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SOLAR RADIATION WITHIN AN OAK—HICKORY FOREST: AN EVALUATION OF THE EXTINCTION COEFFICIENTS FOR SEVERAL RADIATION COMPONENTS DURING FULLY-LEAFED AND LEAFLESS PERIODS

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ABSTRACT

Baldocchi, D.D., Matt, D.R., Hutchison, B.A. and McMillen, R.T., 1984. Solar radiation within an oak—hickory forest: an evaluation of the extinction coefficients for several radiation components during fully-leafed and leafless periods. Agric. For. Meteorol., 32: 307—322.

Global shortwave, photosynthetically active, net and allwave radiation was measured above, and at several levels within an oak—hickory forest with instruments mounted on a moving tram system. Profiles of radiation flux densities were quantified using extinction coefficients based on the Beer—Bouguer law. Data are reported here from periods when the forest was both fully-leafed and leafless.

In the fully-leafed forest the solar radiation components are attenuated exponentially in the following manner: PAR $> Q^* = K\downarrow > Q\downarrow$, where PAR is photosynthetically active radiation, Q^* is net radiation, $K\downarrow$ is shortwave radiation and $Q\downarrow$ is allwave radiation. PAR attenuation is greater than that for the other components because leaves preferentially absorb PAR. This preferential absorption causes the ratio, PAR/$K\downarrow$, to decrease from 0.49 above the canopy to 0.27 at the forest floor.

During the leafless phenoseason, the radiation components are attenuated exponentially as follows: $Q^* > K\downarrow =$ PAR $> Q\downarrow$.

$K\downarrow$ and PAR are attenuated in a similar manner during this phenological phase because no leaves are present to absorb PAR preferentially. The magnitude of the attenuation coefficients for Q^*, $K\downarrow$ and PAR is much greater during winter leafless period because solar elevation angles are lower and the canopy consists of dark, opaque, woody biomass.

Shortwave beam radiation is not attenuated in an exponential manner. Consequently, extinction coefficients for beam radiation, $\gamma(S)$, were computed separately for the upper canopy and lower canopy. A comparison between measured and modeled $\gamma(S)$ show periods of reasonable agreement and disagreement. Deviations from theory are attributed to clumping and gaps in the canopy.

INTRODUCTION

Forests, which constitute about 10% of the earth's total surface area (Olson et al., 1978), play an important role in the earth's surface energy

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balance, hydrological cycle and primary productivity. Detailed information regarding the radiation environment above and within forests is, therefore, of great value if we are to understand and accurately model mass and energy exchanges between the forest canopy and the atmosphere.

The radiation environment within vegetated canopies is primarily a function of sun—earth geometry, canopy architecture, optical properties of the phytoelements and the ratio between diffuse and direct radiation (Colwell, 1974; Ross, 1976, 1981). Much is known about the radiation environment within homogeneous, agricultural monicultures (see Ross, 1981 for a review). However, studies of the radiation environment within forests are relatively rare. Most of the studies that have been undertaken within forests have been made within conifer stands (e.g., Reifsnyder et al., 1971; Gay et al., 1971; Tajchman, 1972; Norman and Jarvis, 1974, 1975; Jarvis et al., 1976; Sinclair and Knoerr, 1982). Anderson (1964), Miller (1969), Horn (1971), Hutchison and Matt (1976, 1977), Rauner (1976), Thompson and Hinckley (1977) and Floyd et al. (1978) are among the few workers who have reported solar radiation measurements above and within deciduous forests.

Additional solar radiation studies within forests are warranted for several reasons. First, forests are much more complex than the often studied agricultural monocultures. For example, forests have a canopy which, in the case of many deciduous stands, may be composed of trees of different ages and species. This causes the canopy architecture to be quite complex and heterogeneous. The optical properties of the forest are also more complex because of the multi-specied nature of the canopy and because the dark, opaque, woody biomass accounts for an appreciable portion of the light-attenuating elements. Secondly, many of the past studies were either limited in scope or were performed with inappropriate techniques or inadequate sensors.

In view of these limitations, a comprehensive study of the radiation environment above and within an east Tennessee oak—hickory forest was initiated. The objective of this study was to measure within-canopy vertical profiles of total, direct beam and diffuse shortwave radiation, photosynthetically active radiation, net radiation and incoming allwave radiation during the fully-leafed and leafless phases. Profiles of the various radiation components were quantified and compared, using extinction coefficients based on the Beer—Bouguer Law. The extinction of beam radiation is also compared with theoretical values computed from the model of Anderson (1966).

MATERIALS AND METHODS

This study was performed on the U.S. Department of Energy Oak Ridge Reservation immediately west of the Oak Ridge National Laboratory's Walker Branch Watershed Research Facility (lat. 35° 57′30″ and long. W 84° 17′15″, alt. 365 m above mean sea level), located near Oak Ridge, TN.

The site is forested by an uneven-aged oak—hickory (*Quercus* sp. and *Carya* sp.) stand representative of the Appalachian region. The soil at the site is a Fullerton cherty silt loam (Typic Paleudult).

The average height of dominant trees was about 21.5 m, but because of the uneven age structure and mixed species composition, heights ranged from 17 to 26 m. During the fully-leafed season, the leaf area index (LAI) and plant area index (PAI) were 4.9 and 5.5, respectively. During the leafless winter period the PAI was approximately 0.6. Vertical distributions of leaf inclination angles were measured during the summers of 1978 and 1983. These measurements were made at 22 randomly selected locations in sample volumes with a cross-sectional area of 0.25 m^2. Leaf inclination angles were measured at the fall-line of the leaf with a protractor in 1978. A three-dimensional protractor was devised and used in 1983 to measure leaf inclination angles and to minimize errors due to subjectively determining the slope of the non-linear fall-line of the leaf. Further details about the measurement of canopy structure at our site is provided in Hutchison et al. (1982).

Radiation measurements were made using a moving tram system. This system consists of two 33 m triangular towers and a 44 m walkup tower adjacent to the eastern triangular tower. The triangular towers were 35 m apart and supported cable pairs at eight levels strung parallel to the ground and oriented 72° E of north. The cable pairs were mounted at 1, 6, 10.5, 14, 17, 21, 26 and 33 m above the forest floor. Care was taken during installation to minimize canopy disturbance.

Instrumented trams automatically traversed the middle 30 m between the triangular towers on the cable pairs at levels 1—7 at an approximate speed of 0.6 m min^{-1}. The eighth level (33 m) remained stationary and above the forest at a location midway between the two triangular towers. The trams and the radiometry contained within were carefully leveled so that sensing surfaces were within ± 1° of horizontal throughout the traverses, which paralleled the 3% slope of the forest floor.

The radiometers used at each level are listed in Table 1. Each tram was equipped with 6 radiometers to provide measurements of incoming and outgoing flux densities of electromagnetic radiation in 3 wavebands. The wavebands are global shortwave, $K\downarrow$ (0.285—2.85 μm); photosynthetically active, PAR (0.4—0.7 μm) and allwave, $Q\downarrow$ (0.3—60.0 μm. Diffuse shortwave radiation (D) was measured at each level by pyranometers equipped with shadowbands. These instruments were mounted on booms off the two triangular towers.

Sensor signals were connected to a computer-controlled, data acquisition system through individually shielded pairs of twisted leads. Voltage signals were digitized and stored on magnetic tape 3 times per min. Voltage signals were later converted to scientific units and averaged for 1-h periods using a mainframe computer.

The data presented in this paper were obtained during two periods: a

TABLE I

Tram instrumentation

Radiation measurement	Instrument	Waveband (μm)	Manufacturer and model
Shortwave incoming	Pyranometer	0.285—2.8	Kipp & Zonen Model CM-5
Shortwave outgoing	Inverted pyranometer	0.285—2.8	Kipp & Zonen Model CM-5
Allwave net	Net pyranometer	0.3—60.0	Swissteco Model S-1
Allwave incoming	Net pyranometer with black body cavity	0.3—60.0	Solar Rad. Instr. SRI 4 Net[a]
Photosynthetic	PAR pyranometer	0.4—0.7	LI-COR Model LI-190S
Photosynthetic outgoing	Inverted PAR pyranometer	0.4—0.7	LI-COR Model LI-190S
Shortwave diffuse	Pyranometer with shadowband	0.285—2.8	Eppley Radiometer Model 0-48

[a] Black body cavity temperature measured with Yellow Springs Model YSI-44032 thermisters.

TABLE II

Daily total of $K\downarrow$, PAR, Q^* and albedo in the days used in this analysis measured above the canopy

Julian Day	$K\downarrow$	PAR (MJ m^{-2} day^{-1})	Q^*	$Q\downarrow$	Albedo
20	2.44	1.27	1.16	29.9	0.40
25	12.05	5.51	3.36	35.0	0.28
26	8.53	3.96	3.32	36.3	0.29
267	16.97	7.83	7.69	42.5	0.08
268	16.06	7.67	8.13	43.5	0.09
269	18.02	8.48	9.37	46.5	0.10
270	17.99	7.17	7.92	44.5	0.12
271	19.68	9.17	9.44	46.1	0.09
272	18.18	8.62	8.94	44.5	0.10
273	18.32	8.66	9.77	47.0	0.12
274	15.51	7.27	8.25	46.4	0.12

winter leafless period (January 20—26, 1981) and a late-summer, fully-leafed period (September 25—30, 1981). The winter data included clear, partly cloudy and overcast conditions. The September data contained clear and partly cloudy conditions. The morphology of the canopy, during September, was representative of the summertime, fully-leafed phase because little leaf senescence or abscission had occurred. Mean daily flux densities of radiation in four wavebands and albedo are presented in Table II.

The mean insolation values presented here do not describe the radiation environment within a forest completely because the frequency distribution of insolation inside a canopy is not always Gaussian. Unpublished data showing that the frequency distribution is skewed during the leafing season, and is approximately Gaussian during the leafless phenoseason has been obtained. Knowledge of the frequency distribution of insolation is particularly critical when using insolation values to model such non-linear processes as photosynthesis and stomatal resistance. This presentation of mean attenuation coefficients is useful because these data can be used to describe the seasonal dynamics of the radiation regime within a forest, and can be used in models that simulate processes which are linearly dependent on insolation (e.g., transpiration). A paper describing the statistics associated with actinometric measurements made within a forest is in preparation.

RESULTS AND DISCUSSION

Extinction coefficients of solar radiation

Fully-leafed canopy

The radiation profile within a canopy can be approximated by an exponential relationship (Rauner, 1976; Ross, 1981). This relationship is generally expressed as a form of the Beer—Bouguer Law

$$I(\mathrm{f}) = I_0 \exp(-\gamma f) \qquad (1)$$

where $I(\mathrm{f})$ is the flux density of a given radiation component below a cumulative plant area (or leaf area) index, f. I_0 is the radiation flux density incident upon the canopy, and γ is the extinction coefficient for the radiation component of interest. Values of γ decrease as the canopy's ability to attenuate solar radiation decreases. For the case of global radiation, γ ranges from approximately 0.20, for erectophile canopies, to approximately 1.10, for panophile canopies (Monteith, 1973).

Equation 1 was derived on the assumption that a canopy is a homogeneous, turbid medium (Ross, 1981). Since this assumption does not hold for all canopies, it is important that eq. 1 is tested to determine whether it adequately describes the radiation environment within the Walker Branch Watershed, oak—hickory forest. Equation 1 can be represented graphically by plotting $\ln(I/I_0)$ against f. Such a plot is shown in Figure 1 for shortwave ($K\downarrow$), photosynthetically active (PAR), net (Q^*) and incoming allwave ($Q\downarrow$)

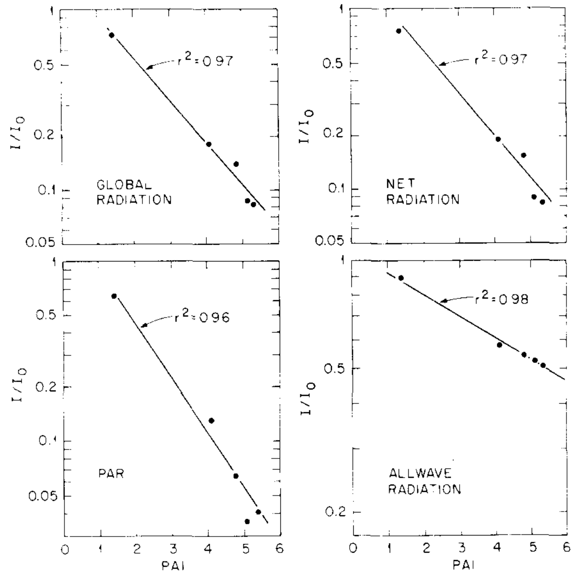


Fig. 1. Plots of I/I_0 against cumulative PAI, f, for a typical period. Plots are presented for $K\downarrow$, Q^*, PAR and $Q\downarrow$. Data are from September 30, 1981, 1100 h. I/I_0 is plotted on a logarithmic scale.

radiation. These data are from a typical 1-h period in the fully-leafed forest. Data from only 5 of the levels is presented since the tram at 17 m malfunctioned. Figure 1 shows that eq. 1 describes the radiation environment within the forest reasonably well because the coefficients of determination (r^2) are large ($r^2 \geqslant 0.96$). These results support the use of extinction coefficients to quantify the total radiation environment within this oak—hickory forest.

Mean values of γ for $K\downarrow$ Q^*, PAR and $Q\downarrow$ for the fully-leafed forest are shown in Table III, on a leaf area (LAI) and plant area (PAI) index basis. These coefficients were calculated using a least-squares fit technique, regressing ln (I/I_0) against f. The mean extinction coefficient is greatest for PAR and is least for allwave radiation (see Table IV for mean comparisons). Furthermore, mean comparisons, using Student's t-test, indicate that γ values for $K\downarrow$ and Q^* are the same at the 5% level of significance. Extinction coefficients, calculated on a PAI basis, as expected, are smaller than those computed on a LAI basis because PAI > LAI at a given level.

The mean extinction coefficient for PAR is greater than those for the other radiation components because leaf pigmentation and anatomy causes leaves to absorb preferentially PAR over near-infrared radiation (0.7—2.85 μm) (Loomis, 1965; Gates et al., 1965). This difference in leaf optical properties leads to a depletion of PAR, relative to shortwave radiation, with depth in the canopy.

Allwave radiation has a very low extinction coefficient because a

TABLE III

Mean extinction coefficients (γ) for $K\downarrow$, Q^*, PAR, and $Q\downarrow$ are presented on a leaf area (LAI) and plant area index (PAI) basis[a]

Variable	n	$\bar{\gamma}$ (LAI)	Std. dev.	$\bar{\gamma}$ (PAI)	Std. dev.
$K\downarrow$	36	0.579	0.178	0.506	0.133
Q^*	52	0.592	0.158	0.536	0.153
PAR	71	0.732	0.141	0.655	0.139
$Q\downarrow$	56	0.129	0.065	0.115	0.057

[a] Measurements were made during September, 1981 in a fully-leafed oak—hickory forest. n is number of hourly periods and Std. dev. is standard deviation.

TABLE IV

Comparisons of γ for different components of solar radiation

Variable		Hypotheses			δ	C.I.
x	y	H0 $(x = y)$	H1 $(x < y)$	H2 $(x > y)$		
γ on an LAI basis						
$Q\downarrow$	$K\downarrow$		*		−0.450	0.063
$Q\downarrow$	Q^*		*		−0.463	0.047
$Q\downarrow$	PAR		*		−0.603	0.038
$K\downarrow$	Q^*	**			−0.013	0.074
$K\downarrow$	PAR		*		−0.153	0.068
PAR	Q^*			*	0.140	0.055
γ on a PAI basis						
$Q\downarrow$	$K\downarrow$		*		−0.391	0.048
$Q\downarrow$	Q^*		*		−0.421	0.045
$Q\downarrow$	PAR		*		−0.540	0.036
$K\downarrow$	Q^*	**			−0.030	0.062
$K\downarrow$	PAR		*		−0.149	0.055
PAR	Q^*			*	0.119	0.054

* The stated hypothesis is significant on the 0.025 level of probability for a one-tailed t-test.

** The stated hypothesis is significant on the 0.05 level of probability for a two-tailed t-test.

H0, H1, and H2 are the stated hypotheses, δ is the difference of the means and C.I. is the 95% confidence interval.

substantial portion of this radiation consists of incoming longwave radiation (the magnitude of incoming longwave radiation (2.85—60 μm) is typically on the order of 300—400 W m^{-2}). Little longwave radiation is attenuated by the canopy because the leaves are almost blackbodies (Idso et al., 1969) and so are excellent absorbers and emitters of longwave radiation. This near-blackbody characteristic of leaves also explains why γ values for $K\downarrow$ and Q^* are identical; only the shortwave component of Q^* is significantly attenuated by the fully-leafed canopy.

The extinction coefficients for $K\downarrow$, Q^* and PAR agree reasonably well with coefficients derived from the European oak forest data of Rauner (1976). Rauner (1976) reported that extinction coefficients for $K\downarrow$ and Q^* are quite similar (0.42 and 0.47, respectively, on a PAI basis) and that γ(PAR) is larger, ranging between 0.6 and 1.0.

Thompson and Hinckley (1977) measured $K\downarrow$ profiles within a Missouri oak—hickory forest. They did not compute an extinction coefficient, but they reported that their forest, with a LAI of about 6.7, attenuates about 87% of the global radiation incident upon it. This translates to a $\gamma(K\downarrow)$ of about 0.30, somewhat less than reported here. The difference between values of $\gamma(K\downarrow)$ reported by Thompson and Hinckley (1977) and $\gamma(K\downarrow)$ values reported here may be due to either a difference in the forest stands, their forest had an LAI greater than ours, or to a difference in measurement techniques. Thompson and Hinckley (1977) used six stationary solarimeters at each level — an insufficient number of replicates according to Reifsnyder et al. (1971).

Floyd et al. (1978) measured PAR above and below a mixed-oak forest during several phenological stages. They reported that 98% of incident PAR was attenuated by the forest canopy after complete foliar development. This value agrees reasonably well with the results reported here (see Figure 1).

Information regarding the depletion of PAR within a canopy is a requisite for modeling photosynthesis correctly from profile measurements of shortwave radiation. Figure 2 shows the mean vertical profile of the ratio, PAR/$K\downarrow$, an indicator of PAR depletion. Each datum is the mean of 60 daylight hours, observed during the fully-leafed phenoseason. The mean ratio, PAR/$K\downarrow$, is 0.49 above the canopy. This value agrees with that reported by Stanhill and Fuchs (1977), and Szeicz (1974a). Within the canopy PAR/$K\downarrow$ decreases with cumulative PAI. At the forest floor this ratio is 0.24, i.e., a 50% reduction from that above the canopy. The variation of PAR/$K\downarrow$ within the canopy is much greater than above it. This is because light within the canopy consists of shortwave beam radiation, rich in PAR, and diffuse shortwave radiation, depleted of PAR by the filtering effect of leaves.

The ratio of PAR/$K\downarrow$ near the forest floor (0.24) is greater than similar ratios computed from data in the literature for several agricultural crops. For example, PAR/$K\downarrow$, below a PAI of 5, is ≈ 0.17 in corn (Hatfield and Carlson, 1979; Ross, 1981), whereas it is ≈ 0.20 and 0.24 in wheat and beans, respectively (Szeicz, 1974b). The greater PAR depletion within a corn canopy can be explained by the fact that corn leaves have a lower PAR reflectivity than oak leaves, but have similar reflectivities in the near-infrared band (see Gates et al., 1965. Uchijima, 1976). Profiles of the depletion of

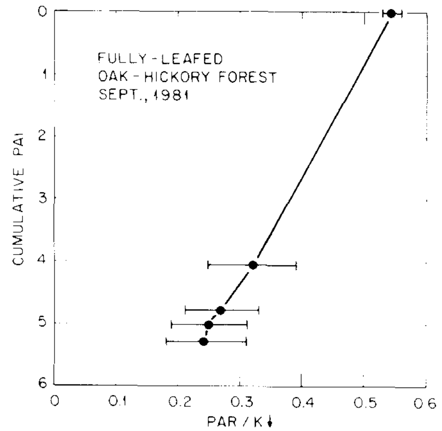


Fig. 2. Vertical profile of the ratio PAR/$K\downarrow$. Data are for the fully-leafed phenoseason. A regression of the data yielded PAR/$K\downarrow = 0.49 - 0.047 f$; $r^2 = 0.99$.

PAR relative to $K\downarrow$ have not been previously measured in deciduous forests. Vezina and Boulter (1966), Federer and Tanner (1966), and Floyd et al. (1978), however, have measured the spectral composition of light below a deciduous forest and have reported an appreciable depletion in PAR.

Leafless canopy

Mean extinction coefficients for the leafless, oak-hickory forest are presented in Table V. The relationships among these coefficients are much different than those for the fully-leafed forest presented in Table III. The mean extinction coefficient is greatest for Q^*, followed by PAR and $K\downarrow$ and $Q\downarrow$ (see Table VI for mean comparison statistics).

The attenuation of Q^* is greater than that of $K\downarrow$, during the leafless period, because the leafless forest does not trap reflected and radiated energy as well as its fully-leafed counterpart (see Baldocchi et al., 1984). The extinction coefficients for $K\downarrow$ and PAR, on the otherhand, are similar because no leaves are present to absorb PAR preferentially.

The extinction coefficients, in the winter forest, for $\gamma(K\downarrow)$, $\gamma(Q^*)$ and γ(PAR) are much greater than those in the fully-leafed forest. Two factors account for this observation. First, leaves transmit and scatter radiation and have high reflectivities in the near-infrared band. As a result, the presence of leaves causes forward scattering of radiation and facilities the penetration of radiation into the canopy. Boles and branches, on the other hand, are opaque and have low reflectivities (Federer, 1971). Consequently, such forward scattering does not occur in the leafless forest. Secondly, solar elevation angles are much lower during the winter leafless periods. The path length of the solar beam through a winter leafless forest is, therefore much greater than through a summer, fully-leafed forest. The winter forest, as a result, attenuates insolation more effectively. This latter argument is

TABLE V

Mean extinction coefficients (γ) for a leafless oak—hickory forest[a]

Variable	n	$\bar{\gamma}$ PAI	Std. dev.
$K\downarrow$	26	1.12	0.18
Q^*	23	1.75	0.22
PAR	19	1.06	0.17
$Q\downarrow$	23	0.15	0.20

[a] Measurements were made during January, 1981.

TABLE VI

Mean comparison of γ for different solar radiation components of the winter leafless oak—hickory forest

Variable		Hypotheses				
x	y	H0 ($x = y$)	H1 ($x < y$)	H2 ($x > y$)	δ	C.I.
$Q\downarrow$	$K\downarrow$		*		−0.97	0.10
$Q\downarrow$	Q^*		*		−0.60	0.12
$Q\downarrow$	PAR		*		−0.63	0.12
$K\downarrow$	Q^*		*		−0.63	0.12
$K\downarrow$	PAR	**			−0.06	0.11
PAR	Q^*			*	0.69	0.12

* The stated hypothesis is significant on the 0.025 level of probability for a one-tailed t-test.

** The stated hypothesis is significant on the 0.05 level of probability for a two-tailed t-test.

H0, H1, and H2 are the stated hypotheses, δ is the difference of the means and C.I. is the 95% confidence interval.

supported by the modeling results of Federer (1971), which show that the attenuation of insolation by a leafless deciduous forest increases with decreasing solar elevation.

The γ values presented here for $K\downarrow$ and Q^* agree well with similar coefficients computed from the data of Rauner (1976) for a leafless oak forest; $\gamma(K\downarrow)$ and $\gamma(Q^*)$ were 1.00 and 1.62, respectively, resulting in the leafless forest attenuating about 50% of incoming solar radiation. This latter value agrees well with the experimental data and modeling results of Federer (1971) for a leafless hardwood forest. Hutchison and Matt (1977), on the other hand, reported that a leafless stand of tulip poplar attenuates about 90% of incoming solar radiation. Their site, however, was in a topographic depression and was therefore subject to its effects. The value for PAR of

Floyd et al. (1978) may be artificially low since they made measurements at only one location.

Extinction of beam radiation

Fully leafed canopy

The attenuation of shortwave beam radiation (S) by a canopy is reasonably well understood theoretically. This attenuation is primarily a function of Earth-Sun geometry and leaf orientation (see Lemeur and Blad, 1974; and Ross, 1976 and 1981 reviews). Theoretical relationships, however, have rarely been tested with solar radiation data measured in forests.

Several analytical expressions have been derived for the extinction of beam radiation by a canopy (see Anderson, 1966; Ross, 1981). For an erectophile canopy, the beam extinction ($\gamma(S)$) coefficient is expressed as

$$\gamma(S) = 2 \cot \beta / \pi \tag{2}$$

where β is solar elevation angle. Beam extinction for a planophile canopy can be expressed as

$$\gamma(S) = 1 \tag{3}$$

For the more general case, where leaves are inclined at a constant angle, θ, $\gamma(S)$ is expressed as

$$\gamma(S) = \cos \theta, \tag{4a}$$

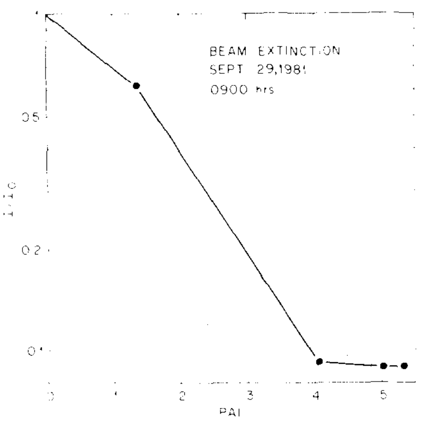
for $\theta \leqslant \beta$; and as:

$$\gamma(S) = \cos \theta \; [1 + (2/\pi)(\tan \phi - \phi)] \tag{4b}$$

for $\theta > \beta$, where

$$\phi = \cos^{-1} (\tan \beta \cot \theta).$$

In order to test which relationship best applies to the forest studied here, beam extinction coefficients from the shortwave beam radiation profile measurements were calculated using the least-squares fit technique described above. However, these data did not fit the exponential relationship (eq. 1) well; r^2 values were generally low ($r^2 < 0.5$) and $\gamma(S)$ was generally not significantly different from zero. A plot of some data from a typical 1-h period confirms that the data do not behave in the expected long-linear manner (Fig. 3). The shape of this curve suggests that leaf inclination angles change with depth in the canopy. Measurements of leaf inclination angle distribution of this canopy substantiate this hypothesis. As shown in Fig. 4, the leaf inclination angle distribution in the subcanopy is extremely planophile (over 50% of the leaves are inclined at an angle $\leqslant 10°$.). At higher canopy levels, leaf inclination angles are more erect, with a mean inclination angle of about 40°. These results are consistent with those of Miller (1967), who also reported that the leaf orientation of an oak forest progresses from



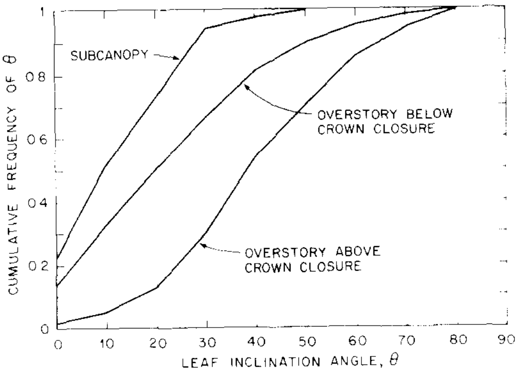


Fig. 3. Typical plot of I/I_0; for shortwave beam radiation (S), against PAI. I/I_0 is plotted on a logarithmic scale.

Fig. 4. Leaf inclination angle frequency distribution for the fully-leafed oak—hickory forest.

planophile in the lower canopy to a more erect orientation in the upper canopy.

In order to quantify beam penetration into the fully-leafed, oak—hickory forest, we computed beam radiation extinction coefficients for two separate layers: firstly, the overstory, between the top of the canopy and 14 m and secondly, the understory, between 14 and 1 m. Figure 5 shows the beam extinction coefficients for understory and overstory canopy layers as a function of time and solar elevation. Each hourly datum is the mean value from 6 days during the fully-leafed period. Theoretical values for canopies with horizontal leaves (eq. 3, $\theta = 0$) and two different, but constant leaf inclination angles (eq. 4; $\theta = 30°$ and $\theta = 60°$) are also presented.

Extinction coefficients for the overstory are low in magnitude ($0.35 \leqslant \gamma(S) \leqslant 0.60$) throughout the day. These experimental extinction coefficients are lower than the theoretical values for $\theta = 60°$. Direct measurements of leaf inclination angle proved that θ is about 40°. Therefore, because a combination of clumping and gaps in the canopy facilitates the penetration of beam radiation into the canopy (see Lemeur and Blad, 1974; Norman and Jarvis, 1975) this seems to account for our observation.

Extinction coefficients for the lower story range between 0.9 and 1.8. During the first part of the day (0800 to 1300 h) these coefficients agree reasonably well with theoretical values for a planophile canopy, whereas later in the day they are unreasonably large. Good agreement between measured and calculated beam extinction coefficients was expected since the lower story canopy is planophile (see Fig. 4). The large afternoon values are probably due to light having to penetrate through a denser portion of the canopy. This reasoning is plausible since an underestimation in f, due to clumping, would cause $\gamma(S)$ to be overestimated.

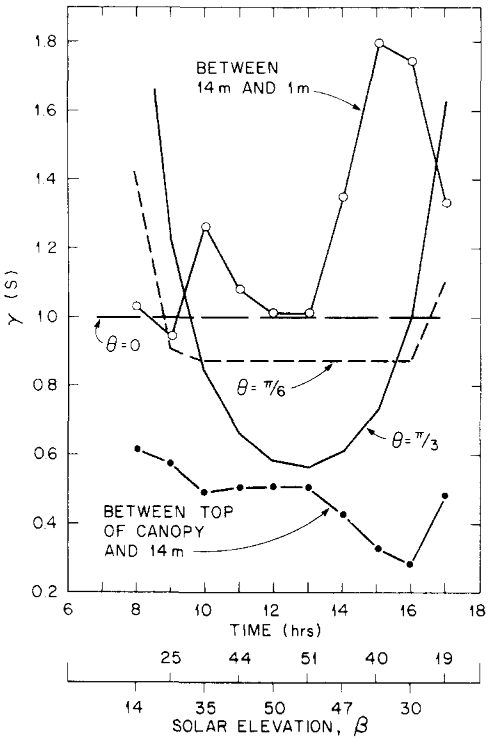


Fig. 5. Diurnal course of the shortwave beam radiation extinction coefficient computed for the layer between 1 and 14 m and between 14 m and the top of the canopy. Theoretical values for constant leaf inclination angles of 0°, 30°, 60° are also given. Each hourly datum is the mean of six days from the fully-leafed period.

Leafless canopy

The beam extinction coefficient was also calculated for the winter leafless forest. Due to the absence of leaves, the profile measurements fit the exponential relationship well, yielding a $\gamma(S)$ value of 1.23 ± 0.27. This beam extinction coefficient corresponds to a 48% attenuation of incoming beam radiation by the leafless oak—hickory forest.

CONCLUSIONS

Profile measurements were made of $K\downarrow$, Q^*, PAR and $Q\downarrow$ within an eastern Tennessee oak-hickory forest during a fully-leafed and leafless period. During the fully-leafed period, the canopy attenuated total radiation components in an exponential manner. Extinction coefficients (b) based on the Beer-Bouguer Law were calculated and showed that

$$\gamma\,(\mathrm{PAR}) > \gamma\,(Q^*) = \gamma\,(K\downarrow) > \gamma\,(Q\downarrow)$$

Extinction coefficients for each radiation component are greater when expressed on a PAI basis than on an LAI basis.

The preferential absorption of PAR by leaves causes PAR to be depleted more rapidly than $K\downarrow$ with depth in the canopy.

Shortwave radiation is not attenuated in an exponential manner because leaf inclination angles progress from planophile in the lower canopy to more erect distributions in the upper canopy. Beam extinction coefficients, computed for two discrete layers compare reasonably well with theoretical values. Gaps in the canopy, and clumping of leaves in the canopy, however, affect the attenuation of beam insolation and account for differences between measured and theoretical values.

During the leafless phenoseason total radiation components are attenuated by the canopy such that

$$\gamma\,(Q^*) > \gamma\,(K\downarrow) \;=\; \gamma\,(\mathrm{PAR}) > \gamma\,(Q\downarrow).$$

The effects of dark, opaque woody biomass and low solar elevation angles cause the extinction coefficients for $K\downarrow$, Q^*, PAR and beam radiation to be greater than when the forest is fully-leafed.

The architecture of a forest canopy is much more complex than that of annual crops. Therefore, further improvement in the understanding of the radiation regime within natural canopies can only be accomplished through detailed measurements of canopy structure, and by incorporating the effects of clumping and vertical variations of leaf orientation into phytoactinometric models.

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