
8	23		0·46	0·51
9	34		0·57	0·54
10	43		0·66	0·58
11	49		0·72	0·62
12	52		0·74	0·63
13	49		0·72	0·62
14	42		0·65	0·58
15	33		0·56	0·54
16	22		0·45	0·51
		$\bar{G}$ =	0·61	0·57

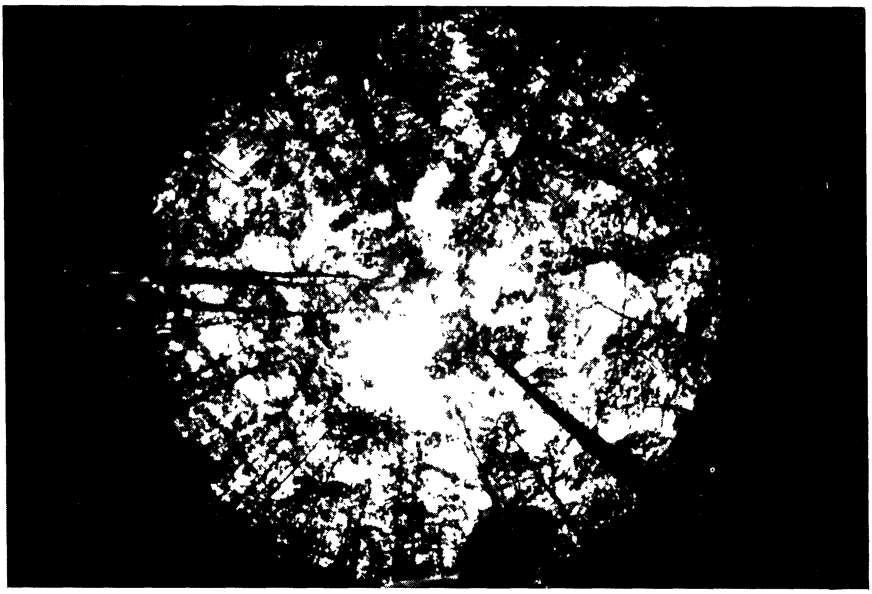

FIG. 11. A hemispherical field-of-view photograph of the fully-leafed oak–hickory canopy.

radiation by causing leaf overlap and increasing the frequency of large gaps (Lemeur & Blad 1974; Norman 1975; Norman & Jarvis 1975; Ross 1976 1981; Oker-Blom & Kellomaki 1983). Photographic evidence supports our contention that this canopy had clumped foliage and an appreciable occurrence of large gaps (Fig. 11).

The simulation of the penetration of S inside a canopy with clumped foliage can be improved by using a negative binomial distribution to predict the probability of beam interception (P) (Acock, Thornley & Warren Wilson 1970; Nilson 1971). The assumptions in applying the negative binomial relationship are: (i) the stand consists of a finite number of equal and statistically independent layers; and (ii) within each layer more than one contact between a light ray and the foliage is possible. The probability of beam interception based on the negative binomial distribution is:

$$P = \exp\left[\frac{-f}{g}\ln\left(1 + \frac{Gg}{\sin(\beta)}\right)\right] \tag{13}$$

where g is an index of foliage dispersion. g is defined as f/n, where n is the number of layers. g increases as the clumpiness of the canopy increases and approaches zero as the dispersion of the foliage becomes more random, causing eqn (13) to reduce to the Poisson distribution, eqn (1).

Beam penetration has been computed using eqn (13) to examine whether it would provide a better fit to the data and provide a better means of estimating the probability of beam interception in a clumped canopy. Calculation of g from an empirical fit of the direct shortwave radiation data gave $g = 2{\cdot}42$.

Figure 12 presents vertical profiles of mean daily direct shortwave radiation computed with: (i) de Wit's model (eqn (7)); (ii) the negative binomial relationship (eqn (13)); and (iii) the Poisson distribution (eqn (1)). These values are compared with the measured vertical profile of S. The results show that the negative binomial relationship fits our data

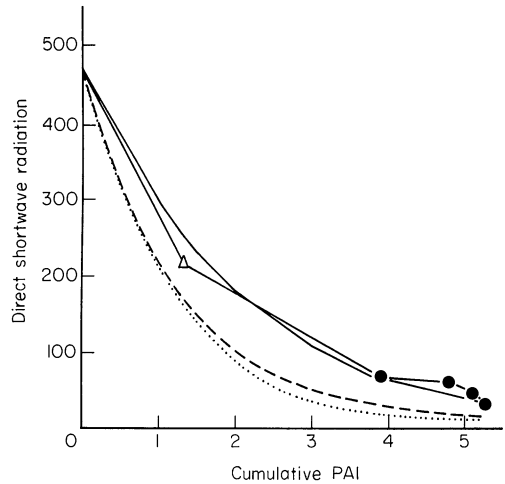

FIG. 12. A comparison of vertical profiles of direct shortwave radiation computed, with the negative binomial and Poisson distributions and de Wit's model, and measured values. (· · · · · ·), Poisson distribution; (——), binomial distribution; (– – – –), de Wit's model; (—●—), measured; (—△—), estimated.

very well, agreeing within 20 W m^{-2} of the measured values. The negative binomial distribution, thus, provides an improved means of simulating direct radiation within this clumped forest canopy.

Another approach for treating the effects of clumping uses non-random grouping theory (Norman & Jarvis 1975; Oker-Blom & Kellomaki 1983). These theories were developed for shoots and whorls in conifers and must be modified to be applied in a deciduous forest canopy. A third approach uses a three-dimensional model which treats the canopy as an array of ellipsoids (Norman & Welles 1983) to simulate the radiation environment inside a canopy. This method also must be modified since Norman & Welles (1983) assume a random distribution of foliage within each ellipsoid.

Diffuse shortwave radiation, theoretically, increases with depth into the crown because intercepted direct shortwave radiation is converted into diffuse shortwave radiation via scattering by the foliage elements (Hutchison & Matt 1976; Norman 1979; Ross 1981). However, an increase in D with depth into the crown was not observed (Fig. 5). The clumped nature of the foliage is responsible for this observation since clumping of the foliage increases beam penetration, thereby minimizing its interception and conversion to scattered diffuse radiation.

Since the agreement between values of D measured and simulated with Norman's model are within 20 W m^{-2}, it is likely that the optical properties used here are reasonable. It is unlikely that errors in the parameterization of optical properties are involved in these differences since errors in these optical properties must be unreasonably large to account for the differences reported here (see Ross 1981). Furthermore, we measured most of the optical properties to minimize errors in their parameterization.

The effects of clumping do not account completely for de Wit's model underestimating D, however. De Wit's model simulates a strong decrease in D with depth into the upper canopy. This suggests that de Wit's model underestimates scattering. This suggestion is supported by Fig. 13, which shows that the magnitude of downward scattering is less than 5 W m^{-2}, a small value compared to the magnitude of scattering which occurs in typical

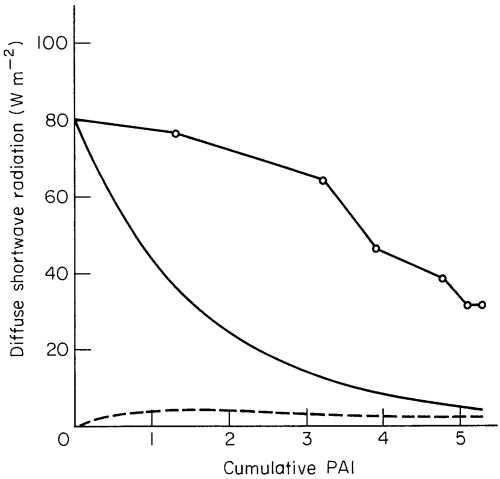

FIG. 13. Vertical profiles of downward scattered and downward directed diffuse shortwave radiation, computed with de Wit's model, and measured *D*. (----), downward scattered; (——), de Wit's model; (—●—), measured.

plant canopies (see Ross 1981). This underestimation of scattering is also why de Wit's model does not perform as well as Norman's model.

Errors in the scattering coefficients can account for some error in the computation of scattering. However, the use of scattering coefficients for *Quercus alba*, the predominant species at this site, minimized this error. Furthermore, it is doubtful that errors in the scattering coefficient are responsible for the underestimation of scattering since the magnitude of the underestimation of D is so great. In view of these results, further improvement in the treatment of scattering is needed. One approach is to incorporate the method of Norman, Miller & Tanner (1971) and Norman (1979) which uses an iterative technique to compute the reflected and transmitted radiation in the upward and downward directions for PAR and NIR, separately.

The underestimation of PAR (Fig. 7) at cumulative PAI equal 1·3 provides further evidence that clumping enhances beam penetration. Good agreement between measured and simulated PAR in the lower canopy, on the other hand, is an artifact of leaves having high absorptivities in the PAR waveband. Consequently, canopy radiation transfer models are less subject to error in computing PAR flux densities deep inside vegetated canopies.

Diffuse shortwave radiation deep inside the canopy is comprised mostly of NIR (Baldocchi *et al.* 1984a). Since Fig. 5 shows that the agreement between simulated and measured diffuse radiation is within 20 W m^{-2}, we can conclude that the theory and optical properties used to compute diffuse NIR are reasonable. The underestimation of NIR (Fig. 9) is mainly due to gaps in the canopy enhancing the penetration of beam NIR.

Reflectivities of PAR and R_g computed with Norman's model overestimate observed values (Fig. 10) because clumping of the foliage increases beam penetration and reduces the amount of radiation intercepted and scattered upward in the upper canopy. The relatively good agreement between measured reflected R_g values and those computed with de Wit's model (Fig. 10b) is due to compensating errors. Clumping of the foliage causes the model to overestimate the amount of direct shortwave radiation that is intercepted in the upper canopy and is converted into upward scattered radiation. This overestimation, however, is compensated by the underestimation of scattered radiation.

This study has shown that vertical profiles of solar radiation components computed with Norman's model are in closer agreement with measured values than are those computed with de Wit's model. However, both models considerably underestimate the radiation regime in an oak–hickory forest because its foliage is clumped.

Utilization of these models to estimate non-linear, light-dependent, biological processes, such as canopy photosynthesis and stomatal resistance, may result in sizable errors in the estimation of these processes since clumped foliage of a deciduous forest causes both models to incorrectly partition solar radiation into its direct and diffuse components.

Until better, yet simple, phytoactinometric models are developed, the ultimate decision regarding whether or not to apply these models in deciduous forests with clumped foliage depends on the user's needs and the user's tolerance for error.

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