INTERNAL REPORT 60

RADIATION BUDGET OF THE FOREST--A REVIEW[1,2]

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FOR REVIEW ONLY

NOT FOR PUBLICATION

[1]The work described here was supported by funds provided by the U.S. Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Research Act of 1964, and administered by the Water Resources Research Institute, Oregon State University, and in cooperation with the Coniferous Forest Biome, Ecosystem Analysis Studies, U.S./International Biological Program. This is Paper 882, Forest Research Laboratory, Oregon State University.

[2]Based upon a paper presented to the Third Eastern Forest Meteorology Conference, State University of New York, College of Forestry, Syracuse, 13-14 September, 1971.

Keywords: Radiation, Forest Radiation

ABSTRACT

This review concentrates on 160 recent publications dealing with various aspects of radiation exchange in forest vegetation. The articles are discussed with respect to the following categories: definitions, instrumentation, the modification of radiation by vegetation, and radiation budgets. The papers reviewed have appeared for the most part during the period 1966-1971. The studies published during this period indicate continued interest in the role of radiation in energy budgets and in ecology. The quantity, quality, and direction of this recent research are encouraging, and offer promise for continued progress in our understanding of an important and complex environmental variable.

INTRODUCTION

The first quantitative attempt to measure light in the forest appears to date from 1857 (Hartig 1877). This simple photographic technique has been elaborated upon by many workers during the past century. Evaluations of the early attempts to measure radiation include the reviews of Shirley (1935, 1945), Miller (1955), Terrien et al. (1957), and Sauberer and Härtel (1959). An unusually thorough series of reviews appeared during the first half of the past decade (Tranquillini 1960, Anderson 1964, Dirmhirn 1964, Gates 1965, Miller 1965, Monteith 1965, Reifsnyder and Lull 1965, Gay 1966, and Geiger 1966).

As careful attention already has been given to the early studies, this review focuses on the many radiation publications that have appeared in the 6-year period 1966-1971. The studies published during this period indicate continued interest in the role of radiation in ecology and in heat-budget studies. Also, improvements have been made in sensors, recorders, and measurement techniques. A few older papers that were overlooked in earlier reviews have been included. A survey of work now available will prove useful to those researchers interested in the problem of radiation exchange in the forest.

No unique scheme of classification seems to exist for these recent papers, as they have resulted from a variety of experimental objectives; however, they can be grouped roughly with some overlap, into the following categories: definitions, instrumentation, modification of radiation by vegetation, and radiation budgets. This review considers primarily papers available in English, or those originating in Western Europe.

DEFINITIONS

General agreement is evident on terminology in radiation research, although the adoption of standard symbols appears long overdue. This section also considers recent papers that appear helpful in characterizing the climatological aspects of the radiation fluxes over natural surfaces.

Terminology

The following basic symbology is extracted from that proposed by the World Meteorological Organization (1971, ch. IX):

Instrument	Flux	Wavelength	Symbols		
			Down	*Up*	*Net*
pyrradiometer	allwave	0.2 - 100μm	Q↓	Q↑	Q*
pyranometer	global	0.2 - 4μm	K↓	K↑	K*
pyrgeometer	longwave	4.0 - 100μm	L↓	L↑	L*

The source should be consulted for details. The proposed scheme appears worthy of adoption, as its use would minimize present difficulties in the interpretation of radiation symbols.

Radiation Climatology

Definitive texts include Perrin de Brichambaut's (1963) and Robinson's (1966) works on solar radiation and Kondrat'yev's (1965) comprehensive treatment of radiation exchange in the atmosphere. Particularly useful, general papers are those of Brooks (1964), Blackwell (1966), and Collingbourne (1966).

The spectral distribution of global radiation has been measured by Gates (1966), Robertson (1966), Bonhomme et al. (1967), and Bonhomme (1969). Szeicz (1966) reported that visible (0.2-0.7 μm) radiation was a relatively constant fraction, 0.40 ± 0.03, of the incident daily total of global radiation. Paltridge (1970) found photosynthetically active radiation to be a constant 0.39 of the global radiation on clear days; he reported more variation under cloudy skies. Ultraviolet radiation in alpine environments is considered by Caldwell (1968).

The relation between insolation and slopes has been considered further by Frank and Lee (1966) and Garnier and Ohmura (1968). Lee and Baumgartner (1966) and Turner (1966) evaluate the insolation of slopes in the field. Furnival et al. (1970) describe their method for calculating global radiation on a horizontal surface in the absence of an atmosphere. Jeník and Rejmánek (1969) define radiation that would be received in the absence of an atmosphere as "potential direct solar irradiation" and discuss its effects in ecology.

Thermal radiation from the atmosphere is evaluated by Idso and Jackson (1969). Measurements of net and longwave radiation for the period 1962-1964 at Copenhagen are reported by Jensen and Aslyng (1967). Linacre (1967) proposed several methods for estimating net radiation from measurements of other climatic parameters.

INSTRUMENTATION

Standard Measurements

Standard pyranometers and pyrradiometers have become well accepted for measuring the radiation-exchange components. Robinson (1966, ch. 7) reviews these thoroughly, and Federer (1967) surveys proposed new instruments. Latimer (1971) has prepared an excellent field manual for radiation-measurement programs.

A small thermoelectric pyranometer was constructed by Bringman and Rodskjer (1968). Byrne et al. (1969) describe a resistive-element pyranometer for global radiation measurements, but Kerr et al. (1967) have developed a cosine-corrected silicon photocell sensor, with signal integrator, for global radiation measurements. Paltridge (1969) described a radiometer that measures the net exchange of longwave radiation beneath a filter of black polyethylene.

The errors in standard radiometers have continued to receive attention. Marsh (1970) describes use of the Abbot pyranometer as a calibration standard. Collins (1966) has evaluated cosine errors in pyranometers, and Collins and Walton (1967) describe resistance compensation circuits to minimize the temperature coefficient of thermopile pyranometers. Hart and Rosenberg (1967) constructed a shield to minimize errors in measuring albedo with inverted pyranometers. McCulloch and Wangati (1967) have described their calibration experiences with the Bellani-type spherical pyranometer.

The spectral transmissivity of polyethylene was measured by Collins and Kyle (1966). Idso (1970) concluded that addition of white paint to polyethylene-shielded pyrradiometers was unnecessary. Calibration techniques for net pyrradiometers were described by Bazashkova et al. (1968) and by Paulsen (1967). A new method was proposed by Idso (1971) for the longwave calibration of pyrradiometers.

Anderson (1967) evaluated the effective heat-transfer coefficients in three pyranometer designs and discussed requirements for linearity and sensitivity. The temperature dependence of plated thermopiles was analyzed by Höhne (1961), and the caustic formed by light passing through a glass hemisphere was discussed by Wörner (1953).

Reifsnyder (1967a) has considered view factors in the field placement of radiometers. The calibration techniques and care in reduction of field data described by Morgan et al. (1970) are especially noteworthy.

Nonstandard measurements

Measurements of diffuse global radiation are facilitated with Sumner's (1968) motor-driven occulting disk. Brechtel (1968) has tested an inexpensive allwave radiometer based upon the temperature-dependent chemical reactions of a sucrose solution. Stoutjesdijk (1966) constructed a simple radiation thermometer, and Scoyoc (1969) discussed emissivity and transmissivity errors in radiation thermometry.

The development of sensors to measure photosynthetically active radiation has progressed. Federer and Tanner (1966b) define the errors for several photocell and filter combinations. They conclude that a selenium photocell with Wratten 85C filter closely approximates the photon response of photosynthesis. McPherson (1969) and Biggs et al. (1971) describe other photocell-filter combinations. Paltridge (1970) has developed a unique filter made from chlorophyll extracts. McCree (1966) has used a simple filter to adapt a standard pyranometer for measuring visible radiation. McCree (1968) also discusses the use of photographic film for spectral radiation measurements.

Czopek (1971) reviews methods for measuring photosynthetically active radiation. A handbook by Hallaire et al. (1970) contains several chapters devoted to the design of instruments to measure solar, net, and spectral radiation above and within plant canopies.

Dirmhirn (1968) points out difficulties in using photocells to measure radiation that has been "filtered" by vegetation. Wiens (1967) and Getz (1968) report on simple photocell measuring-systems. The cosine response of photocells can be improved by a hemispherical diffuser (Byrne 1966) and by a more elaborate, geometric diffusing disk (Kerr et al. 1967).

Recording photometers have been designed by Brach and Mack (1967) and Berry and Raney (1968). Integrating photometers were described by Setlik (1968) and Brach et al. (1970).

Bolsenga (1968) has developed a photocell-filter combination weighted to the response of the human eye for use in studies of visual albedo.

MODIFICATION OF RADIATION BY VEGETATION

Plant canopies differentially absorb and transform radiation. This process is considered here in relation to the optical properties of individual leaves and of canopies, to observed variations of radiation intensity within the canopy, and to experimental design.

Optical Properties of Vegetation

Work defining the spectral reflection and transmission of leaves and needles is reviewed by Dirmhirn (1964) and Gay (1966). The relative curves for these properties appear well worked out, and the integrated absorptivity in full sunlight is about 0.50. Recent work has concentrated on the role of the canopy in the modification of radiation.

Bray et al. (1966) document the low visible reflectivity of vegetated surfaces. Values at 60°-65° solar altitude were 2.2 percent for forest, 5.3 percent for short grass, and 12 percent for sand. Federer (1968) looked at spatial variation of albedo, net radiation, and surface temperature, and concluded that one or two sample sites per cover type would be sufficient. The reflectivity of a red pine stand rose from 10 percent to about 20 percent after a heavy snowfall (Leonard and Eschner 1968a). Federer (1969) has considered albedo from leafless hardwood forests during the winter and spring. The global radiation absorption of a leafless oak forest was studied by Grulois and Schnock (1967). Grulois (1968a) has given further consideration to the annual variation in global reflection from this oak forest. Relative transmission through crop canopies was considerably higher on cloudy days than on clear days (Kornher and Rodskjer 1967).

Reflection coefficients characteristically show higher values with large solar zenith angle; Brown et al. (1970) report that the dependence on zenith angle disappears when the inverted pyranometers are appropriately shielded. Stanhill et al. (1971) found that errors in reflectivity might reach 20 percent for solar elevations of 60° and 30 percent for elevations of 10°. Stewart (1971) found a pronounced dependence of solar reflectivity from a pine forest upon the elevation of the sun.

Infrared thermometry of vegetation was refined by Fuchs and Tanner (1966) and Lorenz (1966) as they showed the importance of reflectivity. Idso et al. (1969) substantiated earlier reports of the relatively high emissivity of leaf elements. Lorenz (1970) showed that the surface temperatures of plant canopies could be approximated by infrared thermometers positioned at oblique viewing angles, though Fuchs et al. (1967) reported little effect of viewing angle on crop canopy temperatures. The infrared temperature measurements of Lorenz and Baumgartner (1970) in a spruce forest revealed that the canopy remained close to air temperature throughout the day.

The spectral absorptivity of canopies was documented further by Federer and Tanner (1966a), Vezina and Boulter (1966), Freyman (1968), and Atzet and Waring (1970). Coniferous canopies appeared to be rather neutral in absorptivity, but deciduous canopies absorbed selectively in the blue and red regions of the spectrum.

Variation of Radiation Within the Canopy

The complex problem of defining the radiation field within canopies has attracted the attention of physiologists working with photosynthetic processes. A great deal of theoretical work has been reported in the past few years. Publication of the British Ecological Society Symposium on Light (Bainbridge et al. 1966) is noteworthy. Also, attention should be directed to the fundamental studies of radiation and vegetation by an interdisciplinary team in the Academy of Sciences of the Estonian S.S.R. (Bell and Chmora 1962) under the direction of J. Ross. A recent bibliography (Estonian Institute of Physics and Astronomy 1969) contains 78 titles relating to radiation and vegetation, although, unfortunately, much of this material is unavailable to western scientists. An example, however, is a review of radiation in plant canopies by Niilisk et al. (1970). Another translation from an IBP symposium (Nichiporovich 1967) contains many interesting papers on Russian work in radiation and canopy structure within crops.

The works noted below have been divided into two broad groups. The first group is concerned with the development and testing of general models for plant canopies; the second is concerned with continued measurement and definition of the forest radiation climate.

The basic models consider the role of canopy elements in absorbing, reflecting, and scattering radiation. Initial considerations are given to this problem by Anderson (1966a, 1966b), Chartier (1966), Evans (1966), and Verhagen and Wilson (1969). Cowan (1968) considers canopies with various leaf orientations and different wavebands of radiation. The incidence of global radiation on inclined surfaces within ideal canopies is treated by Anderson and Denmead (1969). Anderson (1969) compares two scattering theories in crop canopies and discusses (1970) the relative distribution of direct and diffuse global radiation on the forest floor. Nilson (1970) introduces a model to account for "clumping" of the canopy elements.

Impens and Lemeur (1969a) reported that net radiation extinction with depth into a canopy was related to leaf area by a more complex exponential form than the simple Beer's law often assumed. Grulois (1967) found global radiation decreased with oak leaf area in close agreement with Beer's law. Rodskjer and Kornher (1971) also found Beer's law useful in predicting the transmission of visible and near infrared radiation in crops. Reifsnyder et al. (1971) concluded that Beer's law applied to the direct-beam solar radiation penetrating a pine canopy. A constant-ratio law appeared more appropriate to a hardwood canopy, however.

Based on shadow-stick readings, Miller (1969a) concluded that the negative exponential model overestimated the percentage of full sun penetrating aspen and oak canopies. He also noted (Miller 1967, 1969b) that global radiation in gaps near the top of aspen canopies could exceed that incident upon the canopy by as much as 7 percent because of scattering by leaves.

The leaf-area index of tropical stands was predicted successfully by the ratio of light intensity at 800 nm to that of 675 nm on the forest floor (Jordan 1969).

The continued definition of forest radiation climate emphasizes measurements. Global radiation measurements were reported beneath a forest (Schomaker 1968) and in a clearing (Clements 1966). Global and allwave measurements with simple sensors were tabulated by Lull and Reigner (1967) and by Perttu (1970). Mukammal (1971) reported on measurements of the radiation-exchange components within the crowns of a pine forest, and Muller (1971) related pine canopy transmission to biomass.

A thorough study of light measured with selenium photocells in stands of spruce, Douglas-fir, and pine was reported by Mitscherlich et al. (1967). Grulois and Vyncke (1969) and Vyncke (1969) described the light climate of an oak forest. Perry et al. (1969) used chlorophyll light meters to relate the transmission of photosynthetically active radiation to basal area in pine stands. Roussel (1970) applied his prior work on light measurements to problems in silviculture.

Reifsnyder and Furnival (1970) analyzed the energy available in sunflecks in two different stands.

Methods for collecting radiation data included fixed instruments and use of mobile sensors. Impens et al. (1970), Gay et al. (1971), and Reifsnyder et al. (1971) described statistical analyses of data collected by networks of radiometers within canopies. Deviations seem to be reduced more rapidly by averaging radiometers in space than by averaging observations in time. More radiometers appear needed for sampling beneath coniferous canopies than for hardwood canopies. The use of moving sensors above a forest canopy was described by Leonard and Herrington (1966) and Leonard and Eschner (1968b). The use and interpretation of a moving pyranometer beneath a canopy was discussed by Rodskjer and Kornher (1966). Hutchison (1971) described his use of fixed and moving sensors in an attempt to define the solar-radiation climate of a deciduous forest.

CANOPY RADIATION BUDGETS

Despite the interest in photosynthesis, dry-matter production in forests utilizes only one percent or less of the incident visible energy (Leak 1970). Radiation budgets therefore have been concerned primarily with heat-budget analyses. Reifsnyder (1967b) pointed out the dearth of complete-radiation-budget studies and presented his own measurements above and below a pine canopy. Rauner and Rudnev (1968) also analyzed shortwave and allwave radiation measurements above and below coniferous and deciduous canopies. Galoux and Grulois (1968) reported radiation-budget measurements above an oak forest for one clear and one cloudy spring day. As discussed by Baumgartner (1967), higher values of net radiation reported over forests can be attributed to the low albedos of forests.

The annual global radiation budget of an oak forest (Grulois 1968b) revealed that the summer reflection was 16.6 percent, the leaf absorption was 31.1 percent, and cortical absorption was 44.4 percent. During winter, reflection was 12.2 percent and cortical absorption was 52 percent. Federer (1971) found that a leafless hardwood forest with snow on the floor reflected 20 percent and absorbed 65 percent in the stems and branches.

Hornbeck (1970) reported that net radiation over hardwood forest did not differ greatly from that of a clearcut area except during periods of snow cover. The higher albedo of the forest apparently compensated for the higher emission of thermal radiation by the clearcut. The net longwave exchange over forest canopies at night was found by Bergen (1969) to be small.

Seasonal measurements in a red pine forest (Mukammal 1971) revealed effectiveness of space-averaged samples collected by moving sensors. The net radiation values beneath the canopy were small and close to the value of transmitted solar radiation. In an unusually complete study of forest-radiation budget, Gay and Knoerr (1970) measured the incoming and outgoing fluxes of global and allwave radiation above and below a pine canopy for clear weather in spring and fall and discussed the radiation budget of the forest and the canopy.

The radiation budgets define the way radiant energy is transformed between spectral regions and into other energy forms. Interest has developed in evaluating these transformations from consideration of radiation fluxes measured above the exchanging surfaces. Monteith and Szeicz (1961) earlier had defined a relation between net longwave and net allwave radiation and derived an empirical "heating coefficient" that appeared related to thermal properties of the irradiated surface. The coefficient was examined by several workers (Stanhill et al. 1966, 1968, Galoux and Grulois 1968, Davies and Buttimor 1969, Idso et al. 1969, and Impens and Lemeur 1969b) and was questioned by Idso (1968). Gay (1969, 1971) summarized data about this relation and concluded that the heating coefficient concept does provide an index to the thermal characteristics of the surface. In particular, the technique confirms that forests, in comparison with other types of natural surfaces, are efficient in transforming and dissipating the large amounts of radiant energy that they absorb.

DISCUSSION

Our understanding of the characteristics of the sources and fluxes of radiation incident upon natural surfaces has advanced. Routine measurements of fluxes other than global radiation are just beginning, however. The instruments now available appear adequate for measurements in and above canopies. Coordination of field techniques and of the selection of study sites would enhance greatly our ability to generalize from published data.

Theoretical models of radiation distribution within canopies are developing more rapidly than they can be tested. They are complex and, as Niilisk et al. (1970) point out, ". . . a precise and yet simple enough model is needed." The necessity for considering the vertical distribution of foliage in the models is becoming apparent. Such information is still rare for forests, though it is now available at least for red pine in Connecticut (Stephens 1969), for Douglas-fir in the northwestern United States (Kinerson and Fritschen 1971), and for the spruce forest near Munich that has been the site for A. Baumgartner's widely known investigations (Droste zu Hülshoff 1970).

Despite the relevance to energy balance, radiation-budget studies are not yet common in forest stands. Also, sampling techniques and statistical analyses of radiation measurement on the forest floor evidently need further refinement.

This brief review has concentrated on the studies of radiation in vegetation that have appeared since 1966. The quantity, quality, and direction of this recent research are impressive and hold promise for continued progress in our understanding of an important and complex environmental variable.

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