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RADIATION MEASUREMENTS
by various instruments in the open and in the forest

U. S. FOREST SERVICE RESEARCH PAPER NE-84
1967

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Contents

Importance of Radiant Energy

THE RECENT REVIVAL and intensification of interest in radiant energy in the forest has developed partly from a better understanding of the close relationship of radiant energy to the physiological processes that govern tree growth and transpiration. There is also a growing appreciation among foresters that forest-streamflow relationships are governed mainly by the interaction of forest cover and radiant energy.

This interest has been stimulated by the recent invention of inexpensive instruments that permit the measurement of various portions of the energy spectrum. Shortwave instruments cover the wave-length range from 0.3 to 4.0 microns and measure both beam and diffuse components of solar radiation; longwave instruments cover a range of 4 to 100 microns and measure the terrestrial or thermal radiation emitted by natural objects at or near the earth's surface; and instruments that measure visible light cover that portion of the spectrum from 0.4 to 0.7 microns.

We made a study to examine how much and in what way various instruments agree in their measurements of shortwave radiation, and to describe the seasonal effects of oak and pine canopies on shortwave, longwave, and net radiation. The study was conducted on the Lebanon Experimental Forest, near New Lisbon, New Jersey.

Methods

STUDY PLOTS

Radiation measurements were taken in three plots located within 300 yards of each other. One plot was an open area; one was a 100-x-100-foot area in a stand of mature oak, and one, of equal size, was located in a stand of mature pitch pine. The plots were almost level and had deep, well-drained, sandy soils. For sampling purposes the two forested plots were gridded into 10-foot squares whose intersections were marked with steel rods.

The open area was part of a clearing of about 5 acres. Radiation measurements were taken at an unshaded point over bare soil approximately 200 feet from the surrounding oak trees, which were about 40 feet tall.

The oak plot contained 115 chestnut oak, black oak, and white oak trees with an average diameter breast high of 4.1 inches and a basal area of 66 square feet. Dominants within the even-aged stand were 9 to 10 inches in diameter, about 40 feet tall, and 65 years old. Stocking was about 0.8 normal. Five or six small pines were removed from the stand before radiation measurements were begun. Summer canopy closure, as measured with a spherical densiometer, was about 65 percent, and winter closure about 15 percent. The forest floor was a patchy intermixture of about equal areas of bare soil, oak leaves, and moss.

The pine plot contained 32 pitch pines about 50 feet tall, 90 years old, and with an average diameter at breast height of 9.3 inches and a basal area of 70 square feet. Stocking was about 0.67 normal. Canopy closure was about 24 percent. Before measurements were begun a considerable oak understory, which had been killed by fire in 1963, was removed. The forest floor was a fairly uniform covering of pine needles, 1/4 to 1/2 inch deep, over 1/2 to 1 inch of humus.

PERIOD OF RECORD

Radiation measurements were taken on 33 days during the period from April 17, 1964, to April 27, 1965. Each day measurements were begun at sunrise and taken hourly until sunset. During

16 days of measurement the oaks were in full leaf (the growing period), and during 13 days they were leafless (the dormant period).

From hourly estimates of cloud cover, 10 days were classified as uniformly clear (0 to 14 percent cloud cover), and 11 days were classified as uniformly cloudy (55 to 91 percent cloud cover). Four days had cloudy mornings and clear afternoons, and 2 days had the reverse condition. Six days were classified as irregularly cloudy. On 3 days (one cloudy and two clear) there was snow on the ground.

INSTRUMENTATION

Shortwave radiation was measured with four instruments, and longwave radiation was measured with one instrument. A daily record of shortwave radiation was also obtained from the Weather Bureau. Net shortwave, net longwave, net radiation (net all-wave radiation), and direct irradiation were calculated. Direct beam solar irradiation in langleys for each day of record were estimated from tables prepared by Fons *et al. (1960)* for a zero slope and atmospheric transmission of 0.9. Visible light was measured with one instrument. Cloud cover, in tenths of the sky covered, was estimated every hour.

Shortwave and longwave radiation measurements are expressed in langleys per day (a langley is 1 gram calorie of radiant energy per square centimeter). Visible light at noon is expressed in foot-candles. Units of measurement and the instruments used to measure radiant energy in the forest (including the instruments used in this study) have been described by Reifsnyder and Lull *(1965)*.

The instruments employed in this study were used as follows:

Shortwave Radiation

Eppley pyranometer.—Radiation in langleys per day for the 33 days of record, as recorded on the Eppley pyranometer, was obtained from the U. S. Weather Bureau Station at New Brunswick, N. J., 40 miles north of the Lebanon Experimental Forest.

Economical radiometer.—Three instruments were built by Irvin C. Reigner according to instructions given by Swan *et al. (1961)*

to measure incoming shortwave radiation in the open and beneath the canopies and to measure outgoing radiation from bare soil and forest floors. In the forest plots these instruments (and the pyranometers and atmometers) were read hourly and moved every 2 hours to randomly selected points on the grid.

Bellani spherical pyranometers.—These instruments were placed in insulated wooden containers to facilitate grid-sampling. The instrument on the pine plot was broken in November so that measurements for the last 12 days of record were not obtained. Pyranometers were calibrated at the open plot against daily langleys measured with the pyrheliograph.

Pyrheliograph.—The pyrheliograph was operated in the open plot only. Recorded langleys per minute were read either at 15-minute intervals, from a chart, or in multiples of 15 minutes during a period of little change, and were multiplied and added to get langleys per day.

Livingston atmometers.—One pair of black and white atmometers was employed in each plot from April 17 to November 2 when readings were discontinued because of freezing weather. The three black and three white atmometers were calibrated separately in the open with one black and one white designated as a standard. Differences in evaporation between black and white pairs measured in cubic centimeters and divided by daily langleys from the pyrheliograph for the calibration periods, give a calibration factor of 9.6 langleys per cubic centimeter.

Longwave Radiation

Economical radiometer.—Longwave radiation from economical radiometer readings was calculated according to procedures described by Swan *et al.* (1961).

Net Radiation

Economical radiometer.—Net shortwave, net longwave, and net radiation values were computed according to procedures given by Swan *et al.* (1961).

Visible Light

Brockway exposure meters, Model S, were used to measure visible light at 20 randomly selected points every hour in the forested plots, and at one point in the open every 30 seconds for 10 minutes each hour. Photocell readings were converted to foot-candles, according to the manufacturers' instructions, and then converted to langleys with the approximation that 7,000 foot-candles equal 1 langley per minute.

Results

SHORTWAVE RADIATION

Comparison of Instruments in Open Plot

Daily total shortwave radiation in langleys in the open for the 33 days of record was computed from measurements taken with the Eppley pyranometer (Ep), economical radiometer (Ec), Bellani pyranometer (B), pyrheliograph (Py), and the photocell (Ph). Simple correlation coefficient between daily values for the total record and for clear and cloudy days are given in table 1.

For the 33-day record the highest correlation was between the economical radiometer and the pyrheliograph, and the lowest was between the Bellani and Eppley pyranometers. Correlations of the pyrheliograph and the economical radiometer with the other three instruments on the plot were somewhat higher than correlations of the distantly located Eppley pyranometer with these instruments. In each of the correlations the coefficients were higher for clear days than for cloudy days.

Linear regressions for predicting daily radiation in langleys, with four instruments, and with the pyrheliograph used as the standard, are given in table 2 together with standard errors of estimate. For the total record and for clear and cloudy days the best estimates were made with the economical radiometer. Except for the Bellani pyranometer, standard errors were substantially smaller on clear days than on cloudy days. Standard errors in these predictions may be derived partly from the pyrheliograph record. In two recent comparisons with Kipp solarimeters, standard

Table 1.—*Correlations between daily total shortwave radiation as measured by five instruments*

Item[1]	Ep	Ec	Py	B	Ph
			TOTAL RECORD (33 days)		
Ep	—	0.935	0.945	0.851	0.936
Ec	0.935	—	.986	.927	.974
Py	.945	.986	—	.925	.981
B	.851	.927	.925	—	.904
Ph	.936	.974	.981	.904	—
			CLEAR DAYS (10)		
Ep	—	.994	.995	.976	.989
Ec	.994	—	.998	.973	.989
Py	.995	.998	—	.974	.994
B	.976	.973	.974	—	.962
Ph	.989	.989	.994	.962	—
			CLOUDY DAYS (11)		
Ep	—	.822	.810	.802	.867
Ec	.822	—	.978	.964	.978
Py	.810	.978	—	.954	.963
B	.802	.964	.954	—	.913
Ph	.867	.978	.963	.913	—

[1] Eppley pyranometer (Ep), economical radiometer (Ec), pyrheliograph (Py), Bellani pyranometer (B), and the photocell (Ph).

errors of pyrheliographs were found to be 19 and 21 langleys per day. The correlation coefficient in each case was 0.990.[1]

The relationships between daily values of the pyrheliograph ($\hat{Py}$) and direct-beam solar-irradiation estimates (X) for the 33-day record, gave a simple correlation coefficient of 0.856 and the regression equation:

$$\hat{Py} = 0.5505X + 20.8$$

The standard error of estimate was 82 langleys. Including percent of cloud cover, with an arc sin transformation (angle = arc sin $\sqrt{\text{percent}}$) gave the following equation:

$$\hat{Py} = 0.004993X\ (150 - \text{angle}) + 6.93$$

The correlation coefficient increased to 0.963, and the standard error of estimate was reduced to 43 langleys.

[1] Information provided by C. Anthony Federer, Watershed Management Research Project, Northeastern Forest Experiment Station, Durham, N. H.

Table 2.—*Regression equations and standard error of estimates for predictions of daily total radiation as measured with the pyrheliograph used as the standard*

Instrument	b-coefficient	a-constant (langleys)	Standard error of estimate (langleys)
TOTAL RECORD (33 days)			
Economical radiometer	0.8185	−2.68	27
Photocell	.8727	−27.50	31
Eppley pyranometer	.8482	−11.98	52
Bellani pyranometer	.8830	58.17	61
CLEAR DAYS (10)			
Economical radiometer	.8000	−.50	12
Photocell	.9418	−66.04	23
Eppley pyranometer	.8878	−25.78	20
Bellani pyranometer	.9538	44.32	46
CLOUDY DAYS (11)			
Economical radiometer	.8446	−8.25	29
Photocell	.7791	12.31	37
Eppley pyranometer	1.0472	−85.77	81
Bellani pyranometer	.8485	51.44	41

Correlation of the 18-day record from the atmometers with concurrent values from the pyrheliograph gave a correlation coefficient of 0.808. A regression for the prediction of daily pyrheliograph values ($\hat{P}y$) from atmometer values (X) gave the equation:

$$\hat{P}y = 0.6190X + 179.7$$

with a standard error of estimate of 68 langleys.

Mean incoming daily shortwave radiation from the pyrheliograph record for the growing season was 434 langleys and for the dormant season 287 langleys. Therefore, the standard error of estimate of 27 langleys from the most closely correlated instrument, the economical radiometer, was about 6 percent of the growing-season mean and 9 percent of the dormant-season mean. The standard error of the photocells, 31 langleys, indicated a close relationship between visible-light and shortwave measurements. Eppley pyranometer values from 40 miles away, and estimates of daily irradiation corrected for cloud cover, had about the same magnitude of error, 52 and 43 langleys. The Bellani pyranometers and atmometers also had about the same degree of error, 61 and 68 langleys. These last two instruments were not considered useful because of operational difficulties, danger of breakage, and high threshold values.

Daily Shortwave Radiation Beneath the Canopies

Daily and seasonal amounts of incoming and outgoing shortwave radiation are indicated in figure 1. This figure brings out the pronounced seasonal variations in the incoming radiation, and the changing relationship between plot values with seasonal changes in the oak canopy. In sharp contrast are the comparatively small amounts and small variations in outgoing radiation; high values on January 19 and February 3 were due to reflection from snow.

During the 33 days, the oak plot received 53 percent of the shortwave radiation received in the open, and the pine plot received 63 percent as measured by the economical radiometer (table 3). The percent-of-open values principally reflect differences between the oak and pine plots in stocking and canopy closure during the growing season, and between deciduous and evergreen effects in the dormant season. More shortwave radiation penetrated the oak canopy in the dormant season than in the growing season despite a dormant-season reduction of about one-third in the available incoming amount. More shortwave radiation was reflected from the open plot than from the forested plots. For the total period there was little difference in the amounts reflected from the oak and pine plots.

On the 2 cloudiest days during the dormant season the oak plot received 77 and 79 percent of radiation in the open, and on the 2 clearest days 66 and 75 percent (table 4). Comparable values for the 2 cloudiest and 2 clearest days in the growing season were 44 and 46 percent and 50 and 23 percent. Greater proportions on cloudy days, due to the greater penetration of scattered radiation, have been reported by others *(Reifsnyder and Lull 1965)*.

In the pine plot, with lower canopy closure, differences in the

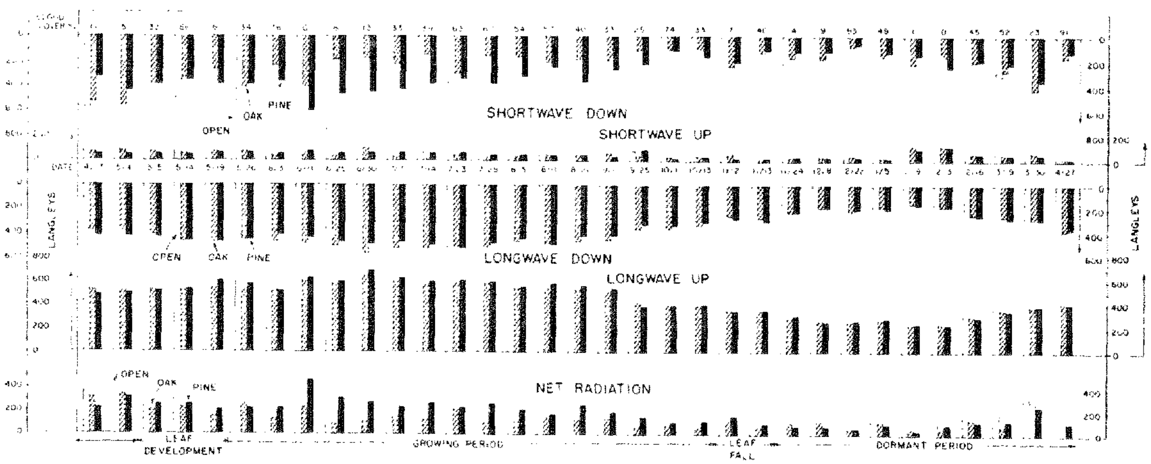

Figure 1.—Daily incoming and outgoing shortwave and longwave radiation and daily net radiation.

Table 3.—*Mean daily radiation*

Period	Number of days	In langleys: Open	In langleys: Oak	In langleys: Pine	Percent of open: Oak	Percent of open: Pine
		SHORTWAVE RADIATION				
Total:						
Incoming	33	448	237	284	53	63
Outgoing	33	81	49	45	—	—
Growing season:						
Incoming	16	525	205	341	39	65
Outgoing	16	85	40	49	—	—
Dormant season:						
Incoming	13	361	278	221	77	61
Outgoing	13	78	59	44	—	—
		VISIBLE LIGHT				
Total:	33	449	147	237	33	53
Growing season	16	528	102	287	19	54
Dormant season	13	360	197	186	55	52
		LONGWAVE RADIATION				
Total:						
Incoming	33	364	386	380	106	104
Outgoing	33	482	438	446	91	93
Growing season:						
Incoming	16	443	477	453	108	102
Outgoing	16	583	519	534	89	92
Dormant season:						
Incoming	13	269	275	289	102	107
Outgoing	13	361	341	337	94	93
		NET RADIATION				
Total:	33	244	133	177	55	73
Growing season	16	301	124	218	41	72
Dormant season	13	184	145	128	79	70

proportions recorded on cloudy and clear days were not as marked. On the 2 cloudy days during the dormant season 59 and 61 percent of the radiation in the open was received, and on 2 clear days 52 and 76 percent. During the growing season the respective values were 72 and 47 percent, and 76 and 60 percent.

The estimated transmission of solar radiation of the two forest plots in relation to stem density (the summation of diameters breast height per acre) taken from a relationship developed by Miller (1959), and actual transmission, were as follows:

Plot	*Stem density (in./acre)*	*Estimated transmission (%)*	*Actual transmission (%)*
Oak: growing period	2,252	38	39
Pine	1,302	60	63

Miller's relationship, developed from radiation measurements in pine stands, in this instance works well for oak in full canopy.

Estimates of transmission from crown closure measurements were not as good:

Plot	*Crown closure (%)*	*Estimated transmission (%)*	*Actual transmission (%)*
Oak: growing period	65	8	39
dormant period	15	63	77
Pine (a)	24	43	62
Pine (b)	24	58	62

The oak and pine (a) estimates were made from Miller's relationship *(1959)*, and the pine (b), the best estimate, from a crown closure-percent transmission curve developed for jack pine *(Vézina and Péch 1964)*. In the first three cases, transmission is more closely estimated by simple subtraction of crown-closure percent from 100. The poorness of these estimates corroborates Miller's conclusion that stem density is a better indicator of transmission than crown closure.

Table 4.—*Shortwave radiation on clear and cloudy days*

Period	Date	Percent	In langleys			Percent of open	
			Open	Oak	Pine	Oak	Pine
Growing season:							
Clear	6/11	0	803	399	607	50	76
	6/25	6	766	176	460	23	60
Cloudy	6/3	76	492	217	353	44	72
	10/1	74	241	112	113	46	47
Dormant season:							
Clear	1/19	1	290	212	150	73	52
	2/3	0	325	214	247	66	76
Cloudy	12/22	83	103	79	61	77	59
	4/27	91	202	159	123	79	61

Albedos

Mean albedos (outgoing shortwave radiation divided by incoming) and their standard deviations were calculated for the soil surface of the open plot and for the forest floors of the oak and pine plots for the 30 days of record (excepting the 3 days with snow cover), for 10 days of the dormant season when the oaks were leafless, and for 16 days of the growing season when hardwoods were in full leaf. The results are given in table 5, together with daily albedos for the 3 days of snow cover.

Albedos of the forest floor averaged 0.19 for the oak plot and 0.14 for the pine plot and were similar to canopy values that range from 0.15 to 0.20 for hardwoods and 0.10 to 0.15 for conifers *(Budyko 1956)*. Differences in albedos of the 30-day record among the three plots were highly significant ($F = 7.08$). There was little or no difference in albedos during the dormant and growing seasons in the open and pine plots. The forest floor of the oak plot reflected more shortwave radiation in the summer than in the winter, but the difference evaluated in a t-test proved non-significant ($p = 0.10$).

Smaller albedos of the deeper snow in the forested plots may

Table 5.—*Mean albedos and their standard deviations and albedos for days of snow cover*

Period		Plot					
		Open		Oak		Pine	
		Albedo	Standard deviation	Albedo	Standard deviation	Albedo	Standard deviation
30-day record		0.16	0.03	0.19	0.05	0.14	0.06
Growing season		.16	.03	.20	.04	.14	.07
Dormant season		.16	.03	.17	.04	.15	.05
Days with snow							
Date	*Depth (inches)*						
12/22	1	.25	—	.25	—	.32	—
1/19	7	.72	—	.59	—	.59	—
2/3	1	.54	—	.48	—	.53	—

have been due to stems or footprints in view of the radiometer and to the greater proportion of infrared radiation beneath the canopy.

VISIBLE LIGHT

The mean daily value of visible light measured with photocells and converted to langleys is given in table 3. Visible light was more greatly affected by canopies than was shortwave radiation since the foliage transmitted less of the visible light than the infrared. For instance, during the growing season the oak plot received 19 percent of the visible light received in the open, and the pine plot received 54 percent; comparable values for shortwave radiation were 39 and 65 percent (table 3). Dormant-season percents were 55 and 52 for visible light and 77 and 61 for shortwave radiation.

Photocells can provide a good estimate of shortwave radiation in the open, as noted earlier, but cannot be used to estimate it beneath the canopy.

Visible Light at Noon Beneath the Canopies

Visible light at noon beneath the canopies was measured to compare canopy effects on maximum values of visible light and to describe its area variation. Photocell readings, taken at 20 points in the forested plots at noon, were converted to foot-candles; and mean values and standard deviations were calculated for the 20 readings taken at 30-second intervals in the open area. Mean values by periods and for specific days are given in table 6.

For the 33-day record the oak plot received 37 percent of the light received in the open, and the pine plot received 52 percent.

Table 6.—*Visible light at noon*

Period	Number of days	In foot-candles			Percent of open	
		Open	Oak	Pine	Oak	Pine
Total	33	7,000	2,590	3,640	37	52
Growing season	16	7,840	1,610	4,130	21	53
Dormant season	13	6,090	3,640	3,080	60	51

Table 7.—*Visible light at noon on clear and cloudy days*

Period	Date	Percent	In foot-candles			Percent of open	
			Open	Oak	Pine	Oak	Pine
Growing season:							
Clear	6/11	0	9,945	2,955	5,270	30	53
	6/25	6	9,675	1,936	5,205	20	54
Cloudy	6/3	76	7,620	1,980	2,852	26	37
	10/1	74	6,285	1,136	3,232	18	51
Dormant season:							
Clear	1/19	1	7,200	3,098	3,772	43	52
	2/3	0	7,350	3,405	3,404	46	46
Cloudy	12/22	83	1,200	588	602	49	50
	4/27	91	1,470	1,062	870	72	59

The oak plot received somewhat more light than the pine plot in the dormant period; but in the growing period it received less than half of that received in the pine plot, and less than one-quarter of that in the open. In both seasons, the pine plot received about one-half of the light measured in the open. The differences in light measured at the open plot in the dormant and growing periods result from different positions of the sun and different degrees of cloudiness (mean daily cloudiness in the dormant season was 32 percent, and in the growing season 40 percent).

On clear and cloudy days during the growing season the oak plot received about one-sixth to one-third of the light received in the open and one-third to two-thirds of the light received in the pine plot. In the dormant season the oak plot received about one-half to three-fourths of the light received in the open and about the same amount of the light measured in the pine plot (table 7).

On clear days during the growing season all plots received about 1.5 times more light than on cloudy days. During the dormant season the multiple was increased to about 5.0.

Areal variation of noon radiation is indicated by the following coefficients of variation:

	Open	*Oak*	*Pine*
Total record	11	47	38
Growing season	14	85	33
Dormant season	9	30	46

During the growing season the greatest variation was found on the oak plot, and during the dormant season in the pine plot. Greater variation in the open plot during the growing season was probably due to greater cloudiness.

LONGWAVE RADIATION

Daily incoming and outgoing daytime longwave radiation of the three plots are given in figure 1. Mean values by seasons are given in table 3.

In both seasons incoming radiation from atmosphere and overhead foliage and branches is greater beneath the canopies than incoming radiation to the open from atmosphere alone. Differences in outgoing radiation stem from differences in surface-soil temperatures resulting from variation in shading.

Daily values shown in figure 1 point up the large seasonal difference in longwave radiation, the relatively small difference between plots (as compared with shortwave radiation), and the overall negative net values.

NET RADIATION

Daily Net Radiation

Daily net radiation from economical radiometers is given in figure 1. Mean values by seasons are given in table 3. Net radiation from the growing to the dormant season in the open and pine plots is reduced about one-third, but in the oak plot it is increased about one-third because of the differences in seasonal distribution of shortwave radiation noted above. Small differences in longwave radiation between plots suggest that net radiation differences can be attributed mainly to variation in shortwave distribution.

Net Radiation and Shortwave

About one-half to two-thirds of the shortwave radiation as measured with the economical radiometers appeared as net radiation. The net to shortwave ratios were as follows:

	Open	*Oak*	*Pine*
Growing season	0.57	0.60	0.64
Dormant season	.51	.51	.58

Maximum daily ratios for the open, oak, and pine plots were 0.70, 0.76, and 0.82 respectively. Minimum values of 0.07, 0.16, and 0.23 were for days of snow cover.

The relationships of net radiation to shortwave and to net shortwave radiation are given in table 8. The simple correlation coefficients indicate that from 89 to 94 percent of the variation in net radiation is attributable to variation in shortwave radiation, and from 92 to 96 percent to net shortwave radiation. Standard errors of estimate are about 10 to 20 percent of the mean net radiation value by seasons.

RADIATION BALANCE ON CLEAR DAYS AND CLOUDY DAYS

Seven days of record were selected to exemplify the radiation balance on clear days and cloudy days during the growing and dormant periods (table 9). Radiation values were from the economical radiometers.

Table 8.—*Relation of daily net radiation to daily shortwave and daily net shortwave radiation*

Plot	Independent variable	Correlation coefficient	Regression statistics: b-coefficient	Regression statistics: a-constant	Regression statistics: Standard error of estimate
				Langleys	*Langleys*
Open	Shortwave	0.942	0.5364	11.3	34
	Net shortwave	.959	.6579	6.4	28
Oak	Shortwave	.948	.6325	-12.3	25
	Net shortwave	.982	.7549	-5.8	15
Pine	Shortwave	.971	.7109	-21.9	22
	Net shortwave	.976	.8159	-18.5	20

Table 9.—*Radiation balance on clear days and cloudy days, in langleys*

Item		Clear days			Cloudy days			
		Example 1 (no leaves)		Example 2 (full leaf)	Example 3 (no leaves)		Example 4 (full leaf)	
Date		12/8	5/4	6/25	4/27	3/9	6/3	8/5
Cloudiness (%)		9	5	6	91	52	76	54
Direct beam		230	779	895	743	490	878	795
Radiation	*Site*							
Shortwave	Open	237	723	766	202	318	492	432
	Oak	177	560	176	159	281	217	157
	Pine	117	433	460	123	208	353	310
Shortwave	Open	45	110	121	17	58	81	61
	Oak	32	84	38	17	49	47	31
	Pine	20	49	154	6	39	53	38
Net	Open	192	613	645	185	260	411	371
	Oak	145	476	138	142	232	170	126
	Pine	97	384	406	117	169	300	272
Longwave	Open	182	365	432	410	283	403	461
	Oak	193	389	506	374	274	469	484
	Pine	202	423	479	380	280	426	471
Longwave	Open	259	561	638	453	360	532	520
	Oak	248	517	567	405	344	508	520
	Pine	248	491	580	406	336	502	538
Net	Open	–77	–196	–206	–43	–77	–129	–125
	Oak	–55	–128	–61	–31	–70	–39	–36
	Pine	–46	–68	–101	–26	–56	–76	–67
Net	Open	115	417	439	142	183	282	246
	Oak	90	348	77	111	162	131	90
	Pine	51	316	305	91	113	224	205

Example 1.
Clear Days, No Oak Leaves,
Winter and Spring
(December 8 and May 4)

Relative magnitudes of shortwave and longwave radiation among the three sites are similar for these 2 days despite the large difference in shortwave radiation received.

For both days the greatest amounts of incoming, outgoing, and net shortwave radiation were measured in the open, the least in the pine plot, and intermediate values in the hardwood area. The greatest amounts of incoming longwave radiation, and the smallest amounts of outgoing were measured under pine. Negative net thermal values increased markedly for open and hardwood sites from the winter to the spring dates; whereas there was a smaller change in net thermal radiation for the pine site.

Net radiation diminished from the open to the hardwood to the pine and was governed mainly by the trend of incoming shortwave radiation.

Example 2.
Clear Day, Full Leaf
(June 25)

A comparison of this radiation balance with that of May 4 points up the canopy change in the oak plot. Incoming, outgoing, and net shortwave radiations were sharply reduced; incoming longwave radiation for the oak plot was greater than that for the open and pine plots, and outgoing radiation was less. Net radiation for the oak plot was but a fifth of its value in early May, but there was little change in the open and pine plots.

Example 3.
Cloudy and Partly Cloudy Days,
No Oak Leaves
(April 27 and March 9)

The 91-percent cloudiness of April 27 reduced shortwave and net radiation by one-fourth to one-third of that of the clear day May 4; reduction in reflected shortwave radiation was even greater. Incoming longwave radiation, for the first time in these examples, was greatest in the open, and there was little difference between incoming and outgoing thermal radiation in the forested plots. Net radiation at the three sites was affected mainly by the distribution of shortwave radiation.

On March 9, with a cloudiness of 52 percent, incoming solar radiation was somewhat greater than on April 27 even though direct beam was much less; longwave values were relatively uniform, and the net value again mainly suggests differences in incoming shortwave radiation.

Example 4. Cloudy and Partly Cloudy Days, Full Leaf (June 3 and August 5)

These 2 days as compared with the clear day of June 25 show a reduced shortwave radiation but a reduction disproportionately less in the oak plot. (The high value of 217 langleys for June 3 is presumably a sampling variation.) With longwave values fairly uniform, net values for the open and pine plots were substantially less than comparable values on June 25, and oak values were greater.

Summary

Within the limited scope of this study certain results were evident. In regard to instrumentation:

- Economical radiometers were not difficult to construct and gave apparently good measurement of incoming and outgoing shortwave and longwave radiation.

- The Bellani pyranometers used in this study were not satisfactory because of their high threshold values and standard errors of estimate. However, other investigators have found various models useful *(MacHattie, 1961; Vézina and Péch, 1964)*.

- Livingston atmometers were relatively insensitive, very likely to damage, and time-consuming to operate; and they could not be used in freezing weather. For shortwave estimation they were not satisfactory.

- Photocells, despite their limitations in the spectrum measured, correlated well with shortwave measurements in the open but because of differential transmission of visible light could not be used to estimate shortwave radiation beneath the canopy.

- The economical radiometer and the photocell were equally effective in measuring shortwave radiation in the open. However, standard errors of estimate of 27 and 30 langleys with these two instruments may preclude their use in studies requiring precise comparisons.

Distribution of radiation in the forest plots was as follows:

- The oak plot received 39 percent of incoming shortwave radiation during the growing season, and the pine plot received 65 percent. Comparable dormant-season values were 77 and 61 percent.

- More shortwave radiation penetrated the oak canopy in the dormant season than in the growing season despite a seasonal reduction of about one-third in the incoming amount in the dormant season.

- The oak plot received a greater proportion of the incoming shortwave radiation on cloudy days, and the pine plot received a greater proportion on clear days.

- The percent of shortwave radiation received in the forest plots was accurately estimated from a stem density-radiation relationship developed by Miller *(1959)*.

- Albedos of the forest floor averaged 0.19 for oak and 0.14 for pine.

- During the growing season the oak plot received 19 percent of the visible measured light at the open plot, and the pine plot received 54 percent; comparable values for the dormant season were 55 and 52 percent.

- At noon during the growing season, visible light throughout the oak plot was about six times more variable, and throughout the pine plot about twice as variable as in the open. In the dormant season, variation in the oak plot was three times that of the open, and in the pine plot five times that of the open.
- Incoming longwave radiation from the sky and canopy was slightly greater in the forested plots than in the open, and outgoing radiation was greater in the open than in the forest.
- Net radiation was greatest in the open plot; during the growing season it was smallest in the oak plot and during the dormant season, in the pine plot.
- From 89 to 94 percent of the variation in daily net radiation was attributable to variation in daily shortwave radiation.

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