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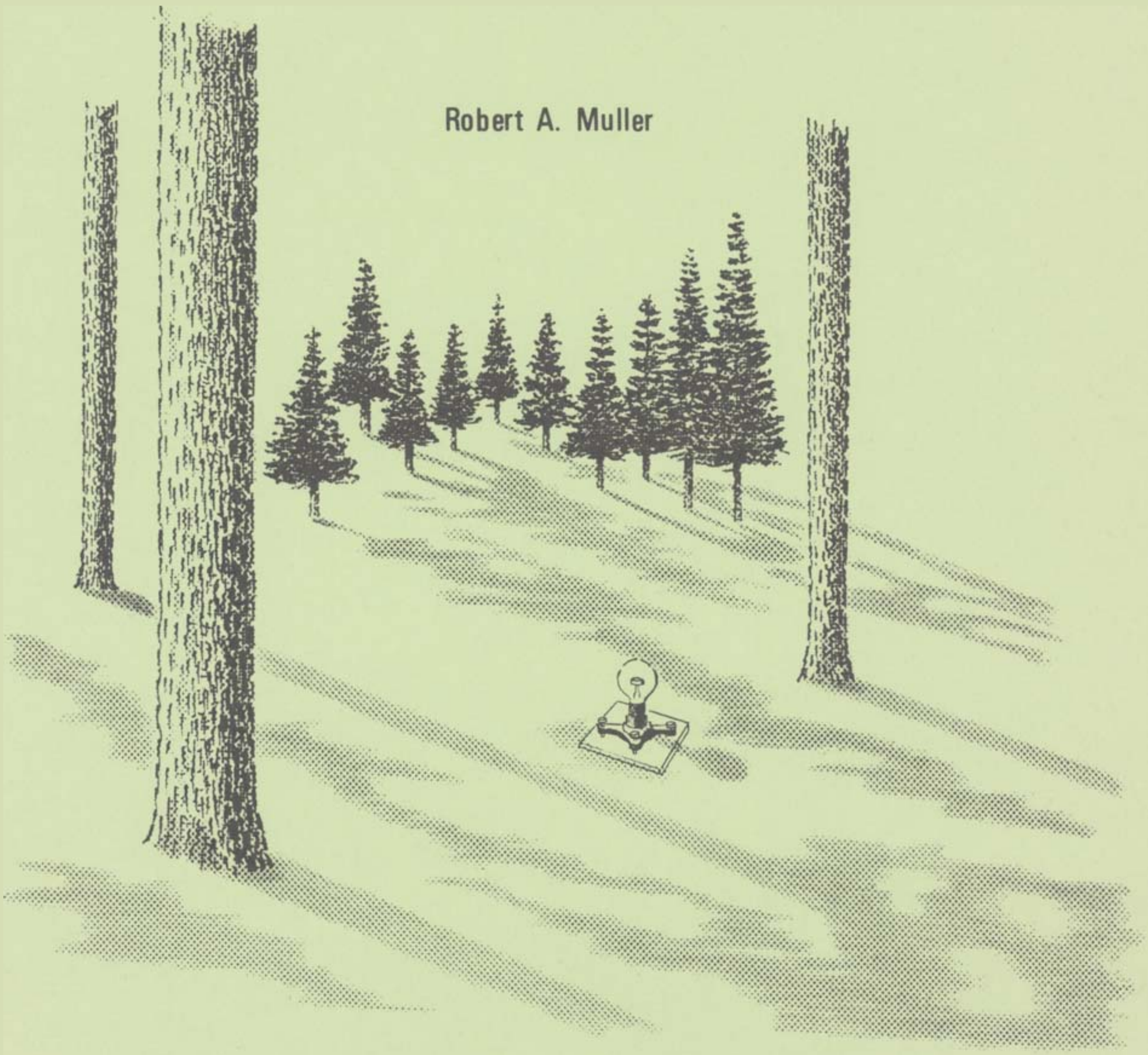
PACIFIC SOUTHWEST
Forest and Range
Experiment Station

TRANSMISSION COMPONENTS OF SOLAR RADIATION

in pine stands in relation to climatic and stand variables

Robert A. Muller



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The Author

ROBERT A. MULLER was formerly with the Station's research staff studying problems in flood and sediment reduction in the conifer zone. He is now an associate professor of geography at Louisiana State University, Baton Rouge. He earned a bachelor's degree in geography (1958) at Rutgers University, and a master's (1959) and doctorate (1962) in physical geography at Syracuse University.

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In a forest, the upper foliage of the crowns serves as an "active surface" between the atmosphere and the ground. At this surface, leaves or needles absorb much of the incoming solar radiation, and on sunny days, air temperatures tend to be highest within the upper crowns. Some of the solar radiation is reflected back to space. The remaining radiation penetrates through crown openings to the forest floor. The measure of the transmission of solar radiation in forest stands is the ratio of solar radiation beneath the crowns to downcoming solar radiation within the atmosphere. (Upward reflection of solar radiation is not treated in this study.)

An understanding of the role of transmission of radiation in the energy balance of forest stands is valuable for studies of the physical environment. Energy balance research centers on how the net radiation of a surface or land cover type is used in the biomass, atmosphere, and soil. For example, botanists, plant physiologists, ecologists, and foresters are interested in the ways in which solar energy regimes at various levels of the stand are related to evapotranspiration, photosynthesis, and regeneration. Hydrologists and climatologists also are concerned with solar radiation transmitted through crowns to the snowpack where some of the energy becomes available for snow evaporation and snowmelt.

Miller (1959) analyzed transmission studies in pine stands, and Anderson (1964) made an international survey and analysis of transmission studies.

This paper reports on a new approach to the problem. It describes an analysis of transmission within three pine stands in northern California, using statistical techniques that are related to a new index of stand biomass affecting transmission. The study draws upon several assumptions to estimate analytically the ways in which solar radiation penetrates downward through pine crowns, and it considers in some detail the relative and absolute significance of sunflecks.

In the professional literature, there is little standardization of radiation and energy budget terms and symbols. The symbols used in this report are listed below and illustrated in *figure 1:*

Measurements above crowns or at nearby open sites

S = direct solar radiation in atmosphere
D = diffuse solar radiation in atmosphere
R = downcoming shortwave solar radiation in atmosphere, = S + D

Measurements below crowns within stand

R* = downcoming shortwave solar radiation
S* = direct solar radiation in atmosphere transmitted as sunflecks through crown openings
Ssca* = direct solar radiation in atmosphere (S) scattered downward by stand biomass
D* = diffuse solar radiation in atmosphere (D) transmitted through crown openings
Dsca* = diffuse solar radiation in atmosphere (D) scattered downward by stand biomass
Dt* = the sum of the three diffuse components (D*, Dsca*, and Ssca*) under the crowns.

METHODS

Pine Stands Studied

To explore the relation of pine species in northern California to rates of transmission of solar radiation, three pine stands, each dominated by a different species, were studied. The stands showed fairly even upper crown surfaces about 50 feet above the ground, and they were large enough to minimize effects of edge for most solar positions. Fairly level sites with reasonably unobstructed horizons were chosen. The stands were selected to represent the range of stand biomass for pines which would commonly be expected in northern California.

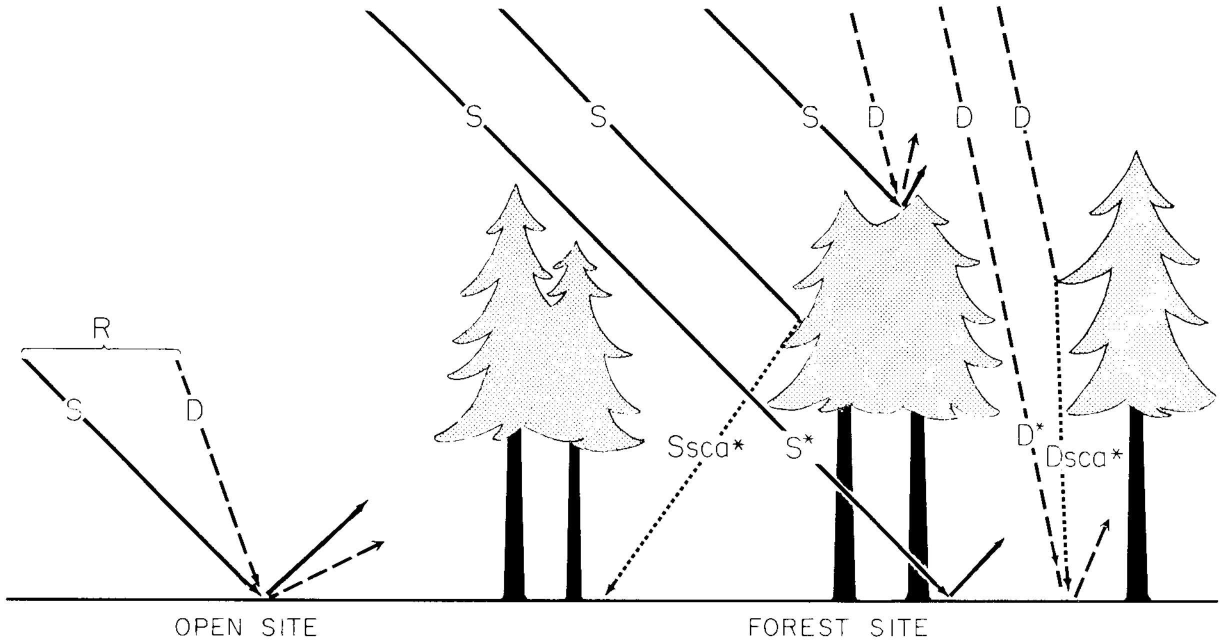

Figure 1–*Components of shortwave radiation budgets. Incoming solar radiation R consists of direct, S, and diffuse, D, radiation downward. Within the stand, direct, S* and diffuse, D* radiation penetrates through crown openings to the floor. Crown biomass scatters some direct, Ssca*, and diffuse, Dsca*, radiation downward to the forest floor. (The asterisk designates transmitted radiation measured under the crowns. The sum of diffuse radiation under the crowns is Dt*.)*

To represent the most dense crown and stand conditions, a stand of Monterey pine *(Pinus radiata* D. Don*)* located in the Berkeley Hills, Berkeley, California, was chosen. This stand was planted for watershed protection in the 1930's.

A ponderosa pine *(Pinus ponderosa* Laws.*)* plantation at the Institute of Forest Genetics, Placerville, California, was selected to represent the more open ponderosa pine stands characteristic of the intermediate western slopes of the central Sierra Nevada. Callaham and Liddicoet (1961) have reported details of the management program for this plantation. During the transmission measurements, half of the trees were removed; measurements were obtained both before and after this treatment.

The third stand, composed primarily of lodgepole pine *(Pinus contorta* Doug].*)* intermixed with a few western white pines and firs, lies near Soda Springs, California, at an elevation of about 7,000 feet in the central Sierra Nevada west of Donner Pass. It was cut over in the 1800's, and a few large firs taller than 50 feet are remnants of the earlier forest.

Square plots were located so that they would be away from the edge effects of the margins of each stand, with no large crown openings directly overhead. Within each plot transmission was sampled by nine Eppley pyranometers. [1] At the ponderosa pine plantation the trees were planted in a square pattern with an 8- by 8-foot spacing between trees. For this plantation site, a plot size with side dimensions of 30 feet was chosen so that the nine pyranometers could be arranged in a square grid of rows and columns of three with an identical spacing of 8 feet.

At the Monterey pine stand, tree spacing was much less regular, and distances between trees were greater than that at the ponderosa pine plantation. To sample much of the transmission variability between trees within the plot, a square plot 50 feet on a side was selected. Within this plot the nine pyranometers were arranged in rows and columns of three, but this time with 15 feet between sensors. Because the trees were quite crowded at the lodgepole pine plot, a plot size of 30 feet on a side was used.

[1] Trade names and commercial products or enterprises are mentioned solely for necessary information. No endorsement by the U.S. Department of Agriculture is implied.

Zones of Stand Influence

To explore the relationships among transmission, solar altitude, stand biomass, and species, the concept of a "zone of stand influence" is useful. The area of the crowns through which sunflecks are transmitted is not usually overhead, but, instead, at some horizontal distance from the plot along the solar azimuth. Only those trees along the solar azimuth which can influence transmission of solar radiation to the plot in an hour are important.

In order for a pyranometer to record a full-intensity sunfleck in the transmission plot, the entire sensing surface must "see" the entire solar disk. The diameter of the sensing element of the Eppley pyranometer is 1.125 inches and the apparent angular diameter of the sun is 32 minutes or 0.53 degree. If the crown is taken as a plane without depth 50 feet above the sensor, and if diffraction effects are ignored, then a full-intensity sunfleck requires a crown opening slightly more than 6 inches in diameter when the sun is directly overhead. For a solar altitude of 30°, the direct solar beam would have to pass through a crown opening with a minimum diameter at the upper surface of the crown of nearly 12 inches; the projection of the path on the ground would extend outward nearly 100 feet along the direction of the solar azimuth. Any tree along the sun's azimuth out to about 100 feet from the sensor could intercept direct solar radiation.

Each pyranometer records only a miniscule sample of transmission in the plot. An estimate of mean hourly transmission at the plot is based on the hourly means of all nine sensors.

To provide an index of stand biomass over and around the plots, stem density in inches per acre and basal area per acre were both measured. There is a different index of crown biomass for each hour of measurement, and the zone of stand influence depends on mean solar altitude and azimuth during the hour.

The path of the direct solar beam p through the stand to a sensor is given by equation (1), where A equals solar altitude, and h equals the height of the upper crowns. The horizontal distance out from the sensor, or the length of the zone of stand influence, is given by equation (2). If the crown and trunk space are assumed to he 50 feet thick, and solar altitude is taken at 33°, the path length p is 91.7 feet, and the length of the zone of stand influence z extends outward horizontally for 77 feet.

$$p = h/\sin A \qquad (1)$$

$$z = h/\tan A \qquad (2)$$

The zone of stand influence in the Monterey pine stand pivots around pyranometer 5 in the center of the transmission plot *(fig. 2).* The long axis of each zone of stand influence is oriented along the mean solar azimuth for the hour. For 0900-1000 hours, February 28, mean solar azimuth is 140° and mean

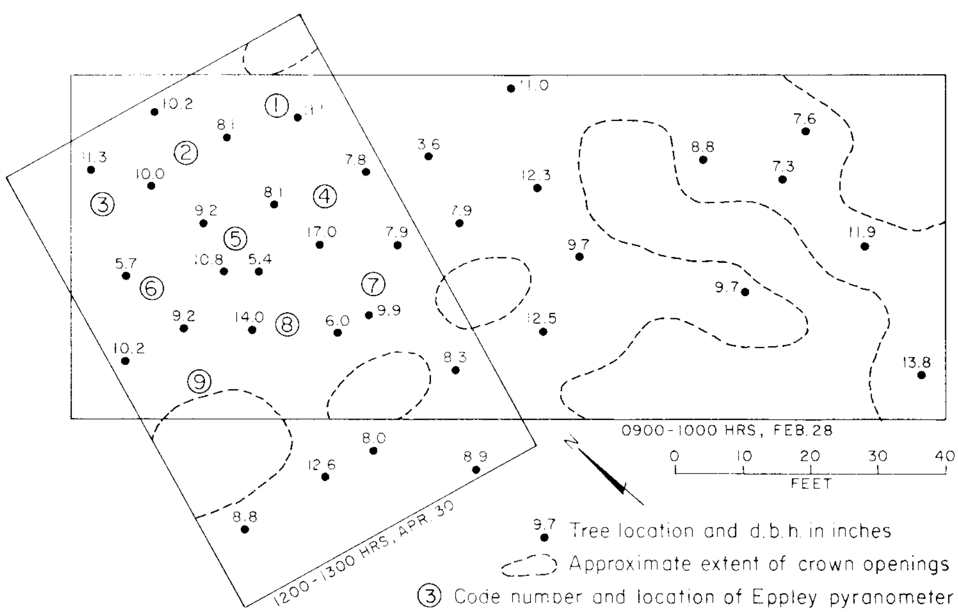

Figure 2–*Zones of stand influence in the Monterey pine stand.*

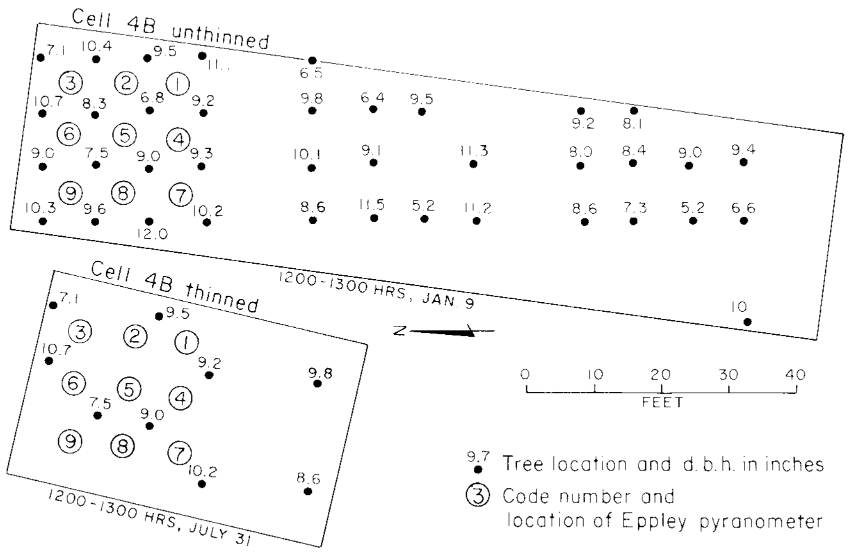

Figure 3–*Zones of stand influence in the ponderosa pine plantation.*

solar altitude is 33°.[2] From the center (pyranometer 5), the transmission plot extends 25 feet along the azimuth of 140°, 25 feet in the opposite direction (azimuth of 320°), and 25 feet out on each side at right angles from the azimuth of 140°: this accounts for the square transmission plot 50 feet on a side. To account for biomass affecting transmission over the entire plot, the zone of stand influence extends the additional 77 feet along the azimuth of 1400. Hence, the total zone of stand influence is a rectangle 127 feet long and 50 feet wide, and its total area is 6,350 square feet. For 1200-1300 hours on April 30, mean solar altitude is 66° and mean solar azimuth is 200°; hence the zone of stand influence is 50 by 72 feet or 3,600 square feet.

Stand Parameters

From the map of the stand, stand parameters can be summed for each zone of stand influence on an hourly basis. In *figure 2* there were 31 trees in the zone of stand influence for 0900-1000 hours; the sum of stem diameters was 296.3 inches and the sum of basal areas was 16.7 square feet. Since the zone of stand influence is 6,350 square feet, stem density is estimated at 1,985 inches per acre and basal area at 115 square feet per acre. Similarly, there were 23 trees with a stem density of 218.5 inches and a basal area of 12.3 square feet in the zone of stand influence for 1200-1300 hours on April 30. The area is 3,600 square feet. Hence, for this zone of stand influence, stem density is estimated at 2,644 inches per acre and basal area at 149 square feet per acre. In winter the edge of the stand has some effect near noon, when the sun is in the south at low solar altitudes *(fig 2).*

The ponderosa pine plantation at Placerville was divided into square cells, each having 16 trees *(fig. 3).* Between each cell were 16-foot-wide corridors at right angles to each other.

The first example, 1200-1300 hours, January 9, represents the zone of stand influence prior to thinning *(fig. 3).* Stem density was 4,050 inches per acre and basal area 200 square feet per acre. The second example shows stand biomass soon after thinning when half of the trees were removed. For 1200-1300 hours, July 31, stem density was about 2,400 inches per acre and basal area about 120 square feet per acre. Transmission measurements soon after thinning were somewhat higher than they would be after the crowns of the remaining pines responded fully to the more open conditions.

The lodgepole pine stand was a more irregular stand, with occasional old firs intermixed with the lodgepole pine *(fig. 4).* For the zone of stand influence for 0900-1000 hours, May 12, stem density amounted to 7,900 inches per acre and basal area was 450 square feet per acre, the largest index of biomass at the three sites. A small opening was included in the zone of stand influence for 1300-1400 hours, May 12; stem density amounted to 5,050 inches per acre, and basal area to 275 square feet per acre. Hence, in

[2] Estimates of mean solar altitude and azimuth can be obtained from equations given in *Smithsonian meteorological tables,* R..J. List. ed. Washington, D. C., 1951, p. 497.

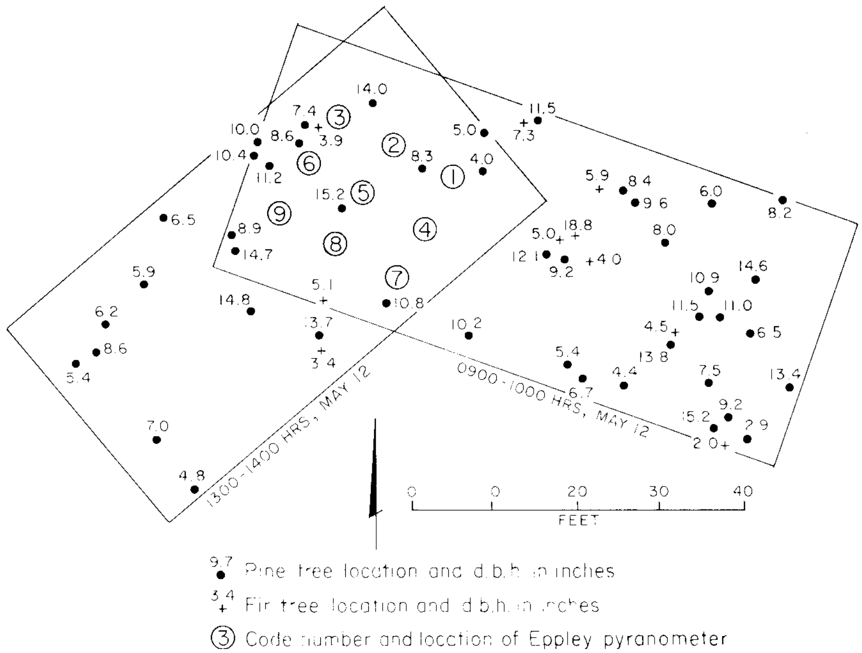

Figure 4– *Zones of stand influence in the lodgepole pine stand.*

terms of these particular stand parameters, the lodgepole pine stand represented the most dense conditions.

Data Collection

For analysis of relationships, measurements of transmission were restricted to clear sky conditions when the solar radiation flux downward changes slowly and systematically. Instantaneous measurements of the millivolt output of each pyranometer were obtained by means of a portable millivolt balancing potentiometer. [3] By use of a junction box, instantaneous measurements of the transmission of solar radiation (R*)[4] by each of the nine Eppley pyranometers within the transmission plot were completed in about 3 minutes. During an hour, transmission (R*) was sampled by the nine pyranometers at 10-minute intervals so that an hourly transmission mean for the plot is based on 54 samples.

The flux of diffuse solar radiation under the stand (Dt*) including direct solar radiation scattered downward by crowns (Dsca*), was sampled by shading the same pyranometers from the direct solar beam. Four-inch aluminum disks were held about 2 feet from the sensor so that the bulb of each sensor was shielded from the direct solar beam (S*). When allowances were made for each sensor to stabilize for shielded conditions, it was possible to measure the millivolt output of all nine sensors in 5 minutes or less. Diffuse solar radiation under the stand (Dt*) was not so variable as direct solar radiation (S*), and hourly means of diffuse solar radiation for the plot were based on measurement sequences at 20- or 30-minute intervals.

Solar radiation in the atmosphere (R) was measured at nearby open sites by one or two Kipp and Zonen solarimeters. The millivolt output of the solarimeters was measured with a second portable balancing millivolt potentiometer on a 10-minute interval;[5] hourly means for insolation (R) above the transmission plots were calculated from these data.

[3] Factory calibration of the Eppley pyranometers was checked occasionally by comparisons of instantaneous millivolt outputs and factory calibration coefficients between sensors during clear sky conditions over periods ranging between 4 and 10 hours. The extreme range was ± 5 percent, and for most circumstances the agreement among sensors was ± 2 percent. The variability among the 10-junction Eppley pyranometers was not systematic usually.

[4] The asterisk is used to symbolize transmitted radiation measured under tree crowns. For a discussion of radiation and energy balance components in forest, see Miller (1965).

[5] During calibration checks, the instantaneous measurements obtained from the solarimeters were found to agree with the Eppley pyranometers within a range of ± 5 percent.

ANALYSES AND DISCUSSION

Regression Analysis

The relationships among transmission, solar altitude, an index of stand biomass, and pine species were determined by multiple regression. [6] Basal area per acre within each zone of stand influence accounted for slightly more of the total variance than did stem density per acre. The relationships for the transmission of solar radiation, direct and diffuse together, under each stand (R*/R) *(fig. 5)*, and the relationships for the transmission of direct solar radiation (S*/R) *(fig. 6)*, are based on 44 hours of data at the Monterey pine stand, 42 hours at the ponderosa pine plantation, and 20 hours at the lodgepole pine stand.

It was not possible to sample transmission for all combinations of solar altitude and basal area. Before the thinning of the ponderosa pine plantation, it was possible to sample only during hours when mean solar altitudes were less than 30°, and the zones of stand influence were all greater than 175 square feet per acre in basal area. At the Monterey pine stand, the geometry of the stand did not permit sampling of transmission under a combination of high solar altitudes and lower classes of basal area. Similarly, at the lodgepole pine stand, all of the zones of stand influence fell within the highest class of basal area.

Because of the influence of sunflecks at high solar altitudes and low basal area, the regression curves for (S*/R) in *figure 6* become unrealistically steep at high solar altitudes. Another factor ignored is that the pines normally carry more needles in spring and early summer, hence lower transmission rates, than in autumn and winter.

The relationship between solar altitude and the proportion of solar radiation transmitted as direct and diffuse solar radiation together (R*/R) is curvilinear. In the Monterey pine stand, an increase of solar altitude of 20° almost doubled the proportion of solar radiation that penetrated through the crowns. The curve for the lodgepole pine stand suggests a similar relationship, but the curves for the ponderosa pine plantation suggest a slightly smaller rate of increase with increasing solar altitude. Tire rate of increase of transmission with solar altitude increased more rapidly in stands of low basal area per acre than in stands of greater density *(fig. 5)*.

At low solar altitudes, changes of stand biomass exert only a small effect on transmission because of the long path lengths of the direct solar beam through scattered crowns *(fig. 5)*. At high solar altitudes, on the other hand, there is a pronounced curvilinear relationship between basal area per acre and percent transmission. This condition is particularly noticeable in the curves for the ponderosa pine plantation. Thinning opened the plantation so that the remaining crowns did not fill the entire crown space. Relationships for the transmission of direct solar radiation (S*/R) are similar *(fig. 6)*.

The relative significance of direct (S*/R) and diffuse (Dt*/R) transmission can also be estimated from *figures 5 and 6*. Even at low solar altitudes. 20° for example, and for basal area of 160 square feet per acre or greater, direct solar radiation contributed between 15 and 28 percent of the total flux of transmitted solar radiation. Under these dense stand conditions, sunflecks were observed crossing the needle-covered floors of the stands at all three sites. Under these same conditions, sunflecks contributed slightly more than half of the total solar radiation flux through the crowns at solar altitudes of 60°. For the most open conditions, basal area of 100 square feet per acre at the Monterey and ponderosa sites, direct solar radiation contributed slightly more than one-third of the solar radiation flux when solar

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[6] The equations and coefficients of multiple determination (R^2) for regression curves in *figures 5 and* 6 are as follows:

	R^2
Monterey Pine Stand	
$\log (R^*/R) = (-5.1020 \times 10^{-3})X_1 + (1.7777 \times 10^{-2})X_2 - 1.4401$	.809
$\log (S^*/R) = (-1.1139 \times 10^{-2})X_1 + (3.2483 \times 10^{-2})X_2 - 1.5965$	.744
Ponderosa Pine Plantation	
$\log (R^*/R) = (-5.3435 \times 10^{-3})X_1 + (8.8304 \times 10^{-3})X_2 - 0.2969$	.912
$\log (S^*/R) = (-8.1978 \times 10^{-3})X_1$ + (1.6536 X 10 21X2 0.5402	.813
Lodgepole Pine Stand	
$\log (R^*/R) = (5.8718 \times 10^{-4})X_1 + (1.6170 \times 10^{-2})X_2 - 1.8593$	.868
$\log (S^*/R) = (7.6940 \times 10^{-4})X_1 + (2.9627 \times 10^{-2})X_2 - 2.8582$	.937

in which,

R* = hourly mean of transmitted solar radiation. direct and diffuse, under the crown

S* = hourly mean of transmitted direct solar radiation under the crown

R = hourly mean of solar radiation in the open

X_1 = basal area of zone of influence in square feet per acre

X_2 = mean hourly solar altitude.

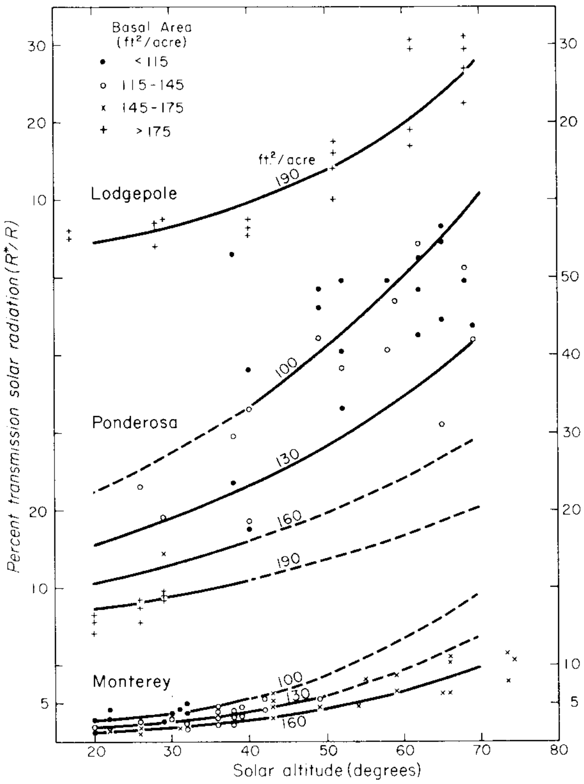

Figure 5–*Percent transmission of solar radiation (R */R) is affected by solar altitude, basal area, and tree species.*

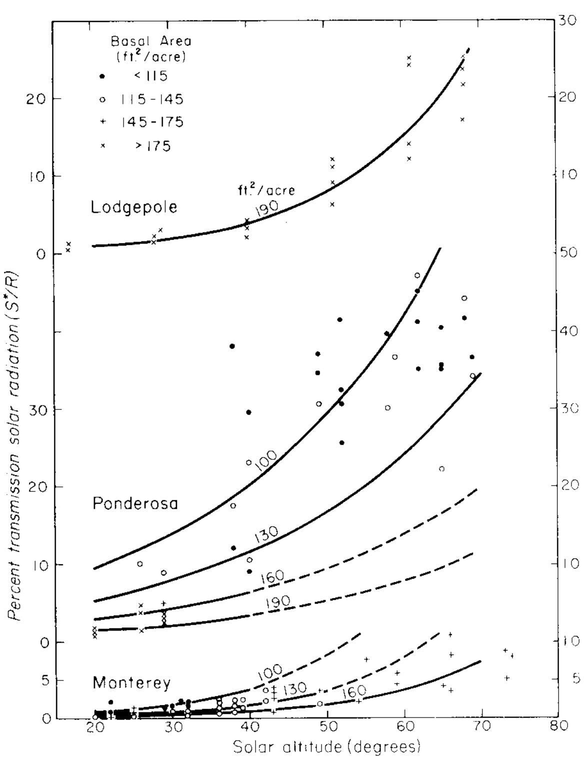

Figure 6–*Percent transmission of direct solar radiation (S*/R) is affected by solar altitude, basal area, and tree species.*

altitudes were about 20°, and more than two-thirds of the total flux when solar altitudes were about 60°.

Diffuse solar radiation under the stands (Dt*) amounted to about two-thirds or more of the total transmitted radiation flux (Dt*/R*) at low solar altitudes. Its relative significance decreased rapidly as solar altitude increased–particularly when basal area per acre was low. The curves in *figures 5 and 6* are particularly unrealistic for higher solar altitudes. This condition is due to the extrapolation of the curves for (S*/R) in *figure 6* to high solar altitudes. The absolute values of transmitted diffuse radiation (Dt*) increased as solar altitude increased, and as basal area per acre decreased, but the increase is small relative to the increase of transmitted direct solar radiation.

Analysis of Transmission Components

The solar radiation transmitted through the crowns can be separated analytically into four components by measuring insolation in the atmosphere diffuse solar radiation in the atmosphere (D), the transmission of solar radiation at the transmission plot (R*), and the transmission of diffuse solar radiation under the crowns (Dt*). To separate insolation (R) into its direct (S) and diffuse (D) components, a shading ring attachment (World Meteorological Organization, 1963) was constructed and used during selected time periods at each of the three stands. A diffuse radiation ring was used with a solarimeter at nearby open sites. It shields the glass domes of the solarimeter from the direct solar beam (S) and yields measurements of the diffuse solar radiation (D) in the atmosphere. Concurrent measurements of insolation (R) are then used to obtain direct solar radiation in the atmosphere (S) by subtraction.

Direct solar radiation in the atmosphere (S), the mean of transmitted direct solar radiation (S*) in the transmission plot at the Monterey pine stand, and the ratio (S*/S) in percent are given in *table 1* for the clear day, February 25, 1964. The ratio (S*/S) reached a maximum of about 4 percent near noon and decreased to 2 percent or less in the afternoon when dense crowns prevented much direct transmission of solar radiation.

During most of this very clear day, diffuse radiation in the atmosphere (D) amounted to only 8

Table 1–Transmission *components of Monterey pine stand, February 25, 1964, by hours (P.s.t.)*

Component	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	Total
	Langleys per hour								
S	24.6	40.8	53.0	59.3	60.9	56.6	47.6	37.1	379.9
S*	.6	1.0	1.0	2.3	1.5	1.1	0.2	0.1	7.8
D	4.1	5.0	5.5	5.8	5.7	5.6	5.4	4.5	41.6
Dt*	.6	.9	1.2	1.2	1.2	1.0	.7	.4	7.2
D*[1]	.2	.2	.2	.2	.2	.2	.2	.2	1.6
Dt*-D*	.4	.7	1.0	1.0	1.0	.8	.5	.2	5.6
Ssca*[2]	.3	.6	.9	.9	.9	.7	.4	.2	4.9
Dsca	.1	.1	.1	.1	.1	.1	.1		.7
	Percent								
S*/S	2	2	2	4	2	2	<1	<1	2
D*/D	15	18	22	21	21	18	13	9	17

[1] Assumed D*/D = 4 percent.

[2] Assumed Dt* - D* = Ssca* + Dsca* and Dsca*/D) = Ssca*/S.

to 11 percent of insolation (R). The ratio (Dt*/D) about noon reached its maximum–slightly more than 20 percent. This ratio was nearly ten times greater than (S*/S), and included the scattering effect of the crowns on direct solar radiation (Ssca*) in addition to transmission and scattering of diffuse solar radiation (D* and Dsca*) in the atmosphere.

These three components of transmitted diffuse radiation (Dt*) can be separated approximately by two reasonable assumptions. Diffuse radiation in the atmosphere comes primarily from regions near the sun and the zenith. With low solar altitudes, on February 25, the Monterey pine transmitted only about 2 to 4 percent of the direct solar beam (S*/S). Since the path length of diffuse solar radiation through the crowns should be, on the average, less than the path length of direct solar radiation on a day with low solar altitudes, it seems reasonable to assume that no more than 4 percent of the diffuse solar radiation in the atmosphere (D) was transmitted through the crown openings (D*). The assumption may represent a slight underestimate near solar noon and a slight overestimate near sunrise and sunset. This assumption of 4 percent transmission is used to obtain the estimate of transmission of diffuse radiation (D*) which amounted to only about 0.2 ly/hour during each of the measurement hours *(table 1).*

The value of (Dt*-D*) is the remaining proportion of diffuse radiation under the stand not accounted for by transmission of diffuse radiation (D*) *(table 1).* This remainder represents the downward scattering of both direct and diffuse radiation in the atmosphere by stand biomass. Assume now that the downward scattering effect of the Monterey pine crowns is relatively equal with respect to direct and diffuse solar radiation in the atmosphere. The remainder (Dt*/D*) can be apportioned to downward scattering of direct (Ssca*) and diffuse (Dsca*) solar radiation according to the relative downward flux of direct (S) and diffuse (D) solar radiation in the atmosphere. Hence, for this clear day, between 50 and 75 percent of the diffuse solar radiation under the stand (Dt*) originated as direct solar radiation. Even if the scattered diffuse solar radiation (Dsca*) is underestimated, diffuse solar radiation in the atmosphere is so small during clear days that any underestimate is of little consequence. The dense foliage of the crowns and the 80- to 100-percent crown closure exclude almost all of the direct and diffuse solar radiation alike.

A similar analysis of transmission components for the ponderosa pine plantation during the clear day, April 29, 1964, about 1 year after the thinning treatment, was made *(table 2).* The remaining pines had not as yet filled in vacant crown space, and canopy closure was estimated to range between 40 to 60 percent.

Since solar altitudes on April 29 were higher than on February 25, 1964, incoming direct and diffuse solar radiation at the ponderosa pine plantation were considerably greater. An upslope mountain breeze occasionally drew a thin plume of smoke over the site from a sawmill several miles away, and the slightly irregular hourly trace of diffuse solar radiation (D) was probably a consequence of the smoke. Between 1200-1300 hours the remaining pines in the zone of

Table 2–*Transmission components of ponderosa pine plantation, April 29, 1964, by hours (P.s.t.)*

Component	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	Total
	Langleys per hour									
S	42.3	61.4	70.8	76.5	75.9	70.3	60.2	47.0	31.4	535.8
S*	19.6	26.4	32.0	30.3	18.4	23.6	23.9	9.7	3.8	187.7
D	8.9	9.8	10.0	9.2	8.2	7.9	8.7	8.0	6.6	77.3
Dt*	7.6	8.2	8.1	8.0	7.9	7.9	7.9	6.6	4.9	67.1
D*	3.1	3.9	4.5	4.1	3.7	3.6	3.5	2.8	2.0	31.2
Dt*-D*	4.5	4.3	3.6	3.9	4.2	4.3	4.4	3.8	2.9	35.9
Ssca*[1]	3.7	3.7	3.2	3.5	3.8	3.9	3.9	3.3	2.4	31.4
Dsca*	.8	.6	.4	.4	.4	.4	.5	.5	.5	4.5
	Percent									
S*/S	46	43	45	40	24	34	40	21	12	35
Dt*/D	85	84	81	87	96	100	91	82	74	87
D*/D[2]	35	40	45	45	45	45	40	35	30	–

[1] Assumed Dt*-D* = Ssca* + Dsca* and Dsca*/D = Ssca*/S.

[2] Assumed.

stand influence reduced the transmission of direct solar radiation considerably.

In this open stand the ratio of transmitted diffuse radiation to diffuse radiation in the atmosphere ((Dt*/D), ranged between 74 and 100 percent. Diffuse radiation within the open plantation was nearly as great as diffuse radiation in the atmosphere. The transmission of direct solar radiation (S*/S) reached a maximum of about 45 percent. Therefore, the transmission of diffuse radiation (D*/D) was assumed to average 45 percent during the 4-hour period centered at noon, and to decrease gradually toward sunrise and sunset as the path length of diffuse radiation in the atmosphere through crown space gradually increased *(table 2).*

Finally, the transmission components during the clear day, May 12, 1964, for the lodgepole pine stand were analyzed *(table 3).* High solar altitudes and a 7,000-foot elevation resulted in a very strong flux of direct solar radiation. A few cumulus clouds upslope and to the east increased diffuse radiation at the site because of reflection downward early in the afternoon. Surprisingly, this increase of atmospheric diffuse radiation was not detected as transmitted diffuse radiation.

Table 3–*Transmission components of lodgepole pine stand, May 12, 1964, by hours (P.s.t.)*

Component	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	Total
	Langleys per hour											
S	23.8	41.1	60.2	74.1	82.7	86.4	85.4	83.8	67.8	56.5	38.2	700.0
S*	0.1	0.8	1.6	9.5	22.1	22.0	15.7	11.2	4.4	2.5	.6	90.5
D	4.2	4.9	5.8	5.9	6.0	6.2	6.1	9.8	7.2	5.0	5.5	66.6
Dt*	1.5	2.4	2.8	4.4	4.8	5.5	4.8	4.9	3.2	2.0	1.2	37.5
D*	.8	1.0	1.4	1.5	1.8	1.9	1.8	2.9	1.8	1.2	1.1	17.2
Dt*-D*	.7	1.4	1.4	2.9	3.0	3.6	3.0	2.0	1.4	.8	.1	20.3
Ssca*[1]	.6	1.3	1.3	2.7	2.8	3.4	2.8	1.8	1.3	.7	.1	18.8
Dsca*	.1	.1	.1	.2	.2	.2	.2	.2	.1	.1	–	1.5
	Percent											
S*/S	<1	2	3	13	27	25	18	13	6	4	2	13
Dt*/D	36	49	48	74	80	89	79	50	44	40	22	56
D*/D[2]	20	20	25	25	30	30	30	30	25	25	20	–

[1] Assumed Dt*-D* = Ssca* + Dsca* and Dsca*/D = Ssca*/S.

[2] Assumed.

Comparisons Among Sites

For the purpose of comparison, the Monterey pine stand can be taken to represent a stand with almost complete canopy closure and an extremely dense crown biomass (needles and twigs). The ponderosa pine plantation can be taken to represent an open stand with a canopy closure of about 50 percent and a minimum of biomass in each crown. The lodgepole pine stand is intermediate in canopy closure with a much more irregular upper crown surface.

Any comparison of the transmission components must take into account the low solar altitudes during February 25 at the Monterey pine stand. Transmission was sampled at the Monterey pine site for seven midday hours during the clear day of April 30, 1963, when solar altitudes were comparable; unfortunately, diffuse solar radiation in the atmosphere was not measured on that particular day. On April 30, transmission (R*/R) during these hours amounted to 6.3 percent, an amount almost double total transmission for February 25, 1964.

For each of these clear days, about 90 percent of insolation was direct solar radiation (S), and only about 10 percent was diffuse solar radiation (D). The amount of transmission of direct solar radiation through the stands as sunflecks (S*/S) in each stand was Monterey–2 percent; ponderosa–35 percent; and lodgepole pine–13 percent. For the clear daylight hours sunflecks (S*) amounted to more than half of the transmitted solar radiation at each stand. Though not unexpected at the open ponderosa pine plantation, it was not expected at the dense Monterey pine stand and for the relatively low solar altitudes, which did not exceed 42° during the measurement period on February 25. The Monterey pine stand data suggest quite strongly that sunflecks account for more than half of the transmitted solar radiation in most if not all pine stands in middle and lower latitudes during clear days.

At each stand, the ratio of diffuse radiation within the stand to diffuse radiation in the atmosphere (Dt*/D) exceeded the ratio for direct solar radiation (S*/S). Indeed, at the open ponderosa pine plantation, the flux of diffuse solar radiation within the stand was almost equal to diffuse solar radiation above the stand.

One component of diffuse solar radiation within the stands (Dt*) is the transmission of diffuse radiation in the atmosphere directly downward through crown openings (D*). In this study, it was assumed that the crowns were about equally open to direct (S*) and diffuse (D*) solar radiation. Hence, the ponderosa pine plantation would be quite open to the transmission of diffuse solar radiation directly downward (D*); in this extreme case this component made up almost half of the diffuse radiation within the stand. Because of the small amount of diffuse solar radiation in the atmosphere during these clear days, the downward scattering of diffuse solar radiation by crown biomass (Dsca*) was the least significant of the transmission components. It amounted to no more than 5 percent transmitted solar radiation (R*) at any of the three stands.

The remaining component of diffuse solar radiation within the stand (Dt*) is direct solar radiation in the atmosphere scattered downward by the crowns (Ssca*). This component was least in the dense Monterey pine stand and greatest in the open ponderosa pine plantation. In the ponderosa pine plantation there was a greater probability that the direct solar beam reflected downward by crown biomass would reach the ground through open spaces between the more widely-spaced crowns. At each stand, this component (Ssca*) made up almost half of the diffuse solar radiation (Dt*) within the stands. Hence, for clear-sky conditions, direct solar radiation in the atmosphere was the primary source of both direct and diffuse solar radiation within these pine stands. Of the direct solar radiation in the atmosphere which was transmitted through the crowns, the direct component was far more significant than the downward scattering component.

Significance of Sun flecks

The significance of sunflecks is illustrated by graphical examples of the downward flux of direct (S*) and diffuse (Dt*) solar radiation under pine stands relative to insolation (R) *(figs. 7,8). Figure 7A* is quite representative of both direct and diffuse transmission under the dense crowns of the Monterey pine stand when solar altitudes are low. On February 25, diffuse solar radiation, closely analogous to shade light, reaching pyranometer 9 changed very slowly through the day. The regime of diffuse radiation at other points within the transmission plot during the day showed small spatial variation of diffuse solar radiation under the dense crowns when solar altitudes were low. The only exception was that solar radiation increased slightly in a southeasterly direction from pyranometer 7; apparently some diffuse solar radiation penetrated from open areas in the irregular margin of the stand *(fig. 2).* Transmitted diffuse solar radiation at pyranometer 9 was greater during April 30 *(fig. 7B),* but the intensity remained quite stable over much of the day.

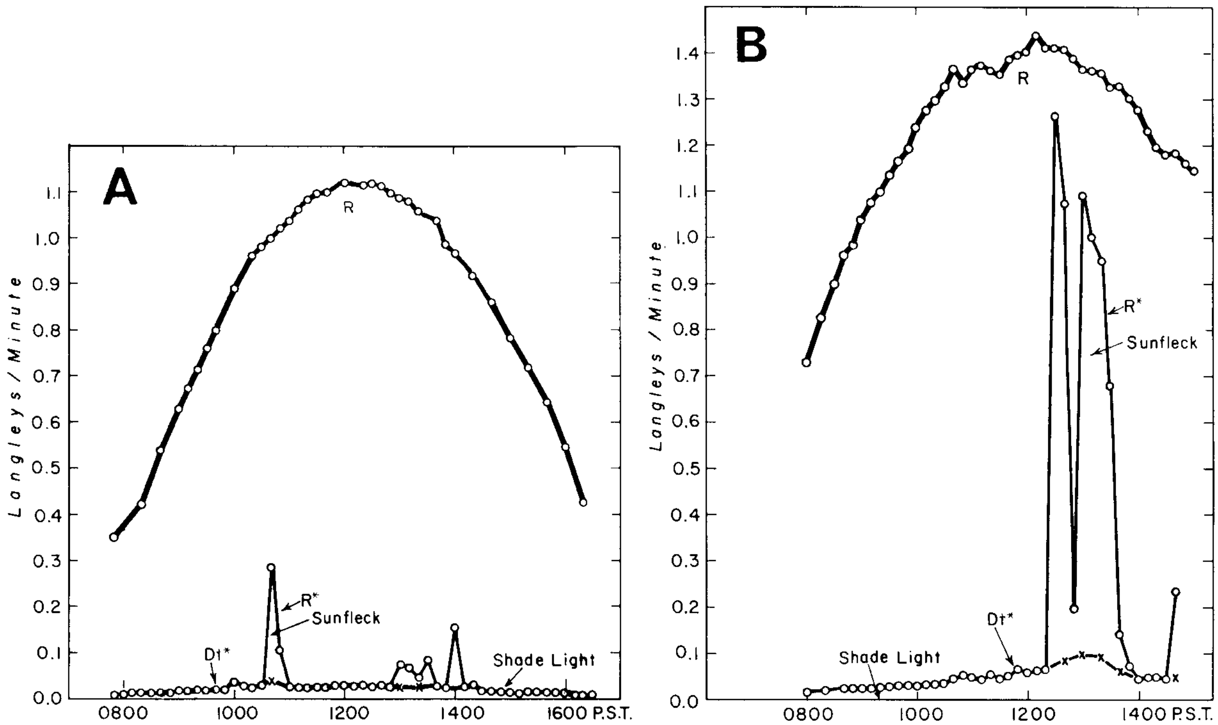

Figure 7 – *Transmission components measured by Eppley pyranometer No. 9, at the Monterey pine stand. A, February 25, 1964: the measurements are representative of both direct and diffuse transmission under dense crowns when solar altitudes are low B, April 30, 1964: transmitted diffuse solar radiation (D*) was greater this day than earlier (see A). R = insolation: R* = insolation under crowns; Dt* = diffuse solar radiation wider crowns.*

The intensity of the sunflecks which passed over pyranometer 9 during February 25 was less than half the intensity of insolation in the open, but on the needle-covered floor of the stand, the sunflecks appeared bright and of almost full intensity to the eye. Nevertheless, these sunflecks contributed about 40 percent of the solar radiation flux to pyranometer 9 between 0800 and 1600 hours. A large almost full-intensity sunfleck passed over pyranometer 9 between 1220 and 1340 hours on April 30. It was the consequences of the relatively large crown opening immediately south of pyranometer 9 *(fig. 2):* the same opening does not produce the same effect on February 25 because solar altitudes were too low.

Figure 8A is representative of transmission at pyranometer I in Cell 30 of the ponderosa pine plantation before thinning. The data are for the clear day of January 11, 1963, when solar altitude on an hourly basis did not exceed 29°. Within the zones of stand influence for January 11, basal area per acre ranged between 180 and 200 square feet. Diffuse radiation (Dt*) under the stand followed a daily regime higher than under the Monterey pine stand. There was very little variation among the other points within the plot. Weak stint-leeks accounted for almost half of the transmitted radiation despite very low solar altitudes.

Figure 8B shows direct and diffuse solar radiation at the same point in Cell 3B of the ponderosa pine plantation a few months after thinning. For the clear day, August 1, 1963, the maximum mean hourly solar altitude was 68°, and the basal area per acre within the zones of stand influence ranged between 90 and 140 square feet. The figure clearly shows the much higher level of diffuse solar radiation within the open stand, and a full-intensity sunfleck between 1115 and 1245 hours. During the passage of this sunfleck over pyranometer 1, the total transmitted flux (R*) exceeded insolation slightly. Since a considerable proportion of the celestial hemisphere was hidden from the sensor by crowns of the remaining trees, the proportion of diffuse radiation in the atmosphere transmitted directly through crown openings to the sensor (D*/D) must have been less than

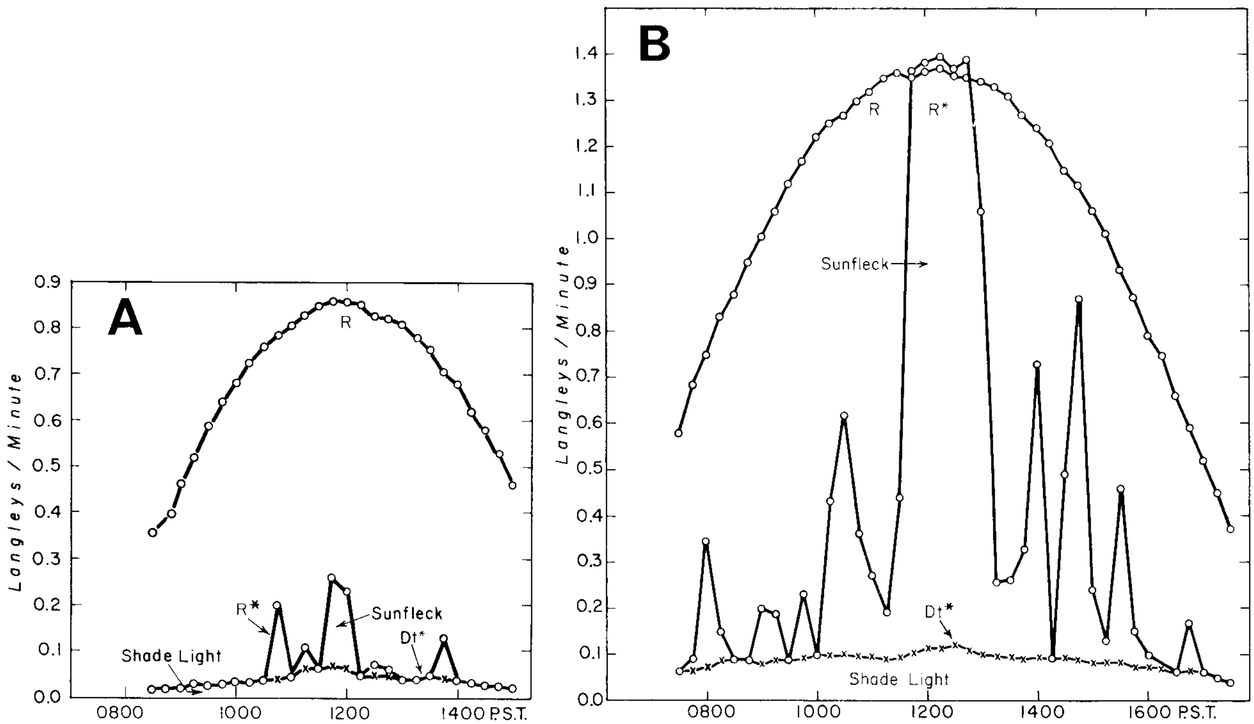

Figure 8–*Transmission components measured by Eppley pyranometer No. 9, at a ponderosa pine plantation. A, before thinning, on a dear day, January 11, 1963. B, alter thinning, on a clear day, August 1, 1963: level of diffuse solar radiation (D*) was much higher than that before thinning. R = insolation; R* = insolation under crowns; Dt* = diffuse solar radiation under crowns.*

the similar proportion for direct solar radiation (S*/S). Hence, the sunfleck must have included downward scattering from nearby crowns (Ssca* + Dsca*). Sunflecks at or slightly above full intensity were not uncommon in Cells 3B and 4B of the plantation after thinning.

CONCLUSIONS

Most investigations of transmission appear to be biased toward summer-season maximum transmission rates. Clearly, transmission is related to daily and seasonal regimes of solar altitude, and comparative analyses among sites and species need to take this into account. At the same site, direct and diffuse solar radiation is probably not transmitted in equal proportions. For meaningful analysis, data collection should be restricted to either clear or cloudy conditions.

In dense stands, at middle latitudes, sunflecks account for a large proportion of the solar radiation reaching the forest floor. On the basis of the sampling of transmission during clear sky conditions at the three sites, it seems reasonable to set down the following generalizations concerning sunflecks as measured by the pyranometer:

1. The precise occurrence of sunflecks at a point on the forest floor is the consequence of the unique distribution of crown biomass within a relatively large area to the cast, south, and west of the point – the zone of stand influence; the crown directly over the sensor is not always the most significant biomass;
2. Because of the daily and seasonal regimes of solar altitude and solar azimuth, sunfleck contributions at a point cannot be predicted from a few random measurements over the year;
3. Because of downward scattering from adjacent crowns, sunfleck intensity may occasionally exceed by rather small amounts the concurrent intensity of insolation;
4. Because of the wide range of sunfleck intensity,

direct solar radiation transmitted through crowns cannot be estimated on the basis of the areal distribution of sunflecks alone;

5. A rigorous analysis of radiation components within a forest stand probably requires an intensive sampling scheme for estimation of transmission of sunflecks for short but seasonally representative time units and

6. Biological activity under the crown must be adapted to the low flux of diffuse solar radiation (Dt*), but at the same time be adapted to sudden impulses of solar radiation associated with the passage of sunflecks which may at times equal or slightly exceed insolation.

SUMMARY

Muller, Robert A.

1971. **Transmission components of solar radiation in pine stands in relation to climatic and stand variables.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta. 13 p., illus (USDA Forest Serv. Res. Paper PSW-71)

Oxford: 111.211–015.24:111.86 (794) [+ 174.7 *Pinus radiate* + 174.7 *Pinus ponderosa* + 174.7 *Pinus contorta*].
Retrieval Terms: pine forests; California; solar energy regime; bioclimatology; pyranometry.

Transmission of solar radiation in forest stands refers to the ratio of solar radiation under crowns to solar radiation in the atmosphere. Data from other studies are not directly comparable because investigations have been carried out over a wide range of solar climates and because of largely unsatisfactory measures of stand biomass which directly produce attenuation of the solar beam downward through crowns.

In a new approach, this study relates the transmission ratio to mean hourly solar altitude and to an index of stand biomass within zones oriented along mean solar azimuths. For three pine species in California, the relationship between solar altitude and transmission was curvilinear during clear sky conditions–transmission increased sharply at higher solar altitudes. Transmission was also inversely related to the index of stand biomass, and in addition, differences probably attributable to crown characteristics of each species were considerable.

The magnitude of the pathways by which direct and diffuse radiation penetrate through the crowns was estimated analytically by means of measurements of direct and diffuse solar radiation by standardized sensors and also by several reasonable assumptions. The data suggest that for clear sky conditions at lower and middle latitudes, sunflecks account for more than half of the transmission even in dense stands. Sunfleck intensity on the forest floor was highly variable; indeed, the intensity of a few sunflecks exceeded slightly solar radiation in the atmosphere because of the downward scattering effects of the crowns.

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