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SEASONAL VARIATIONS IN THE RADIATION REGIME WITHIN AN OAK—HICKORY FOREST*

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ABSTRACT

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Seasonal variations in solar elevation, canopy phenology and leaf pigmentation result in a dynamic variation in the radiation regime within a deciduous forest. Measurements of several insolation components taken within an east Tennessee oak—hickory forest during eight combinations of season and phenological conditions of the canopy are presented. Insolation measurements were made with instruments mounted on a moving tram system at seven levels within, and at one level above the canopy.

The attenuation of solar radiation is least during the leafless phenoseason since only woody biomass is present to intercept and absorb it. Net radiation is attenuated to a greater extent than shortwave and photosynthetically active radiation, which are attenuated to a similar degree, since the sparse woody biomass does not effectively trap the outgoing reflected and radiated radiation. Solar elevation did not influence the attenuation of insolation within the leafless forest under the conditions studied.

The attenuation of insolation within the leafing, spring canopy increases progressively with increasing leaf area. The attenuation among the components, however, varies. Shortwave attenuation progresses at a faster rate with expanding leaf area than photosynthetically active radiation since newly expanded leaves are low in chlorophyll. The penetration of light into the leafing canopy is independent of solar elevations less than 40° and increases linearly with greater solar elevations.

The radiation regime within the fully-leafed canopy is rather static. For daily mean values, no effects of leaf age or seasonal variation in solar elevation are evident. Penetration of light into the canopy, however, increases when solar elevation exceeds 65°.

The attenuation of insolation components diminishes during the autumnal senescence—abscission phenoseason, in response to changes in leaf pigment and loss of foliage. Attenuation of insolation is greater in the autumn than during spring periods with similar leaf area since the sun is lower in the sky in the autumn.

The depletion of photosynthetically active radiation with depth is minimal during the leafless, early leafing and autumnal phenoseasons. Moderate depletion occurs during the late leafing period and maximal depletion occurs during the fully-leafed phenoseason.

INTRODUCTION

Seasonal changes in earth—sun geometry affect solar elevation and azimuth angles and the magnitude of incoming insolation. Notable effects of

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this cycle are seasonal changes in weather and phenological changes of vegetation in temperate and boreal regions. As a result, seasonal variations in the vertical distribution of insolation within vegetated canopies are induced (Anderson, 1964; Hutchison and Matt, 1977a, b).

Forests cover about 36% of the earth's land area, with about 3% of this land area consisting of temperate deciduous hardwoods (Olson et al., 1978). In spite of the ecological importance of this biome relatively few scientists have examined the distribution of insolation within a deciduous forest canopy on a seasonal basis (Anderson, 1964; Rauner, 1976; Hutchison and Matt, 1977a, b). Knowledge of the annual variation in the vertical profile of insolation within vegetated canopies is fundamental in understanding the annual course of mass and energy exchanges such as water vapor, CO_2 and net radiation. For example, phenological alterations in canopy structure and architecture affect insolation profiles, which in turn, influence the partitioning of net radiation into latent, sensible and soil heaf flux (Waggoner et al., 1969; Miller and Stoner, 1979; Baldocchi et al., 1983, 1984a). Changes in vertical distribution of insolation also affect such physiological processes as canopy photosynthesis (Hicks et al., 1969, Uchijima, 1976; Miller and Stoner, 1979; Baldocchi et al., 1984a) and stomatal resistance (Hatfield and Carlson, 1978). Furthermore, resulting changes in the canopy stomatal resistance have feedback effects on CO_2 and water exchange (see Thom, 1975; Jarvis, 1980; Schulze and Hall, 1982) and the deposition of such gaseous pollutants as SO_2 and O_3 (Fowler, 1978; Wesely et al., 1978; Fowler and Unsworth, 1979; Unsworth, 1980). Seasonal studies are, thus, a prerequisite for a better understanding of the annual budget of mass and energy exchanges at the canopy—atmosphere interface.

The paucity of data concerning the seasonality of insolation within forest canopies instigated a program to study such processes. Here we examine the influences of phenology, season and solar elevation on the within-canopy regime of several solar radiation components. The seasonal variation of light quality within the canopy is also examined.

MATERIALS AND METHODS

This study was performed at a site on a ridge 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"N, long. 84°17'15" W, alt. 365 m above mean sea level), located near Oak Ridge, Tennessee. 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 is about 21.5 m, but the uneven-age structure and mixed species composition of the forest causes heights to range between 17 and 26 m. During the fully-leafed season, the leaf area index (LAI), bark area index (BAI) and the plant area index (PAI) are 4.9, 0.6 and 5.5, respectively. The mean basal area of the canopy is about 26 $m^2 ha^{-1}$.

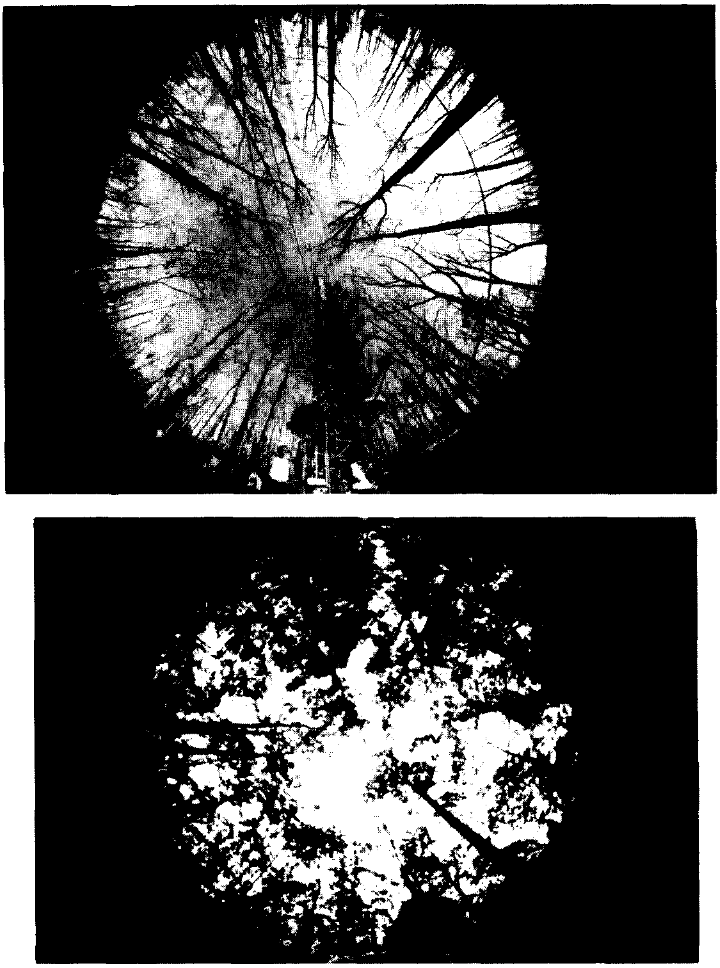


Fig. 1. Hemispherical photographs of the oak—hickory forest in: the leafless stage (above); and the fully-leafed stage (below).

Hemispherical photographs of the canopy in the leafless and fully-leafed stages are presented in Fig. 1. A complete description of the species and canopy architecture at this forest site is presented by Hutchison et al. (1984).

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 are 35 m apart and support cable pairs at eight levels. The cable pairs were strung parallel to the ground and are oriented 72° east. The trams traversed through the canopy on cable pairs at 1, 6, 10.5, 14, 17, 21, 26 and 33 m above the forest floor.

Instrumented trams, on the lowest seven levels, automatically traversed the middle 30 m between the triangular towers on the cable pairs at a speed of about 0.6 m min^{-1}. The tram at the eighth level (33 m) remained stationary

TABLE I

Tram instrumentation

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

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

above the forest at a location midway between the two triangular towers. The trams and the contained radiometry were leveled so that the sensing surfaces were within ± 1° of horizontal.

Each tram was instrumented with six radiometers providing measurements of net (R_n), and incoming and outgoing flux densities of global shortwave (R_g), photosynthetically active (PAR) and allwave radiation (Table I). Diffuse shortwave radiation was measured at each level by pyranometers equipped with shadowbands. These instruments were mounted on booms on the two triangular towers. Diffuse measurements were only made during January and September 1981.

Sensor signals were sampled and recorded with a computer-controlled data acquisition system. EMF signals were digitized and stored on magnetic tape at a rate of three times per minute. EMF signals were later converted to scientific units and averaged for 1-h periods on a mainframe computer.

Studies were conducted in January 1981, February, April, May and June 1980, September 1981 and November 1979, thus, representing eight combinations of phenological periods and seasons, or phenoseasons.

The mean insolation values presented here do not completely describe the radiation environment within a forest since the frequency distribution of insolation inside a canopy is not always Gaussian; several workers have reported that sunflecks cause the frequency distribution inside a fully-leafed forest to be bimodal (Lemeur, 1973; Lemeur and Blad, 1974; Hutchison and

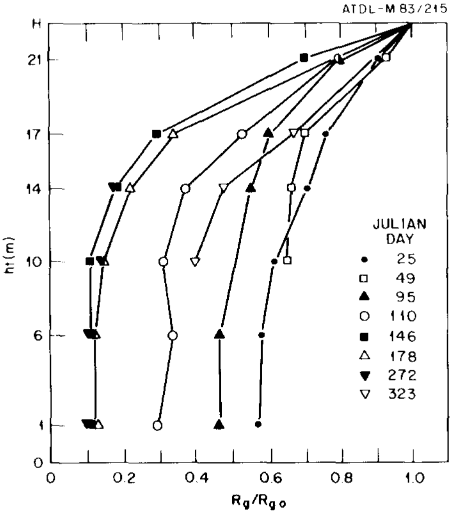
Matt, 1977a; Sinclair and Knoerr, 1982) and we have unpublished data showing that the frequency distribution is skewed during the leafing season and is approximately Gaussian during the leafless phenoseason. Consideration of the frequency distribution of insolation is particularly critical when using insolation values to model such non-linear processes as photosynthesis and stomatal resistance. For example, to account for the bimodal distribution in a fully-leafed forest the beam and diffuse components of insolation must be used separately to model photosynthesis and stomatal resistance correctly (Norman, 1980).

Due to instrumentation constraints, it was not possible to measure the direct and diffuse components of all wavebands during each phenoseason. We do, however, believe that our presentation of mean insolation flux densities is valuable, since these data can be used to describe the seasonal dynamics of the radiation regime within a forest and they can be used in models that simulate processes which are linearly dependent on insolation, e.g., transpiration (Monteith, 1973; Thom, 1975). A paper describing the statistics associated with actinometric measurements made within a forest is in preparation.

RESULTS AND DISCUSSION

Seasonal variation in daily mean insolation profiles

Figures 2—4 show daily mean profiles of R_g, PAR and net radiation (R_n), respectively, for relatively clear days during different phenoseasons. Periods



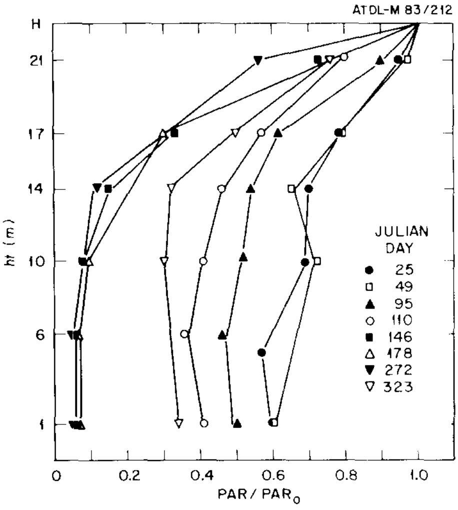


Fig. 2. Seasonal variation in the vertical distribution of shortwave radiation (R_g) normalized by R_{g0}, the incident shortwave radiation at the top of the canopy.

Fig. 3. Same as Fig. 2 except for photosynthetically active radiation (PAR).

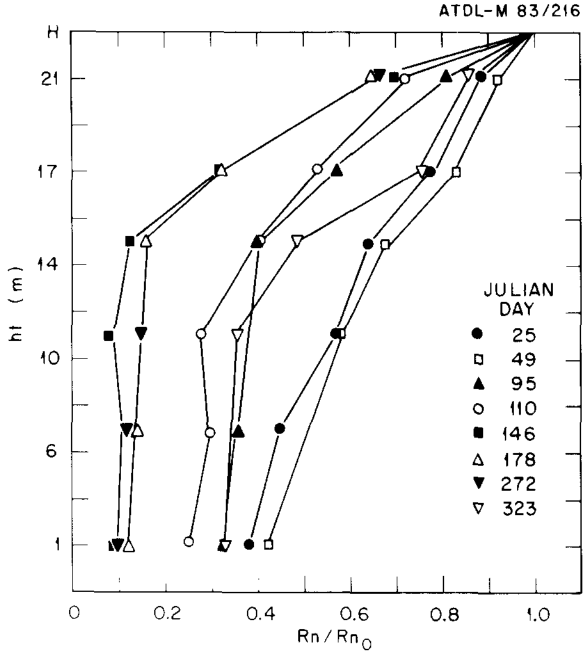


Fig. 4. Same as Fig. 2 except for net radiation (R_n).

represented in these figures include two days from the winter leafless (D25 and D49) and spring leafing phenoseasons (D95 and D110), and a day from the late, spring, fully-leafed phenoseason (D146), the summer, fully-leafed phenoseason (D178), the early, autumn, fully-leafed phenoseason (D272) and the autumn, senescent—abscission (D323) phenoseason.

During all phenoseasons the magnitude of PAR, R_g and R_n decreases with depth in an approximately exponential manner throughout most of the canopy. This exponential decrease of insolation, throughout the year, is expected because a relatively random distribution of phytoelements, which can be assumed here as a first approximation, results in the probability of interception of sunlight being described by a Poisson distribution (Lemeur and Blad, 1974).

Another feature of Figs. 2—4 is that the degree of attenuation varies with time. Attenuation of solar radiation is least during the leafless periods, since sunlight is only attenuated by relatively sparse woody biomass. During the leafless phenoseason PAR and R_g are attenuated similarly (by about 40%) since no leaves are present to preferentially absorb PAR. The attenuation of these insolation components agree reasonably well with similar measurements in deciduous stands (Federer, 1971; Rauner, 1976).

The results presented above are not representative of all mid-latitude, leafless, deciduous forests. For example, Hutchison and Matt (1977a) reported that the mean daily attenuation of R_g by a *Liriodendron tulipifera* forest is of the order of 75—90%. Greater attenuation is observed in the

L. tulipifera canopy because it has a greater biomass density than the oak—hickory forest studied here. Also, the *L. tulipifera* stand is growing in a Karst-type topographic depression; the radiation environment, therefore, may be affected by local topography. At the other extreme, Floyd et al. (1978) reported that a leafless, mid-latitude, mixed-oak forest attenuates only 9% of incoming PAR. This value may be artificially low since measurements were made at only one location.

Figure 5a shows that net radiation is attenuated to a greater degree than R_g during the leafless phenoseason. Rauner (1976) observed a similar relationship, yet did not propose an explanation for the observation. A mechanism is postulated below.

The net radiation flux density at a given level is due to differences between the incoming (↓) and outgoing (↑) flux densities of shortwave (R_g) and longwave (L) radiation

$$R_n = R_g\downarrow - R_g\uparrow + L\downarrow - L\uparrow \tag{1}$$

Net and incoming shortwave radiation are, therefore, attenuated similarly if the incoming flux density of longwave is balanced by the outgoing flux densities of short- and longwave radiation ($L\downarrow = R_g\uparrow + L\uparrow$).

The differential attenuation observed between R_g and R_n can be explained with the aid of Fig. 5b, a presentation of the vertical profiles of R_n, $R_g\downarrow$, $R_g\uparrow$, $L\downarrow$ and $L\uparrow$, for a typical period during the leafless phenoseason. As can be seen in this figure, the sum of the outgoing flux densities of short- and longwave radiation exceed that of incoming longwave radiation, thus accounting for the greater attenuation of R_n in the leafless forest. The mechanism for this observation stems from the fact that the low biomass density of a leafless forest does not provide an effective means for trapping reflected and radiated energy; conversely, in a fully-leafed forest R_g and R_n are attenuated similarly (Baldocchi et al., 1984b) since the presence

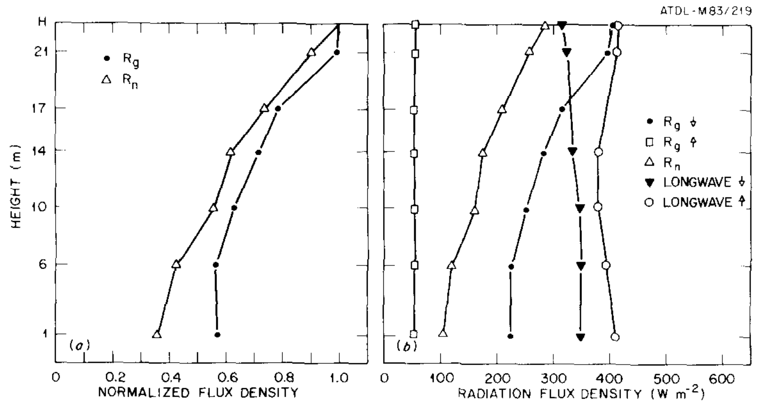


Fig. 5. (a) Normalized flux densities of shortwave (R_g) and net radiation for a typical period during the leafless phenoseason (day 25, 1200 h). (b) Flux densities of incoming and outgoing shortwave and allwave radiation and net radiation for a typical period during the leafless phenoseason (day 25, 1200 h).

of leaves causes the incoming and outgoing fluxes of longwave radiation to be in relative equilibrium and the magnitude of reflected shortwave radiation to be relatively small.

Anderson (1964), Federer (1971) and Hutchison and Matt (1977a, b) reported that solar elevation (β) also influences the mean attenuation of insolation during the leafless period, causing attenuation to be greater during the winter than in spring. This is because, near the winter solstice, low solar elevations cause insolation to pass through long attenuating paths consisting of biomass with a relatively high optical density (i.e., the trunk space). On the other hand, near the spring equinox, higher solar elevations result in shorter attenuating paths through portions of the canopy with lower optical densities (i.e., the crown space). We, on the other hand, observed little variation in the mean normalized profiles of PAR, R_g and R_n between days 25 and 49. This result is mainly due to the small change in the maximum β value between these two days; the difference is about 7°. Such a small change in the maximum solar elevation does not seem to have an appreciable effect on the penetration of solar radiation into a leafless forest. This point is substantiated theoretically using the model of Federer (1971) to compute daily mean values of beam radiation penetration for the solar elevation angles observed on days 25 and 49. Federer (1971) defined beam penetration into a leafless deciduous forest as

$$p = \exp\left[-P_c \csc(\beta) + P_s \cot(\beta)\right] \tag{2}$$

where P_c is the crown parameter and P_s is the stem parameter. For this forest P_c and P_s are 0.25 and 0.14, respectively. Computations show that there is little change in p between days 25 and 49 (mean daily penetration changed from 0.63 to 0.69, a 9% change). The above argument, although based on beam radiation, applies for total radiation since the penetration of diffuse radiation, on a daily basis, can be assumed to be independent of solar elevation (see Hutchison et al., 1980). Any differences in the within-canopy radiation regime during the leafless period should, therefore, be due to differences in beam penetration.

The attenuation of insolation during the spring leafing period (e.g., days 95 and 110) increases progressively with time. This is in response to canopy leaf expansion and is in spite of the increasing solar path. Unfortunately, we are not able to quantify the change in radiation attenuation as a function of increasing LAI during this period since it is logistically impossible to obtain direct destructive measurements of LAI during the brief leaf expansion period. Furthermore, it is also not possible to determine LAI via remote sensing techniques since the insolation attenuation coefficient of an oak—hickory forest changes as the forest transforms from a leafless to a fully-leafed state (Baldocchi et al., 1984b). Data from the spring period do, however, describe the dynamic interaction between leaf expansion and radiation attenuation. For example, in the 15-day period (D95 to D110) the attenuation of PAR, R_g and R_n increases by 18, 30 and 12% respectively.

PAR attenuation increases at a slower rate than R_g during leaf expansion since newly expanded leaves are low in chlorophyll content (Sanger, 1971). This result in PAR reflectance being higher and near IR (NIR) reflectance being lower than that of a mature leaf (Gates et al., 1965), thus accounting for our observation.

After full leaf-cover is attained, the mean solar radiation environment within the canopy remains relatively static; as shown in Figs. 2—4, the mean normalized insolation profiles between late spring and early autumn are nearly identical. No effects of leaf age or change in solar elevation are evident.

During the fully-leafed phenoseason, PAR is attenuated to a greater extent than either R_g or R_n, which are attenuated to a similar degree. Greater PAR attenuation results from leaves preferentially absorbing PAR over NIR (Gates et al., 1965). R_g and R_n are attenuated similarly since the presence of leaves causes the incoming flux density of longwave radiation to be in relative balance with the sum of the outgoing short- and longwave fluxes. Further quantification of the attenuation of insolation components within the fully-leafed oak—hickory forest is presented by Baldocchi et al. (1984b). The attenuation of radiation is similar to values reported by Horn (1971), Rauner (1976) and Floyd et al. (1978), for fully-leafed oak forests.

The commencement of autumnal leaf senescence and abscission results in decreasing attenuation of PAR, R_g and R_n. By day 323, these components are attenuated by only about 65%. The attenuation of insolation is greater in the autumn than during periods in the spring with similar leaf area since autumnal solar path is lower in the sky and because leaf pigmentation is different during these periods; leaf senescence causes chlorophyll to be destroyed much more rapidly than the other pigments, such as the carotenoids (Sanger, 1971).

Influence of phenoseason and solar elevation on PAR penetration

The interactive effect of phenology, leaf area and solar elevation on the radiation regime within the canopy can be studied in greater detail by examining the diurnal variation in the penetration of an insolation component, such as PAR, on a seasonal basis. PAR penetration, defined as the ratio of incoming PAR below to that above the canopy is plotted as a function of β in Fig. 6 to illustrate these interactive effects.

During the leafless phenoseason the penetration of PAR is independent of the diurnal variation in β (Fig. 6a). These results are in accord with computations of total radiation penetration using the model of Federer (1971). Penetration (P) is defined as

$$P = pF + (1 - F)p_d \tag{3}$$

where F is the beam fraction, p is the beam penetration, given in eq. 2 and p_d is the penetration of diffuse radiation, given by

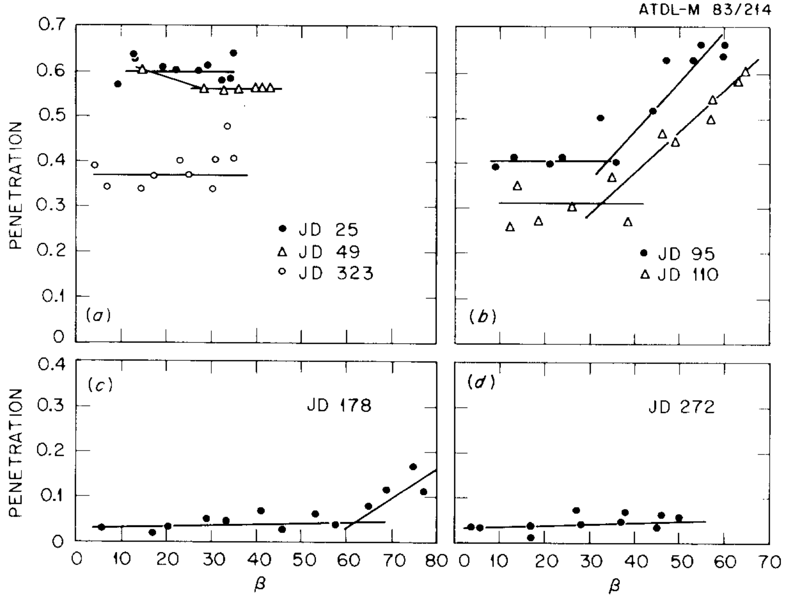


Fig. 6. Penetration of PAR, defined as the ratio of PAR below the canopy to that above the canopy, against solar elevation (B) for: (a) days 25 and 49, the leafless period, and day 323 the autumnal period; (b) days 95 and 110, the spring leafing period; (c) day 178, the fully-leafed summer period; and (d) day 272, the fully-leafed early autumn period.

TABLE II

Values of insolation penetration into a leafless, oak—hickory forest computed with the model of Federer (1971) for data obtained on day 25

β	P	F
9	0.51	0.68
19	0.61	0.38
27	0.65	0.65
33	0.69	0.60
34	0.65	0.44
35	0.69	0.57

$$p_\mathrm{d} = 2\int_0^{\pi/2} \exp\left[-P_\mathrm{c}\csc(\beta) + P_\mathrm{s}\cot(\beta)\right]\cos(\beta)\sin(\beta)\,\mathrm{d}\beta \qquad (4)$$

Table II presents values of P, F and β for conditions encountered on day 25. Little variation in P is predicted for β between 19 and 35°. This is because there was a substantial amount of diffuse radiation then (between 35 and 62% of total insolation) which is enough to mask the effects of solar elevation on beam penetration.

The penetration of light into the canopy during the spring leafing phenoseason is more complex (Fig. 6b). Penetration of PAR is constant for $\beta < 40^\circ$ but increases linearly with $\beta > 40^\circ$. Furthermore, the curve is displaced downward in a relatively parallel fashion as the LAI of the canopy increases. The constant penetration at $\beta < 40^\circ$ results from sunlight passing through a relatively long and dense attenuating path, due to both trunks and crowns. Conversely, at higher solar elevations attenuation by the trunk space decreases, causing the attenuating path to be optically less dense and shorter. The expanding foliage attenuates incoming insolation to some degree since the threshold penetration value (at $\beta = 40^\circ$) is less than during the leafless phenoseason.

The penetration of PAR into the fully-leafed canopy is constant at $\beta < 65^\circ$ and increases linearly with greater elevation angles (Fig. 6c, d). The threshold penetration value at $\beta = 40^\circ$ is not evident during this phenoseason since the denser foliage now obscures the solar disk at higher elevation angles, thus preventing an enhancement of beam penetration with solar elevation. It is only near the zenith that canopy gaps are sufficient to augment the penetration of light.

During the autumn, the penetration of PAR is relatively constant since β is less than 40° throughout the day (Fig. 6a). The diurnal pattern in PAR penetration during the autumn period also supports our earlier contention that there is less penetration into the autumn canopy than there is into a spring canopy with a similar leaf area. This is because low autumnal solar

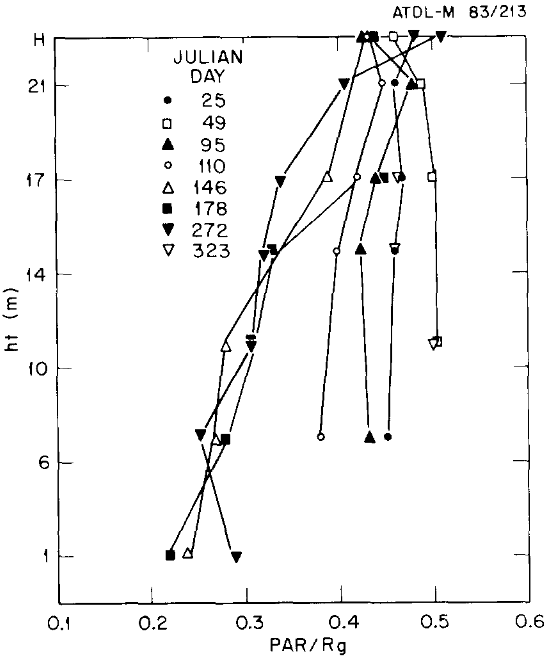


Fig. 7. Seasonal variation in the profile of the PAR/R_g ratio.

elevation angles prevent deep penetration of light into the canopy, as is observed in the spring (Fig. 6b).

Seasonal variation in the quality of light inside the canopy

Global radiation consists of PAR and NIR. Leaves, however, preferentially absorb PAR. As a result, the spectral quality of light should change with depth and phenoseason. This effect is investigated by examining the daily mean vertical distribution of the ratio, PAR/R_g, during the different phenoseasons (Fig. 7). Above the canopy, the ratio PAR/R_g ranges between 0.43 and 0.50. These values fall within the range of values reported by Szeicz (1974), Stanhill and Fuchs (1974) and Ross (1981). Scatter within these limits is a result of PAR/R_g being a function of the proportion of direct and diffuse insolation and of solar elevation (Ross, 1981). During the leafless, late senescing and early leafing periods, PAR/R_g is relatively constant with depth and is not significantly different from the value above the canopy. The reasons for this constancy vary with the phenological state of the canopy. For example, during the leafless phenoseason only woody biomass, which is not known to preferentially absorb PAR, is present. Leaves are present on day 95, but Sanger (1971) reported that chlorophyll content is low in newly expanded oak leaves. Thus, preferential absorption of PAR is minimal on this day. In the autumn, chlorophyll is destroyed much more rapidly than carotenoids (Sanger, 1971). Therefore, even though leaves may be present, differential depletion of PAR with depth into the canopy is not evident. Intermediate depletion of PAR is observed on day 110 since further leaf expansion and development cause a rapid increase in chlorophyll content (Sanger, 1971). Maximum depletion of PAR occurs after the foliage is fully expanded. The ratio, PAR/R_g, decreases with depth to minimum value between 0.22 and 0.29 near the forest floor. This depletion of PAR should be accounted for when measurements of only shortwave radiation are made and are used to drive photosynthetic models.

SUMMARY AND CONCLUSIONS

Seasonal variations in the radiation regime within a mid-latitude, oak–hickory forest have been illustrated. These variations are due to a combination of changes in the solar path, leaf area index and pigmentation of the foliage.

Attenuation is least during the leafless phenoseason since only woody biomass is present to intercept incoming insolation. R_g and PAR are attenuated in a similar manner since no leaves are present to preferentially absorb PAR. R_n, on the other hand, is attenuated to a greater extent because outgoing short- and longwave components are attenuated to a lesser degree than the incoming longwave component. The attenuation of total insolation components is independent of solar elevation during the leafless periods studied since the beam fraction was of the order of 40—70% of incoming radiation and because the solar disk is low in the sky then.

The attenuation of insolation by the leafing canopy is very dynamic. R_g attenuation progresses at a faster rate then PAR since newly expanded leaves are low in chlorophyll; this causes PAR reflectance to be higher and NIR reflectance to be lower than that of a mature leaf. Penetration of insolation is independent of solar elevations less than 40° and increases linearly with greater solar elevations.

The radiation regime is rather static during the fully-leafed phenoseason. No effects of leaf age or seasonal variation in solar elevation are evident. Penetration of insolation into the canopy is independent of $\beta < 65°$ and increases with greater β values.

Attenuation of PAR, R_g and R_n decreases during the autumn senescence-abscission period. Attenuation of insolation components is greater in the autumn than during a spring period with similar leaf area since the sun is lower in the sky during the autumn.

The spectral quality of light within the canopy during the leafless, early leafing and senescent—abscission periods is the same as that above the canopy. Moderate depletion of PAR occurs during the late leafing phenoseason. Maximum depletion of PAR occurs during the fully-leafed phenoseason, with the ratio PAR/R_g, below the canopy, ranging between 0.22 and 0.29.

In view of the findings presented here, seasonal studies of other energy and mass exchanges are encouraged, for concepts developed from studies undertaken during short periods are not always representative of processes occurring during other times.

ACKNOWLEDGEMENTS

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