PACIFIC SOUTHWEST Forest and Range Experiment Station

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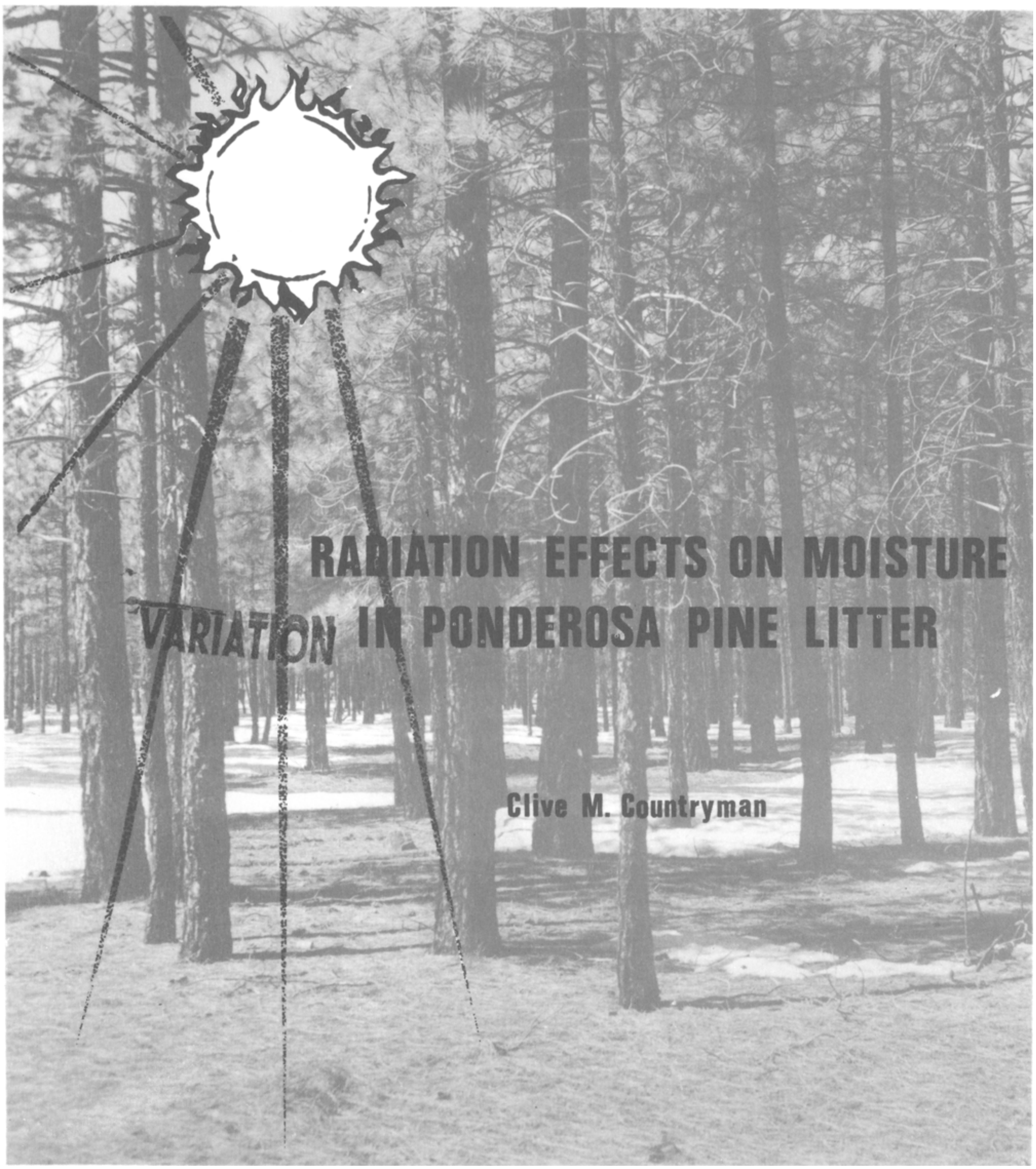

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The Author

CLIVE M. COUNTRYMAN was, until his retirement in 1977, in charge of the Station's fire behavior studies, with headquarters at the Forest Fire Laboratory, Riverside, Calif. He earned a bachelor's degree in forestry at the University of Washington in 1940, and joined the Forest Service the following year.

ACKNOWLEDGMENT

The original study was designed and conducted by Charles C. Buck, former Assistant Director, Division of Forest Fire and Atmospheric Sciences Research, Forest Service, U.S. Department of Agriculture, Washington, D.C., and now deceased.

SUMMARY

Countryman, Clive M.
1977. **Radiation effects on moisture variation in ponderosa pine litter.** USDA Forest Serv. Res. Pap. PSW-126, 23 p., illus. Pacific Southwest Forest and Range Exp. Stn., Berkeley, Calif.
Oxford: 431.2:114.351 — 174.7 *Pinus ponderosa.*
Retrieval Terms: Pinus ponderosa; surface fuels; litter; fuel moisture content; solar radiation.

Reliable estimates of the moisture in wildland fuel are essential for research investigations of fire behavior, and in firefighting, fire use, fire danger rating, and other activities concerned with the ignition and behavior of wildland fire. Although research has ascertained many of the factors controlling the moisture content of wildland fuels and has provided some understanding of the manner in which fuel moisture affects fire, there is relatively little information about the variation in the moisture content of wildland fuels as they exist in place. This study explored the variation in moisture of litter under ponderosa pine (*Pinus ponderosa* Laws.) timber stands.

The study revealed that moisture variations of sufficient magnitude to affect the ignition and behavior of fire can occur within short horizontal distances. These variations were found to be caused primarily by solar radiation reaching some litter areas through openings in the crown canopy, and cooling of the litter directly under the openings at night. Analysis of the data indicates that a close relationship exists between the maximum solar radiation received and the litter moisture. The lower moisture of litter that is exposed to solar radiation and then shaded will persist through the day. Consequently, the history of the exposure of an area of litter to radiation is more important in determining its moisture content at any given time than are the conditions at that time. Because of the strong dependence of litter moisture on radiation effects, any influence affecting the radiation received or lost, such as stand characteristics, time of day and year, latitude, atmospheric conditions, and topographic configuration, will also affect the moisture variation patterns in the litter.

Because of the exploratory nature of the study, the specific results probably apply directly only to the study area. However, the strong relationships found between litter moisture and radiation have important and widespread implications. Other vegetative types also provide only partial protection of surface litter from solar radiation and nighttime radiation losses, and therefore large variation in the moisture of surface fuels are likely in these types too. The results of the study indicate a need for more sophisticated investigations of radiation heating and cooling in various wildland fuel types and situations, with the object of developing area classification systems and measurement techniques permitting realistic estimates of fuel moisture.

The strong influence of fuel moisture on the behavior of wildland fire is well known. Fuel moisture has long been of major import in the prediction of fire behavior for fire control and fire use applications. And as sophisticated fire prediction models requiring detailed fuel moisture data as inputs come into more extensive practical use, information on the variations in fuel moisture assumes even greater consequence.

Extensive research has provided some understanding of the manner in which fuel moisture affects fire behavior, and has ascertained many of the factors controlling the moisture in wildland fuels. However, most investigations of fuel moisture variations have been concerned with changes at a specific point as affected by weather, season of the year, or fuel characteristics, and with wide-ranging effects of altitude, slope, and aspect. There is virtually no knowledge of the spatial variation in the moisture of surface fuels that are intermittently exposed to solar radiation and partially shielded from radiation cooling. Such fuels are an important part of the fuel complex in most wildland fuel types.

During a study of the rate of fire spread in ponderosa pine litter in northern California (Curry and Fons 1938), it was observed that the moisture content of the surface layer of pine needles varied widely over the experimental area. Because fire spread is greatly affected by moisture in this fuel, the observation led to an investigation of the moisture content of the surface litter[1] as it changed during the day, the season, and from place to place. Although the study was exploratory, and conducted nearly a half-century ago, when wildland fire research was still in its infancy, the results provide one of the few observations of the actual variation in the moisture content of the fuel type.

The study was conducted primarily as an aid in fuel moisture sampling and evaluation for the rate-of-spread study, and the results were not published. Recent analysis of the data, however, has revealed that in addition to valuable information on in-place variation of fuel moisture, the study also provides much information on the magnitude of the effects of variations in incoming shortwave solar radiation and outgoing longwave radiation on the moisture content of intermittently exposed and shaded surface fuels. Consequently, the results of the study have much wider application and implications in fire control, fire use, and fuel moisture research than originally anticipated. This report describes the study and the results of the analysis.

STUDY AREA

The study area chosen is at a latitude of 41° 21' N., near the foot of the eastern slopes of Mt. Shasta in north-central California. The study site was level and at an elevation of about 4000 feet. The soil is a sandy loam derived from pumice and lava ash.

The climate of the area is characterized by hot, dry summers and cold winters. Much of the precipitation comes in the form of snow, and snow cover often persists throughout the winter. Occasional thunderstorms occur during the summer, and dry foehn winds frequently appear in the fall. A considerable amount of needle fall occurs each year in the pine stands, but because of the cold winters and dry summers, the pine litter decays slowly. The litter is kept compact by the heavy snowfall.

[1] The term "litter" as used in this paper refers to all organic material above mineral soil.

PROCEDURES

Six transects, each 150 feet long, were laid out in ponderosa pine stands of various ages and densities in the spring of 1936. Stakes set at 5-foot intervals along the transects marked the 30 "sampling stations" from which samples of the pine litter were taken for moisture determination. Samples weighing 60 to 70 grams were collected from an area 5 feet in diameter around the stakes. Only surface needles to a depth of two or three needles were collected, and the needles were replenished from surrounding areas at the end of each sampling period to maintain the litter depth. The moisture content of the samples, on a dry weight basis, was determined by the then newly developed xylene reflux distillation method (Buck and Hughes 1939).

For most sampling periods the litter samples were collected as rapidly as possible — usually 10 to 15 minutes were required to complete the sampling of a transect. For Transect 3 on September 22, however, a different sampling technique was used. This time the stations were sampled successively 15 minutes apart, beginning with Station 1 at 0900 hours and ending with Station 30 at 1615. On September 24 and October 8, paired samples from sunlit and shaded areas were also collected from an area in the vicinity of Transect 3.

Temperature and relative humidity observations were made with a sling psychrometer at the beginning and end of each sampling period for a transect, at the time each sample was taken for Transect 3 on September 22, and for each pair of samples on September 24 and October 8. The intensity of the reflected light from the litter surface was measured with a photronic photographic exposure meter for most sampling periods at each station. Usually these readings were made at 5- to 10-minute intervals starting 30 to 40 minutes before the samples were collected. For Transect 3 on September 22, reflected light readings were made at all stations each time a sample was collected.

Sampling was started in July, and continued at various intervals and times of day until late October. Not all stations of a transect were sampled each time, nor were all transects sampled throughout the season.

Transect Descriptions

Transect I was laid out in a southeast to northwest direction in a dense pole-sized stand of timber approximately 60 feet in height. The crown canopy was also dense, and little direct solar radiation reached the surface — sunlit patches were small and quite uniformly distributed. The litter was about 3.5 inches deep, with a generally uniform surface. However, the litter was more compact at Station 5 because of a deer bed, and some mixing of the surface needles with lower layers occurred when the bed was used. Also, a dead limb with branches at Station 24 held the surface needles somewhat above the more compact litter below.

Transect 2 ran in a southwest to northeast direction in a moderately dense stand of timber averaging 60 feet in height. Openings in the crown canopy were larger than for Transect 1, and the transect crossed an opening about 50 feet in diameter between Stations 10 and 20. Litter within the timber stand was uniform and about 3 inches deep. The surface of the large opening was covered with a thin layer of pine needles and sedge. Some grass also grew under the larger openings in the crown canopy within the timber stand.

Transect 3 was established in a west to east direction in a medium density timber stand with trees averaging 50 feet in height. Individual tree crowns were dense, but openings in the crown canopy were larger and less uniformly distributed than for Transect 1. The litter was about 3 inches deep with a uniform surface.

Transect 4 ran in a south-southeast to north-northwest direction in a timber stand of moderate density and with trees about 70 feet in height. Most of the transect was under a narrow alley between the crowns. The adjoining canopy was generally dense, and there were few other openings. The litter surface was uniform, but the litter varied in depth from 4.5 inches at the SSE end of the transect to 2.5 inches at the NNW end.

Transect 5 started near the edge of a closed, mature timber stand, and then ran in a northerly direction across an open area between Stations 16 and 26, and thence into a young, dense stand of saplings with thin crowns. The litter was about 5 inches deep under the mature timber and 3 inches deep in the sapling stand. The open area was covered with pine needles to a depth of about 0.5 inches, with some moss and sedge also present.

Transect 6 was laid out from west to east in an open, mature timber stand. The crown canopy was mostly closed, but there were some small openings over the transect. The litter was about 4 inches deep with a uniform surface.

Environmental Conditions

The last heavy rainfall of the season in the study area came on June 14. Additional light rain fell on July 8 and 9, but did not penetrate deeply into the litter layer, and no other penetrating rains occurred during the season. Stable weather conditions with generally clear skies usually prevailed for several days before each sampling period. Wind speeds within the timber stands were always low.

Although the surface needles appeared dry when the sampling was started on July 7, the lower third of the litter layer and the soil beneath were still saturated from the June rain and the winter snow. Heavy dew formation was common in July and early August as a result of the cool nighttime temperatures and the high moisture content of the soil and lower litter layers. By September, however, the entire litter layer and soil were dry and dew formation was rare.

RESULTS AND DISCUSSION

Surface litter moisture samples were obtained for a wide variety of environmental conditions and timber stand characteristics. Considerable variation in fuel moisture was found among stations of a transect, and also in the moisture patterns between transects. In general, the variance was greatest when the fuel moisture was high, and tended to decrease as the season progressed. Sampling dates and times, air temperature and relative humidity, and a summary of the surface litter moistures observed for each transect are shown in *table 1*.

Most of the observed differences in moisture content between stations and transects appear to have been caused by variations in the amount and patterns of solar radiation reaching the litter surface. During July and early August, the residual effects of winter snow and the heavy rain of June 14, and the effects of nighttime back radiation were also apparent.

Radiation affects fuel moisture through the complex processes by which the earth's surface and the atmosphere are heated and cooled and the effect of the heating and cooling on relative humidity and fuel temperature. Dead wildland fuels are hygroscopic, and in the absence of free water the moisture content of a piece of fuel depends mostly on the relative humidity of the air immediately surrounding it, but fuel temperature also has an effect. Fuel at a given temperature and exposed to a constant relative humidity will eventually attain a moisture content that is in equilibrium with that humidity and temperature. The moisture content will then remain constant until the humidity or fuel temperature changes. The time required for the moisture to reach the equilibrium value depends principally on the fuel characteristics and the difference between the actual and equilibrium moistures. Temperature and relative humidity are often continuously changing under natural conditions, and consequently the actual moisture in wildland fuels at any given time usually lags behind the equilibrium moisture. The trend in actual moisture, however, is always toward the appropriate equilibrium moisture for the existing conditions.

As long as the mixing ratio[2] of the air remains constant. the relative humidity varies inversely with the air temperature — decreasing as the air temperature goes up and increasing as the air temperature goes down. The main source of heat for warming the air is solar radiation. But because air is nearly transparent to the shortwave solar radiation, the heating is accomplished indirectly. The radiant energy must first strike some solid or semiopaque material before it is converted to thermal energy. Where vegetation is sparse, the conversion takes place principally at the ground surface, thus raising its temperature. The air next to the surface is heated by conduction, and the heat is transferred to deeper air layers by convection. The air is also warmed through absorption of longwave radiation from the heated ground surface by the carbon dioxide and water vapor in the air. Time is required to transfer the heat from the ground surface to the air above it, however, and consequently the air temperature lags behind the surface temperature, with the amount of lag in-

[2] Weight of water vapor per unit weight of dry air.

Table 1 - *Summary of sampling dates and times, air temperature, relative humidity, and surface litter moisture for six transects in ponderosa pine timber in northern California.*

Transect	Date sampled	Time sampled	Stations sampled	Air temperature [1]	Relative humidity[1]	Mean	Moisture range	Variance
	°F						*Percent*	
1	Jul. 7	1310	30	74	29 - 32	8.1	7.4 - 9.2	.18
	Jul. 24	0804	30	61 - 64	64 - 61	15.5	14.2 - 17.2	.36
2	Jul. 7	1350	30	75	31 - 36	6.5	3.7 - 8.8	2.02
	Jul. 24	0823	30	66 - 68	67 - 60	16.7	14.1 - 22.0	5.94
	Jul. 31	1320	12	86	29	6.9	8.9 - 11.7	.89
	Aug. 14	1057	9	81	29	10.4	5.3 - 8.3	.85
3	Jul. 21	1400	29	91 - 90	31	7.2	4.7 - 9.0	1.51
	Sept. 21	1030	15	81	19	7.3	5.8 - 8.3	.32
	Sept. 21	1520	15	84	14	6.0	5.4 - 6.3	.23
	Sept. 22	([2])	29	74 - 87	28 - 12	([2])	([2])	([2])
	Sept. 30	1130	15	71 - 72	20 - 21	7.1	6.2 - 7.7	.18
	Oct. 8	1000	15	75 - 76	18 - 16	8.1	7.8 - 9.1	.14
4	Jul. 21	1400	30	91 - 90	31	8.0	6.5 - 9.4	.44
	Sept. 21	1120	15	81	19	7.7	7.2 - 8.0	.04
	Sept. 23	1400	30	86	12	6.4	5.9 - 6.9	.06
	Sept. 30	0920	30	63 - 65	40 - 34	10.0	9.2 - 11.1	.14
5	Jul. 29	1330	30	85 - 84	33 - 32	7.8	5.6 - 13.3	3.24
	Jul. 31	1030	30	79 - 81	42 - 31	10.2	6.2 - 13.8	2.27
	Sept. 21	1320	15	85	15	6.9	4.9 - 8.8	1.13
	Sept. 30	1515	30	75	15	7.4	5.8 - 8.4	.50
	Oct. 8	1311	15	82	14	6.8	5.7 - 7.8	.42
6	Jul. 31	1120	29	82 - 83	29 - 31	8.6	5.6 - 10.3	1.20
	Sept. 21	1400	15	86 - 85	12- 15	6.1	5.5 - 7.0	.32
	Sept. 24	1005	15	72 - 80	35 - 22	7.8	6.5 _ 8.7	.46
	Sept. 30	1304	30	75 - 74	20 - 19	6.9	6.1 - 7.9	.25
	Oct. 8	1325	15	82	14 - 13	6.2	5.4 - 7.0	.19
	Oct. 23	1123	11	62	25	9.1	8.4 - 9.9	.23

[1] Beginning and end of sampling period.
[2] Stations were sampled 15 minutes apart from 0900 to 1615 hours.

creasing as the distance above the surface increases. During the daytime in the open, then, a temperature gradient, with the air temperature decreasing with height above the ground, is usually present.

Although the earth is always losing heat by longwave radiation, the incoming solar radiation and heating exceeds this loss during most of the daylight hours. At night, however, the back radiation heat loss becomes dominant and the surface of the earth is cooled, in turn cooling the air next to it. The air at higher levels is cooled by mixing with the cold surface layer and also by radiation losses. Consequently, at night the air temperature gradient is opposite that of daytime, and the air temperature increases with height above the ground.

Because of the inverse relationship of relative humidity to air temperature, the relative humidity gradients are the reverse of the air temperature gradients. However, the change in relative humidity with height may not be in direct proportion to the change in temperature because a mixing ratio gradient may also be present. Moist soil and surface fuels may cause the mixing ratio to increase toward the surface, and extremely dry soil and fuel may cause it to decrease. In general, however, the fuel on the surface is usually exposed to higher temperatures and lower humidity during the day than are fuels above the surface or in the shade, and to lower temperature and higher humidity at night.

In timbered areas the tree crowns replace the ground surface as the principal absorber of solar radiation. The crowns do not get as hot as the ground surface in the open, however, because of the different radiation-absorbing characteristics of the living material, the cooling effects of transpiration, and the greater depth through which the radiation is distributed. Air within the stand must also be warmed by downward mixing of the heated air in the crowns, and since warm air tends to rise, the mixing is usually slow. At night the tree crowns reduce radiation heat losses from the litter surface and air within the stand. Consequently, air temperature and relative humidity in the stand have less diurnal fluctuation than in the open. The vertical temperature gradients are also less, and in dense stands the temperature and humidity at the litter surface is often about the same as that measured at the conventional instrument shelter height.

In all but the densest of stands, however, some solar radiation reaches the litter surface through openings in the crown canopy, forming patterns of sunlight on the surface. Litter in the sunlit patches is heated more than shaded areas; therefore the relative humidity of the air surrounding the fuel is lower. At night, the litter below the openings is cooled most by radiation losses, and this results in lower fuel temperature and higher relative humidity than for adjacent areas. If the surface is cooled sufficiently dew or frost may form, particularly when the soil and lower litter layers are moist.

Except for a narrow band near the equator, the sun is never directly overhead, and consequently the solar radiation must usually come through the crown openings at an angle. Because of the radiation angle, timber stand characteristics such as tree height, crown depth and density, opening size and shape, and tree spacing greatly affect the patterns of sunlight reaching the surface and the intensity of the radiation. The sunlit patches on the litter surface move about and the radiation intensity also varies as the sun angle changes during the day. In the northern hemisphere, the solar radiation tends to be directed west of the vertical projection of the opening in the morning, north at noon, and east in the afternoon. As a result, the area cooled most at night may not receive solar radiation at all during the day when the crown opening is small, and only the northern part of the area under the larger openings is likely to be exposed to much solar radiation. The patterns of solar radiation on the surface and radiation intensity also vary with the time of year as the position of the sun with respect to the equator changes.

Surface litter under timber stands, then, is subject to complex and variable patterns of heating and cooling by radiation. Because of the interrelationships of radiation, temperature, relative humidity, and fuel moisture, the patterns of litter moisture can be equally complex and variable. Many of the effects of heating and cooling by radiation appeared in this study, and the data collected gives an insight into the magnitude of the moisture variations that may occur.

Solar Radiation Effects

As indicated earlier, the stations of Transect 3 were sampled at 15-minute intervals throughout the day on September 22, and reflected light readings were taken at all stations each time a moisture sample was collected. These data provided much information on the variation in the amount of solar radiation received by the litter, and the effect of this variation on the litter moisture pattern. The reflected light intensities were normalized to indexes on a scale of 0 to 100. When tabulated by station and time, the indexes show the variation in the intensity of solar radiation reaching the surface at different stations and the manner in which the sunlit areas changed with time (*table 2*). All of the stations received some sunlight during the day, but the relative intensity of the radiation and the time it persisted varied widely among stations. All of the stations were in nearly full shade for half or more of the 7.5-hour period, as could be expected from the dense crown canopy over the transect. Little direct sunlight reached the litter surface after 1500 hours, and only 10 stations had reflected light intensities greater than 50 percent of the maximum observed value at any time. The tendency for the sunlit areas to move from west to east because of the changing sun angle during the day is also manifest in *table 2*, where all of the indexes greater than that for full shade have been delineated.

For convenience in presentation, the air temperature, relative humidity, and litter moisture for Transect 3 on September 22 were converted to indexes based on the highest observed value for the individual parameters (*fig. 1*). The air temperature rose slowly during the forenoon, and then remained constant until late afternoon. The relative humidity pattern was generally the inverse of the air temperature pattern, decreasing during the forenoon, and then changing little until late afternoon. The small dip in the humidity between 1445 and 1530 hours was apparently caused by an influx of drier air from outside the timber stand — the mixing ratio also decreased at this time.

Taken as a whole, the moisture content along the transect decreased most of the day, and then increased somewhat in the late afternoon in much the same way as the relative humidity pattern. However, litter samples taken from adjacent stations and only 15 minutes apart often deviated considerably from the general trend, particularly in the afternoon. To determine if these deviations were associated with the variation in solar radiation reaching the litter at the different stations, the total of the light intensity readings at each station prior to the time the sample was collected was compared to the moisture content at the station. Both moisture content and light intensity totals were converted to indexes on a scale of 0 to 100, with the moisture index based on the minimum observed value and the light index on the highest total for a station. Thus, the moisture index decreases with decreasing moisture content, but the light index decreases with increasing total light intensity to the time of the sample. Consequently, the indexes will move in the same direction if litter

Table 2- *-Reflected light indexes for Transect 3 on September 22 (values greater than that for full shade outlined to show movement of sunlit areas from west to east)*

Time	Station																													
	West																													East
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0900	18	3	2	2	2	2	2	2	4	5	17	43	6	4	2	4	2	2	4	7	3	2	2	11	11	5	2	2	4	50
0915	9	11	4	2	2	2	2	3	2	5	5	36	21	7	3	2	4	2	5	29	5	18	2	4	6	29	9	3	4	3
0930	5	9	6	4	3	2	2	2	2	2	11	11	23	29	6	2	2	4	2	11	10	18	6	3	4	6	29	6	3	10
0945	6	4	5	10	11	5	3	2	2	2	4	29	18	57	29	3	2	2	4	9	23	14	50	4	4	3	11	13	6	4
1000	5	11	5	21	13	7	4	2	2	2	4	6	25	57	32	11	7	2	3	6	16	11	21	57	4	3	3	11	7	6
1015	14	4	4	11	39	11	5	11	2	2	2	7	9	36	71	18	18	6	2	2	11	16	11	64	50	5	3	4	9	5
1030	4	29	4	4	14	32	7	18	11	2	2	5	5	14	71	20	25	43	4	2	2	46	14	32	64	21	4	4	3	6
1045	5	5	11	5	5	25	6	9	29	4	2	2	6	3	36	29	26	57	14	3	4	5	29	8	64	36	23	3	3	2
1100	26	4	21	18	18	4	18	4	11	18	5	2	2	4	16	18	16	64	50	18	2	4	9	21	29	64	30	11	4	3
1115	11	16	3	11	21	29	13	7	8	13	23	11	2	2	2	21	14	57	93	25	16	3	4	9	11	36	64	16	19	3
1130	21	14	14	6	21	32	10	6	4	4	32	11	11	3	3	3	4	29	100	36	21	14	3	4	7	18	36	57	6	29
1145	18	14	18	7	21	29	25	4	21	4	6	11	25	7	3	3	3	14	93	93	21	9	18	3	4	5	23	50	14	18
1200	4	25	7	16	7	10	29	9	9	9	6	7	13	18	5	6	3	3	11	96	46	9	36	5	4	4	6	32	14	6
1215	9	4	7	7	14	11	11	25	4	7	13	4	7	10	14	9	6	4	4	5	50	21	14	14	11	5	4	5	7	13
1230	57	25	3	7	5	18	11	21	5	4	21	11	4	9	9	21	7	4	4	5	4	29	9	23	16	14	11	3	3	6
1245	9	43	50	3	3	10	14	7	6	10	6	23	7	6	4	11	29	5	3	6	20	10	5	10	14	10	36	36	4	3
1300	4	6	21	43	4	3	14	21	6	10	8	8	9	7	7	5	13	29	4	4	9	13	29	25	11	29	9	36	32	4
1315	21	6	11	11	4	7	4	6	27	5	7	11	4	9	43	9	5	14	11	4	4	18	18	36	36	18	29	16	14	11
1330	4	10	18	4	7	4	3	2	5	18	5	27	8	4	8	43	21	7	4	6	11	5	4	50	25	36	14	14	19	5
1345	3	4	6	18	18	3	5	7	2	2	9	13	10	9	4	11	36	29	16	2	4	5	9	6	36	29	16	8	13	7
1400	5	4	4	5	5	5	9	6	4	2	2	4	32	11	7	4	3	21	25	18	4	3	4	6	13	18	14	18	11	16
1415	26	43	18	6	3	3	4	2	9	6	5	2	4	11	14	5	4	3	11	21	16	5	4	5	7	16	7	5	25	13
1430	4	16	46	29	14	10	10	10	6	11	4	5	3	10	9	10	4	3	2	6	4	6	13	11	7	6	9	7	11	4
1445	2	4	5	21	36	14	7	4	8	7	14	5	4	2	6	14	14	5	4	2	6	4	6	10	9	16	6	10	5	5
1500	4	2	3	3	4	14	11	4	3	3	2	3	5	3	6	4	5	4	2	3	2	3	4	4	4	3	7	7	6	6
1515	4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	6	3	9	3	2	2	2	2	2	3	2	2	2	4	3
1530	11	6	9	7	3	3	2	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1545	2	2	2	2	2	5	6	4	4	3	4	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	5	2
1600	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1
1615	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	2	1	1	1	1	1	1	1	2	2	2	1	1	1	1

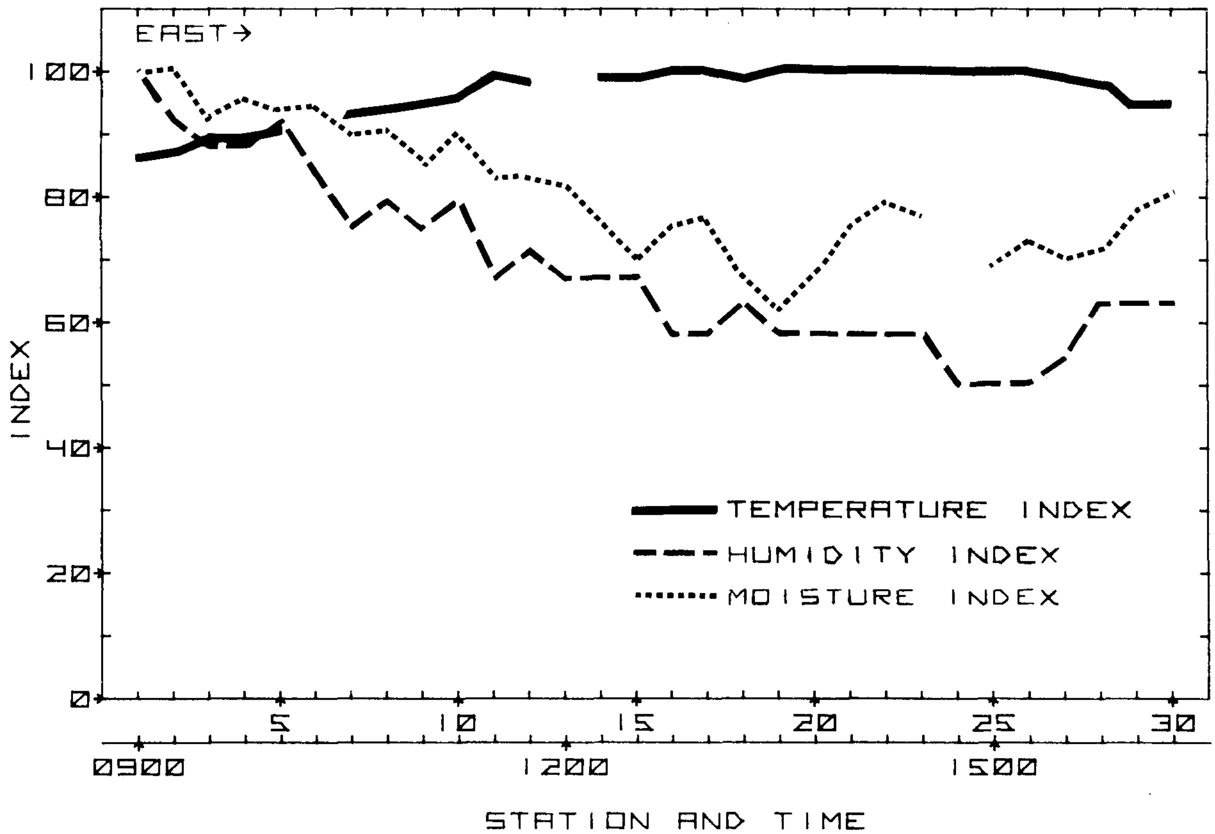

Figure 1 — Temperature, humidity, and moisture indexes for Transect 3 on September 22.

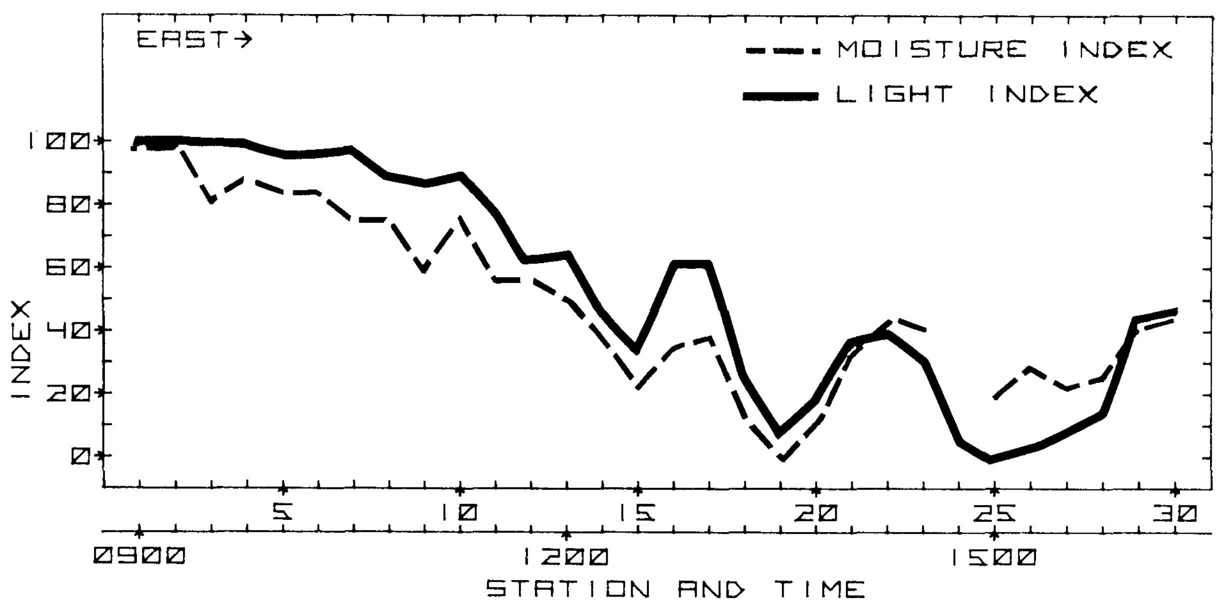

Figure 2 — Moisture and reflected light indexes for Transect 3 on September 22.

moisture is associated with the amount of solar radiation received at a station. When the two indexes are plotted together, a marked similarity in the patterns of moisture and total reflected light intensity is apparent (*fig. 2*).

The nature of the relationship between fuel moisture and the amount of solar radiation (as indicated by the reflected light readings) is shown by statistical analysis. A logarithmic curve was fitted to the data, giving the equation

$$M = 10.496 - 0.7122 \ln I_a \qquad (I)$$

where

M = moisture content in percent
I_a = total light intensity to time of sample
1n = natural logarithm

The correlation coefficient for this relationship is 0.945. Therefore about 89 percent of the variation in moisture along the transect was accounted for by the variation in the total amount of solar radiation received by the litter to the time each sample was collected.

The observations of air temperature and humidity with the sling psychrometer were made 3 to 4 feet above the ground. Because of the air mixing process, these observations are indicative of the general temperature and humidity of the air within the timber stand, and do not necessarily represent the surface conditions — particularly for sunlit areas. In shaded areas, however, the temperature and humidity gradients are small, so the observations do provide an approximation of the surface conditions for such areas. All of the stations of the transect were in shade at least part of the day, consequently the substantial change in relative humidity during the long sampling period might be expected to cause variation in the moisture content of the litter. That is, if all of the stations had been in full shade throughout the day, the moisture content would still have varied along the transect because of the change in relative humidity of the air from the beginning to the end of the sampling period. Adding relative humidity to the analysis through multiple regression techniques, however, did not significantly improve the correlation or the accuracy of equation (1). This is the result of the close interrelationships between solar radiation, air temperature, and relative humidity. Except for a short period near the end of the sampling period, the mixing ratio of the air remained virtually constant, and consequently the change in the relative humidity during the day was controlled almost entirely by the change in air temperature. In turn, air temperature is highly dependent on the total amount of solar radiation received up to a given time. Therefore the amount of solar radiation indirectly controlled the relative humidity.

Because actual fuel moisture lags behind the equilibrium value when relative humidity and temperature are changing, the duration of solar radiation on a given area of litter is an important factor in spatial moisture variations. The data collected on September 22 for Transect 3 are not well suited for determining the precise effect of solar radiation duration and intensity on moisture content — the independent effects of the various influences on the moisture content at each station cannot readily be separated from the combined effects with the available data. However, some insight as to the importance of solar radiation duration can be obtained by correlating reflected light intensities for various time periods with the moisture content of the litter.

Relating the logarithm of the maximum light intensity previous to the time of the moisture sample at each station with the moisture content produced a correlation coefficient of 0.907. This is somewhat lower than the coefficient of 0.945 obtained with the total light intensity to the time of the sample, but the relationship is adequate to explain about 82 percent of the moisture variation among the stations. The logarithm of the total of the maximum light intensity and the highest reading immediately preceding or following it gave a correlation coefficient of 0.940 — almost the same as for the total light intensity to the time of the sample. The logarithm of the total of three consecutive light intensity readings, including the maximum, resulted in a correlation coefficient of 0.954 for the intensity-moisture relationship. Including the logarithm of the relative humidity in the analysis increased the correlation coefficient to 0.967. Approximately 94 percent of the moisture variation along the transect is explained by this latter combination. The equation for the relationship is:

$$M = 6.38 - 0.7179 I_b + 1.3122 \ln H \qquad (2)$$

where

M = moisture content in percent
I_b = total of 3 consecutive light intensity readings including the maximum
H = relative humidity in percent
1n = natural logarithm

Increasing the number of light intensity observations beyond three in the analysis resulted in a decreasing correlation coefficient for both the light intensity alone or in combination with relative humidity.

Since the reflected light observations were made 15 minutes apart, the strong association between the maximum light value and moisture content indicates that the litter moisture responds very quickly to increases in solar radiation. Most of the change in moisture probably takes place in 15 minutes or less. The relatively small change in the correlation coefficient when three consecutive light readings instead of two were used suggests that equilibrium moisture is approached within 45 to 60 minutes after a change in solar radiation intensity occurs, when litter moisture is controlled primarily by litter temperature and the relative humidity of the air surrounding the needles.

Additional support for the hypothesis that the litter moisture responds quickly to exposure to solar radiation was found in the paired sun and shade samples of litter collected in the general area of Transect 3 on September 24 and October 8. On September 24 the paired samples were collected at half-hour intervals from 1000 to 1600 hours. The sun samples were collected from areas that had been exposed to full sunlight for at least 30 minutes. The shade samples were taken from areas known to have been in full shade for at least 30 minutes, but likely were shaded longer since these areas were usually on the north side of trees. The mean moisture content of the sun samples was 4.0 percent, and that of the shade samples 6.2 percent *(table 3)*. The difference in the mean moisture contents is statistically significant at the 1 percent level.

Two pairs of samples were collected at 1340 hours on October 8 from areas that had been in the sun or shade for at least 3 hours. The mean moisture for the two samples collected in the sunlit areas was 3.2 percent, while the mean of the samples in the shade was 6.2 percent - the same as for the shade samples on September 24. The air temperature was 831 F and the relative humidity 13 percent, not greatly different than on September 24. Despite the much longer exposure to direct solar radiation, the moisture content of the sun samples collected on October 8 was not much lower than on September 24, again suggesting that most of the change in litter moisture occurs shortly after exposure to solar radiation.

That moisture content of pine needles reacts quickly to changes in the environmental conditions is also confirmed by a laboratory study of the moisture response of *Pinus radiata* needles (King and Linton 1963). In this study pine needles at equilibrium moisture with a temperature of 841_1 F and a relative humidity of 59 percent

Table 3 — Moisture content of sun and shade samples far Transect 3 on September 24

Time	Air temperature	Air relative humidity	Moisture content: Sun	Moisture content: Shade
	°F		Percent	
1100	83	17	4.8	6.8
1130	85	15	4.1	7.4
1200	85	13	4.1	6.8
1230	87	12	3.9	5.9
1300	87	14	3.6	5.3
1330	84	14	4.7	7.1
1400	85	15	4.8	6.9
1430	85	15	2.9	5.3
1500	84	16	4.3	6.6
1530	84	16	2.5	4.1
1600	85	13	3.2	5.6
Mean			4.0	6.2
Standard deviation			.94	1.00
Standard error			.28	.30
Coefficient of variation			23.4	16.3

reached 50, 75, and 90 percent of the new equilibrium value in 7.4, 12, and 21 minutes, respectively, when the temperature was changed to 134_1 F and the relative humidity to 19 percent. The moisture response of surface needles in the natural situation is likely to be somewhat slower, however, because the lower litter layers provide a moisture source not available to isolated needles in a laboratory study.

Although litter moisture responds rapidly to exposure to solar radiation, attempts to correlate the reflected light readings taken during the 30- to 40-minute period prior to the time of sampling with litter moisture for the different transects gave inconsistent results. High light intensity was usually associated with relatively low moisture, but low moisture was also frequently found when the light intensity indicated full shade. The explanation for this seeming anomaly is found in the way that litter moisture responds to diurnal changes in temperature and relative humidity and the effects of duration and intensity of solar radiation on intermittently exposed litter.

Under fair weather conditions, surface and air temperatures increase during the day and decrease at night, and the relative humidity follows the inverse of this pattern. Because of the close interrelationships of temperature, relative humidity, and fuel moisture, the diurnal equilibrium moisture pattern is similar to that of the relative humidity. But temperature and humidity are usually changing more rapidly than the litter can lose or absorb moisture during much of the diurnal cycle, and consequently the actual litter moisture is usually higher than the equilibrium moisture during the day, and lower at night. Only during the period in the early evening and morning when the trends in temperature and humidity are reversing can the litter moisture "catch up" with the equilibrium moisture.

The temperature of previously shaded litter increases when it is exposed to solar radiation, thus reducing the relative humidity of the air surrounding the needles. The moisture content of the litter then moves toward the lower equilibrium for the new conditions. But when the litter is again shaded, it may or may not increase in moisture content. Because of the lag in moisture behind changing temperature and humidity, the litter cannot attain equilibrium when the exposure to radiation is brief — it just moves closer to the equilibrium value for the shaded condition. If the exposure to radiation is long enough for the litter moisture to reach equilibrium for the exposed conditions, its moisture will likely increase somewhat when it is again shaded. In either case, however, the moisture content of litter that has been exposed to solar radiation will be less than litter that has not been exposed, and a lower moisture will persist at least until the evening reversal period in the trends of temperature and relative humidity.

The likelihood that the moisture of litter exposed to solar radiation and then shaded will remain below that of continuously shaded litter for a considerable time is enhanced by the tendency of wildland fuels to have a lower equilibrium moisture for a given temperature and humidity when they are absorbing moisture than when they are losing it (Blackmarr 1971).

The temperature to which the litter and the air next to it can be raised and the amount that the relative humidity can thereby be reduced, depends on the intensity of the solar radiation as well as the length of exposure. Consequently, litter exposed to intense radiation for a short time may reach a lower moisture than that of litter exposed to lower radiation intensity for a longer period. For example, Stations 19 and 22 of Transect 3 on September 22 were in full shade at the time the litter samples were collected at 1330 and 1430 hours respectively *(table 2)*. But the pattern of exposure to solar radiation of the two stations was quite different. Prior to the sampling time, Station 19 was in full shade or exposed only to low intensity radiation except for a period of very strong radiation between 1100 and 1200 hours. Station 22, on the other hand, was exposed to more sunlight than Station 19, but all of the radiation was of low to moderate intensity. As a result of the relatively short exposure to high intensity radiation, the moisture at Station 19 reached a lower level than that at Station 22, and this lower moisture persisted to the time of the sample (*fig. 1*).

Because of the strong relationship between solar radiation and litter moisture, and the persistence of lower moisture in litter that has been exposed to radiation, the history of the previous exposure of an area to solar radiation is more important in determining the litter moisture at any given time than are the conditions at that time. Consequently, spatial variations in the moisture content of the litter may exist even though all of the litter is in shade at the time the moisture determination is made. The moisture variations created by solar radiation can also be carried over from one day to the next unless the temperature and relative humidity remain constant, or only change very slowly, for a long enough time at the evening or morning reversal periods for all of the litter to approach equilibrium.

Radiation Cooling Effects

Early in the morning, dark-colored patches of litter of varying size and irregular shape sometimes appear in the litter under a timber stand. Examination of these patches will show that the litter in these areas is very moist, and it is this moisture that gives the litter its darker color. The patches of moist litter appear directly under openings in the crown canopy, and are caused by dew formation when nighttime radiation losses through the openings are sufficient to cool the surface air below its dewpoint. They are most likely to appear when the general nighttime air temperatures are cool and the soil and lower litter layers are moist. Even though dew does not form, however, the areas under the openings will be cooled more and therefore have higher humidity and fuel moisture than the surrounding areas under the timber stand.

Diagrams of the openings in the crown canopy above each of the transects were made when the study was started. Unfortunately, these data have been lost, and since the exact location of many of the crown openings is not known, the precise effect of radiation cooling cannot be determined for all of the transects. The location of the large openings along Transects 2 and 5 are known, however, and the data collected in July for these transects clearly show the effects of dew formation on the moisture patterns. The openings were large enough to permit extensive radiation cooling at night, and heavy dew frequently occurred in these openings as well as outside the timber stands during July and early August.

Moisture samples taken in the early forenoon of July 24 on Transect 2 showed considerably higher moisture in the central part of the large opening than in the timber stand where nocturnal cooling was reduced by the tree crowns (*fig. 3*). At the time of the afternoon sampling period on July 7 for this transect, the highest moisture was in the timber stand. However, the moisture was also relatively high over much of the opening, and the highest moisture in the opening was shifted southward as compared to the morning of July 24. Lowest moisture was found near the edges of the opening, particularly on the northern side (*fig. 4*).

The change in the pattern of moisture variation between the morning and afternoon sampling periods was caused by the angle at which the solar radiation reached the transect. The sun is well south of being directly overhead in July at the latitude of the study site, even at noon. As a result, the south part of the opening was partially shaded by the trees on the south side of the opening — at the sampling time on July 7 about half of the opening was in full shade. This part of the transect did not receive enough solar radiation during the day to evaporate the moisture added to the litter by the dew at night. The northern part of the opening was in full sunlight most of the day, and consequently the litter moisture was lowest in this area.

Because of the heavy dew formation and the stable weather conditions, it is probable that the moisture pattern for Transect 2 on the morning of July 7 was quite similar to that on July 24. To provide a measure of the amount of drying at different points on the transect, the ratio of the moisture at each station on July 24 to that on July 7 was calculated, providing an index of relative drying along the transect. This index showed that the maximum drying occurred near the northerly side of the opening, and that the intensive drying extended into the timber stand somewhat on that side (*fig. 5*). There was also an area of intensive drying in the timber stand near the southern edge of the opening. The crown canopy was thinner in this area because of the greater tree spacing, and apparently considerable sunlight reached the surface at this point on the transect. The drying index must be considered as approximate only, since the actual moisture for the morning of July 7 is not known with certainty. However, the index pattern coincides with the pattern of solar radiation intensity that could logically be expected for the transect.

The opening on Transect 5 was about the same size as on Transect 2, and the moisture pattern along the transect was affected by dew formation during the July sampling periods in much the same way. The transect was sampled in the midforenoon of July 31, about 2 hours later in the day than for the morning sampling of Transect 2 on July 24. The peak moisture in the opening was already displaced toward the southern edge of the opening, and the drying at the northern edge was appa-

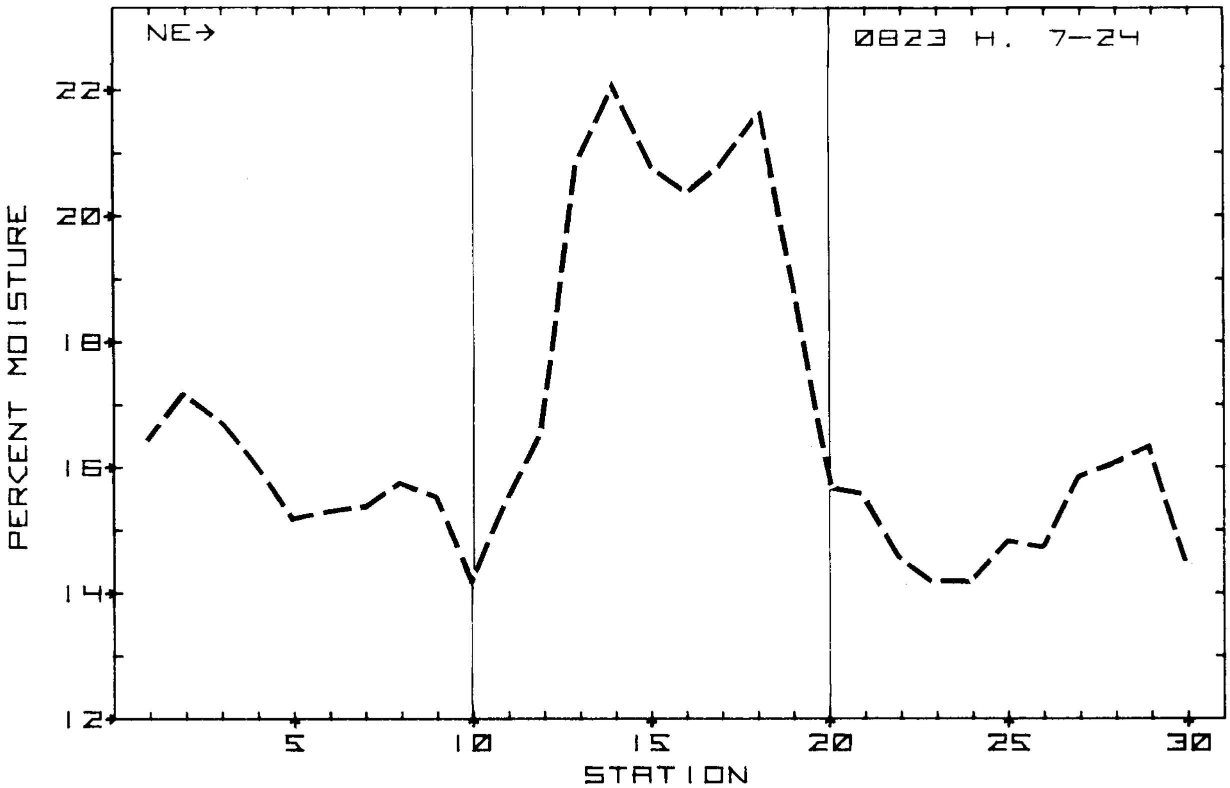

Figure 3 — Moisture content pattern for Transect 2 on July 24.

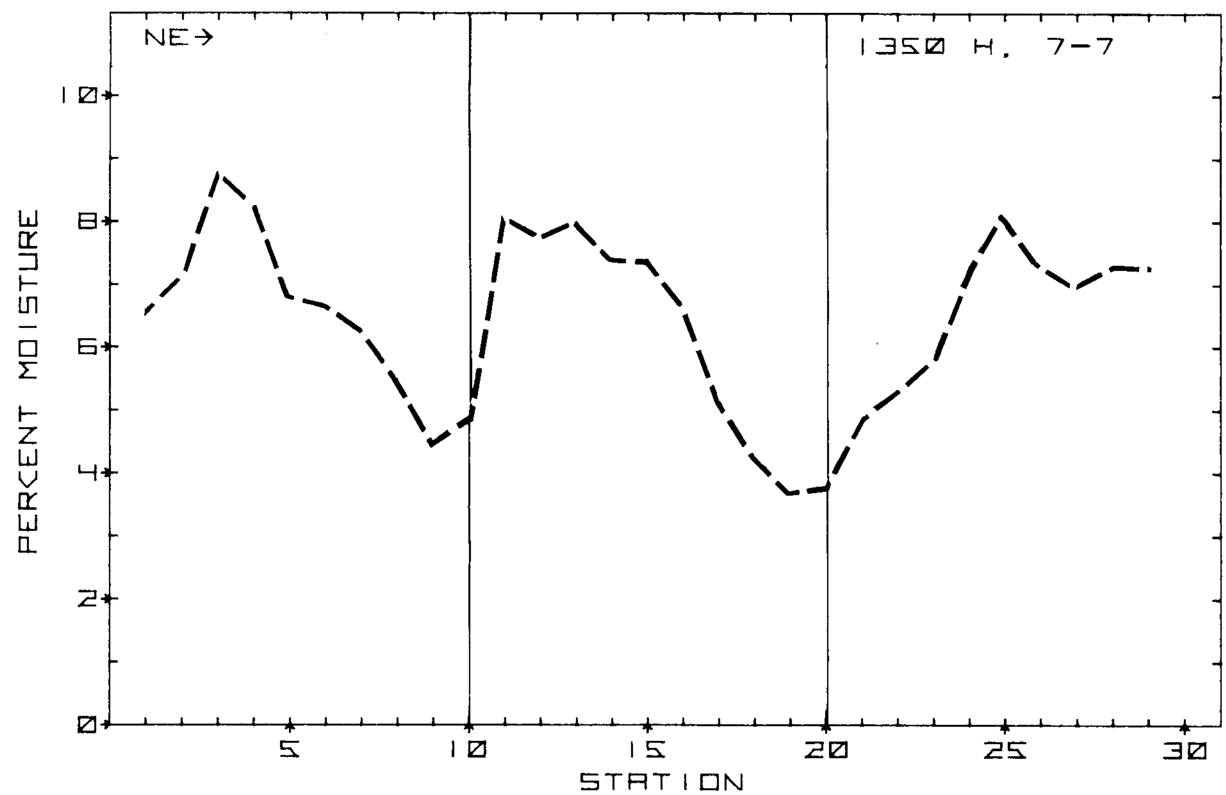

Figure 4 — Moisture content pattern for Transect 2 on July 7.

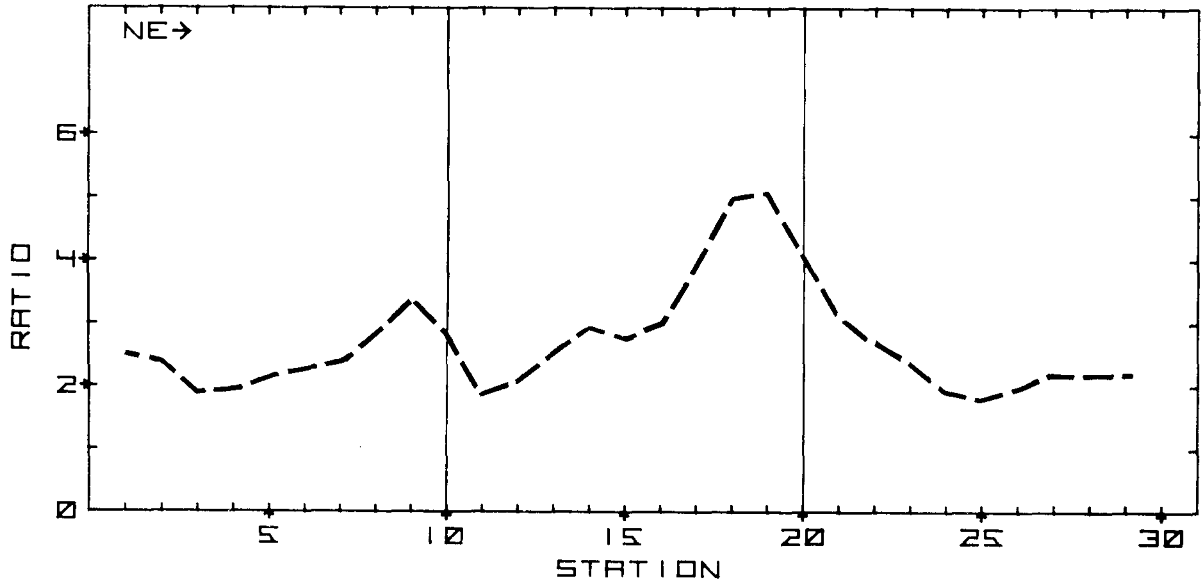

Figure 5 — Drying index for Transect 3.

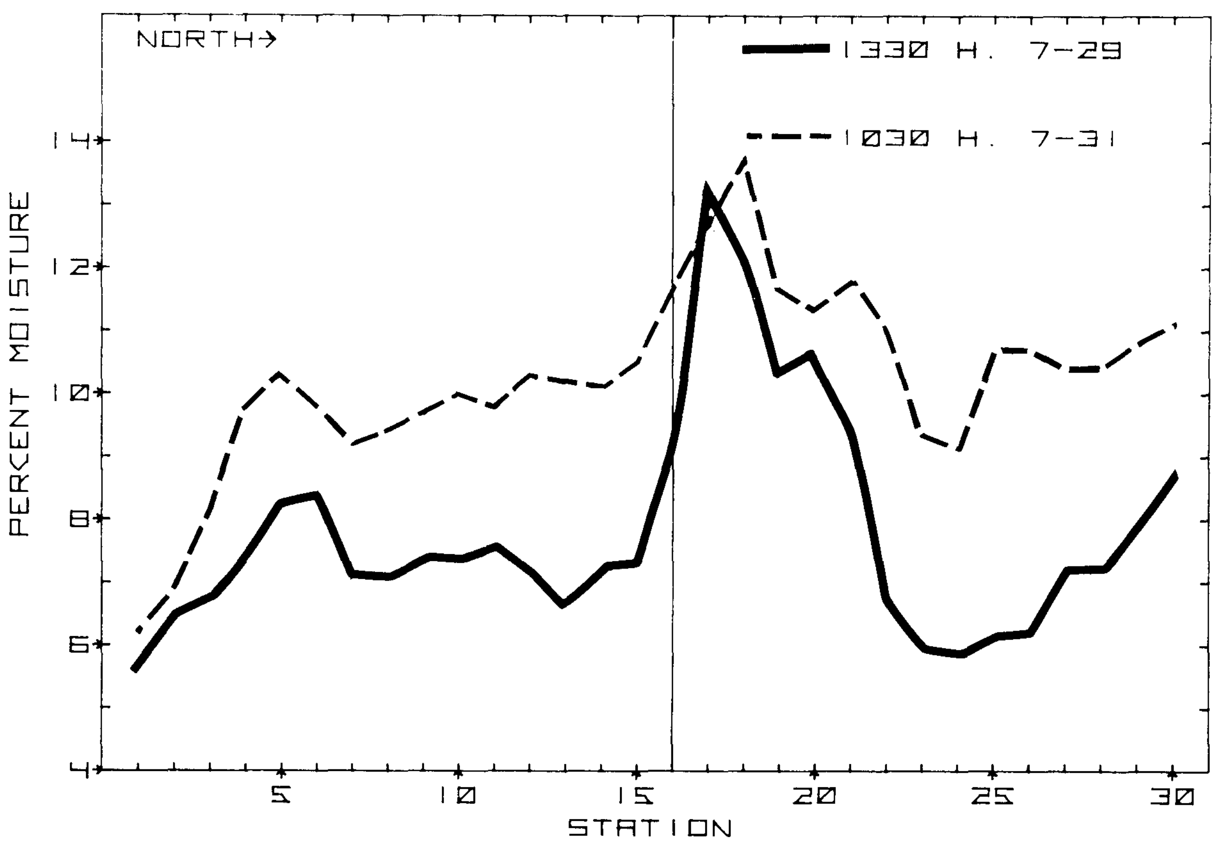

Figure 6 — Moisture content patterns for Transect 5 on July 29 and 31.

rent (*fig. 6*). The maximum moisture was still closer to the southern edge of the opening for the afternoon sampling period of July 29, and the area of low moisture on the northern side was broader, reflecting the longer exposure of the opening to solar radiation. Unlike Transect 2, however, the moisture in the timber stand remained substantially lower than that in the opening in the afternoon. The tall trees and very dense canopy of the mature timber apparently shielded the surface under the stand from direct solar radiation, and prevented much radiation cooling of the litter at night.

Transect Moisture Variations

Earlier, it was indicated that heating by solar radiation is affected by the angle of the sun as it varies during the day and with the time of year, and that the effects of solar heating and radiation cooling on litter moisture vary with the characteristics of the timber stand. The effects of heating and cooling on surface litter moisture are also modified by the moisture content of the soil and lower litter layers. This exploratory study was not comprehensive enough to establish definitive relationships between surface litter moisture and factors that affect it, and it was not designed for that purpose. However, the moisture variation patterns of the transects demonstrate the effects of solar radiation heating and radiation cooling, and give some insight as to the nature and magnitude of the moisture variations and their changes with time of day, season, and timber stand characteristics.

Transect 1 had the most dense crown canopy of all the transects, and the meager amount of direct solar radiation reaching the litter surface is reflected in the small variations in moisture along the transect found on July 7 and 24 (*fig. 7*). Highest moisture occurred in the more compact litter of the deer bed on both days. Lowest moisture in the afternoon of July 24 was at Station 24 where the fallen limb provided better aeration of the surface needles. The moisture content at this station was also relatively low on the morning of July 7, possibly indicating some "carryover" of low moisture from the preceding day. Although the general patterns of moisture variation were similar for the two sampling periods, the variance (*table 1*) was somewhat greater for the morning period when cooler temperature and greater relative humidity produced a higher average fuel moisture.

The tendency for the moisture variation between stations to decrease during the day as drying progressed was evident on other transects also. For example, the moisture variation along Transect 4 at 1120 hours on September 21 was very small — the range was less than 1 percent (*fig. 8*). But considerably more variation was found when the transect was sampled 2 hours earlier in the day on September 30.

The moisture data also indicated a strong tendency for the magnitude of the moisture variations along the transects to decrease as the season progressed. Transect 3 for example, had large moisture variations for the afternoon sampling period of July 21, but 2 months later the variations were small (*fig. 9*). Part of this difference was caused by the more nearly perpendicular, and therefore more intense solar radiation early in the season, but the high moisture content of the soil and lower litter layers was probably an important factor also. The moisture content of the soil and lower litter in areas exposed to direct solar radiation can be expected to decrease more rapidly than in shaded areas. This would deprive the surface needles of a moisture source in the exposed areas and accentuate the moisture differences between sunlit and shaded areas. Late in the season the soil and lower litter was more uniformly dry, and this along with the less intense radiation because of the lower sun angle resulted in less moisture variation.

Transect 4 also showed the seasonal trend of decreasing moisture content. Early in the season the sun was high enough to permit solar radiation to reach some parts of the transect through the narrow opening above much of the transect. This radiation, along with the high moisture content of the soil and lower litter, caused considerable variation in moisture content between stations (*fig. 10*). But later in the season the sun angle was too low to allow radiation to reach the surface through the opening, and samples taken at the same time of day indicated relatively little variation in moisture content along the transect.

Transect 6 in the mature timber stand showed the large moisture variations characteristic of strong solar radiation and high moisture content in the soil and lower litter when the transect was sampled in the forenoon of July 31 (*fig. 11*). The range of moisture content was still moderately large when the transect was sampled again during the morning of September 24, but the pattern of

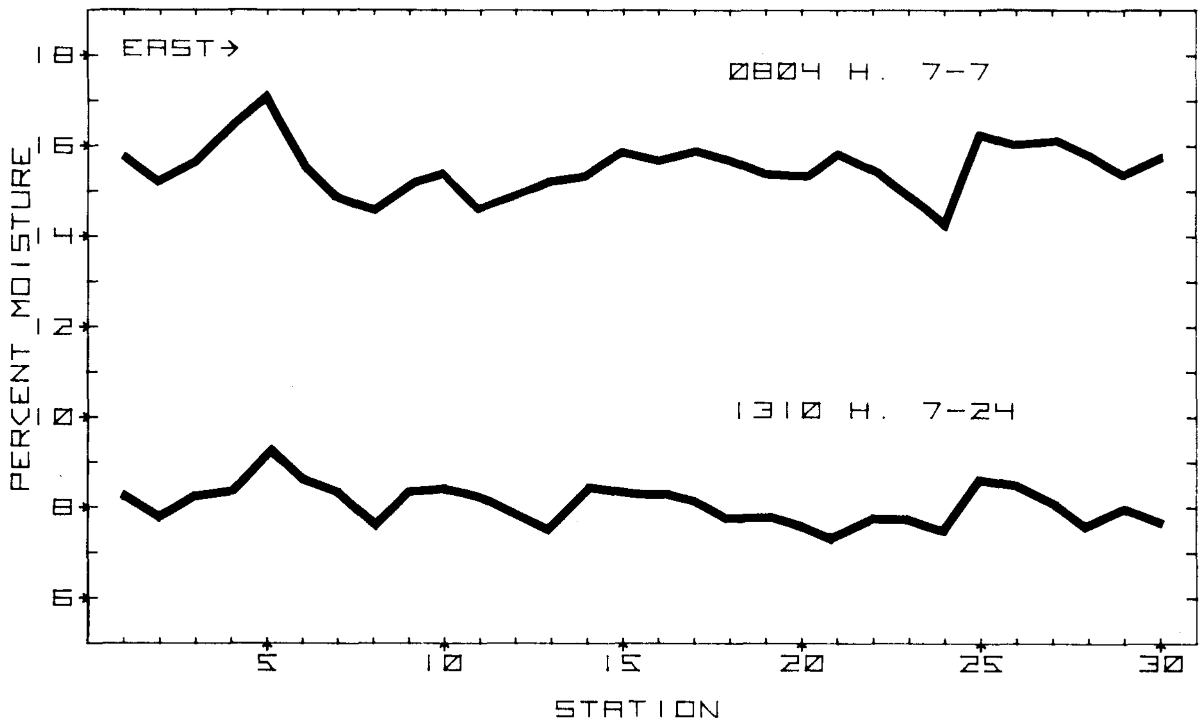

Figure 7 — Moisture content patterns for Transect 1 on July 7 and 24.

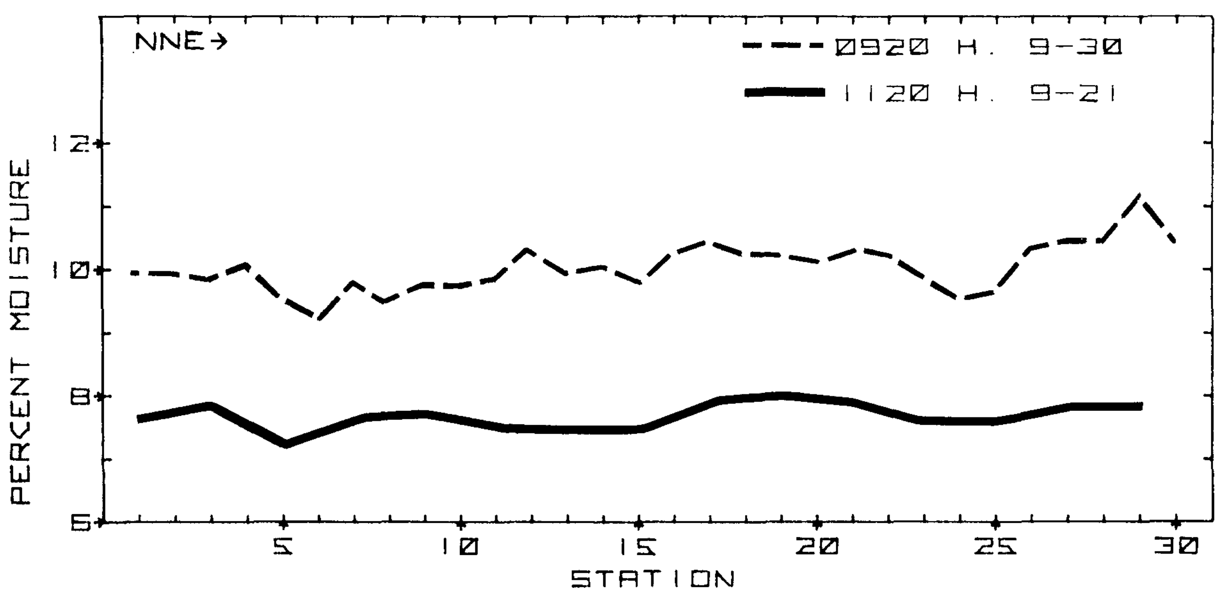

Figure 8 — Moisture content patterns for Transect 4 on September 21 and 30.

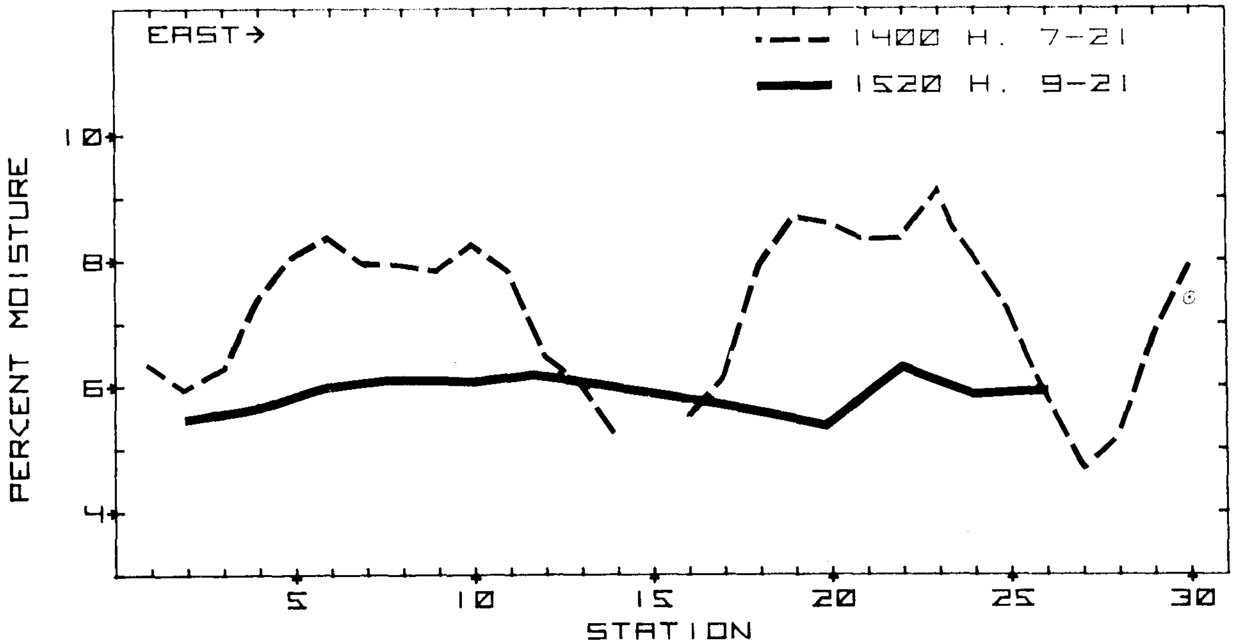

Figure 9 — Moisture content patterns for Transect 3 on July 21 and September 21.

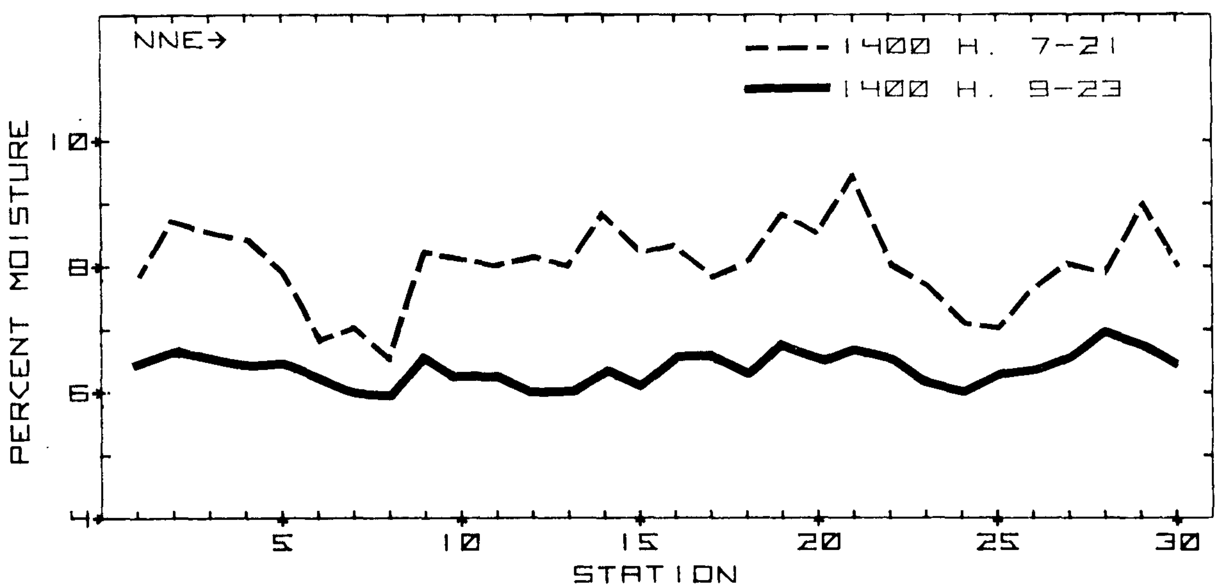

Figure 10 — Moisture content patterns for Transect 4 on July 21 and September 23.

variation showed a marked change. In September the moisture content was highest at the west end of the transect and decreased at nearly a uniform rate to the lowest value at the east end (*fig. 12*), instead of varying widely along the transect as in July. Although the range of variation was somewhat less, the same general pattern of decreasing moisture from west to east was also evident for the afternoon sampling periods in September and early October (*fig. 13*). Detailed information on the characteristics of the timber stand is insufficient to ascertain the exact cause of the change in the moisture variation pattern. Because the trees were tall and the stand was open under the crowns, however, the change in pattern is likely the result of sunlight reaching the litter surface under the crowns during the forenoon in the fall, instead of through the crowns as earlier in the season.

The moisture data collected for Transect 3 at 1030 hours on September 21 and at 1130 hours on September 30 illustrates the effect on litter moisture of the tendency for the more intense solar radiation through the crown openings to shift from west to east as the day progresses. For this comparison, the moisture values were converted to indexes based on the highest and lowest moistures for each sampling period to provide an index of relative moisture variation. Although the patterns of variation were generally similar for the two sampling periods, the pattern for the later time on September 30 was offset to the east (*fig. 14*). This shift corresponds to the shift in the higher reflected light intensities found for this transect on September 22 (*table 2*).

Because of the sun angle at the latitude of the study site, solar radiation can penetrate into timber stands along their southerly edges and at the north edge of the larger openings in the stands. The drying index for Transect 2 (*fig. 5*) shows this "edge-effect" in a large opening. Transect 5 started near the southern edge of the timber stand, and the effect of the penetration of radiation on moisture content is apparent at the starting end of the transect as well as at the northern edge of the large opening. Reflected light intensity observations made at 10-minute intervals for 40 minutes prior to sampling on July 29 indicated that the most intense radiation was being received at the southern end of the transect, and that the intensity was nearly as great for Stations 21 to 25.

Transect 5 was sampled again on September 21, September 30, and October 8 at about the same time in the afternoon as on July 29. Lowest moisture for all three sampling periods occurred at the beginning of the transect, and the moisture increased gradually along the transect toward the northern end (*fig. 15*). The prevailing wind at the study site is usually from the southeast to southwest during the daytime, and the late season moisture pattern is probably the result of an influx of warmer and drier air from the sparsely vegetated area outside of the stand as well as penetration of radiation into the edge of the stand. The greatest range of moisture for these sampling periods was on September 21, and the least on October 8. This difference is consistent with the decreasing sun angle with time of year. Dew did not form during these days, and because of the low sun angle the large opening was shaded throughout the day. As a result, there was no apparent effect of the opening on the moisture variation pattern.

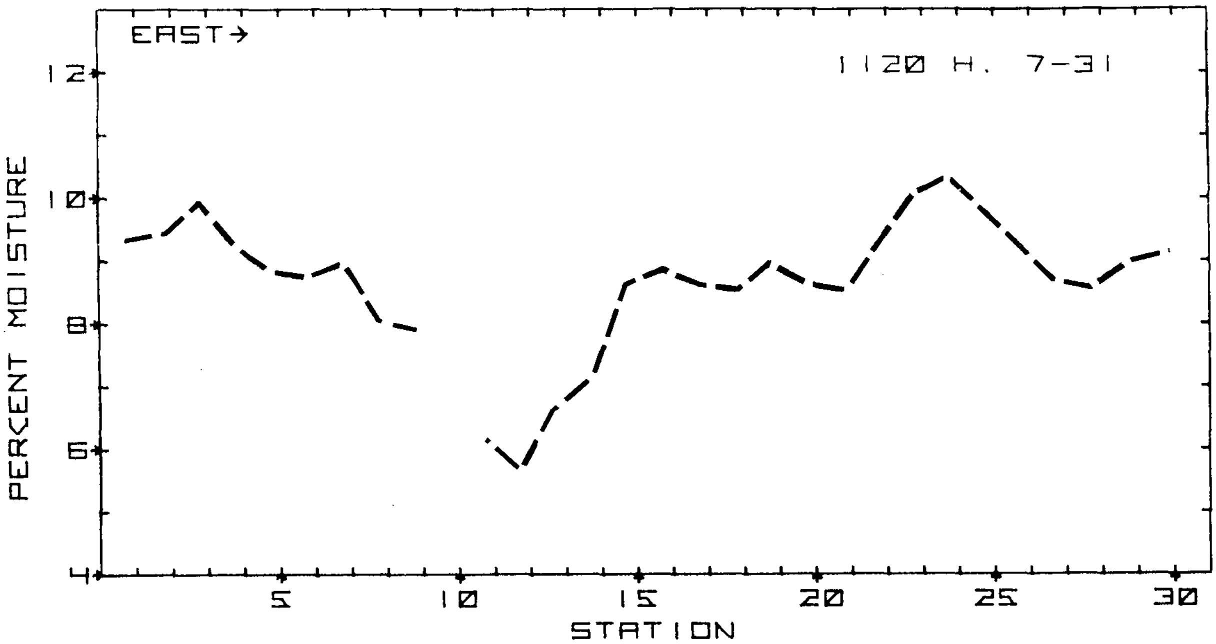

Figure 11 — Moisture content pattern for Transect 6 on July 31.

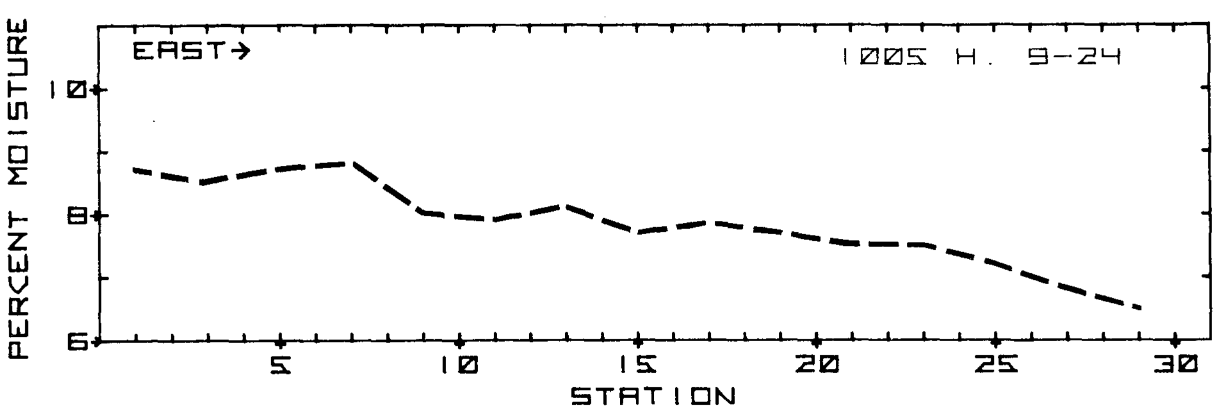

Figure 12 — Moisture content pattern for Transect 6 on September 24.

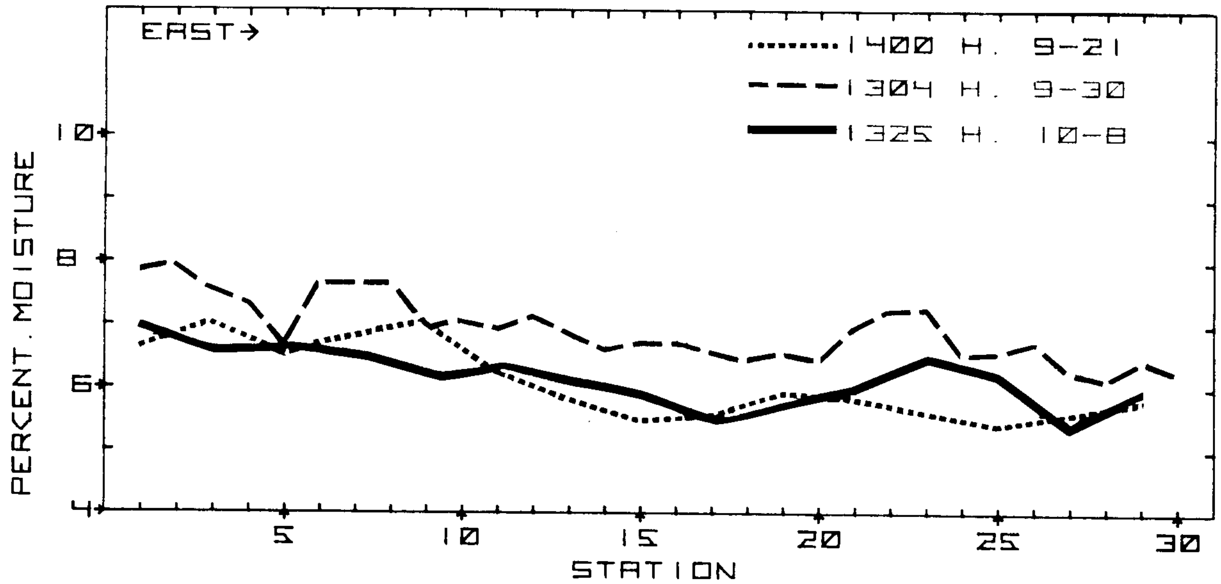

Figure 13 — Moisture content patterns for Transect 6 on September 21, September 30, and October 8.

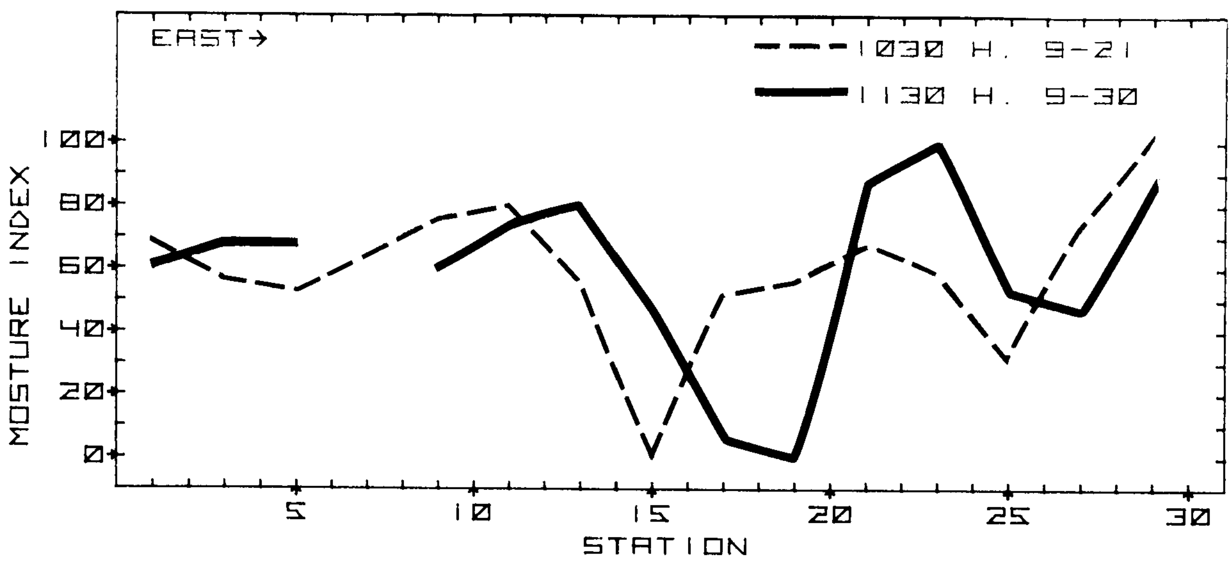

Figure 14 — Moisture indexes for Transect 3 on September 21 and 30.

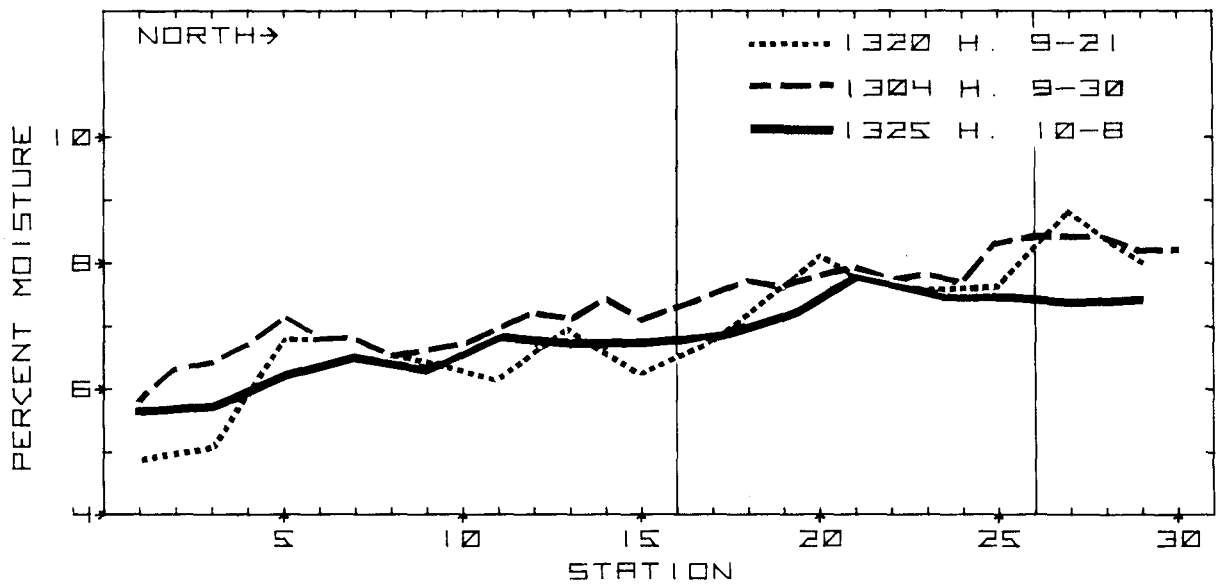

Figure 15 — Moisture content patterns for Transect 5 on September 21, September 30, and October 8.

CONCLUSIONS

This exploratory study demonstrates that variations in the moisture content of litter under ponderosa pine stands can be great enough within short horizontal distances to significantly affect the ignition and behavior of wildland fire. Work by Rothermel and Anderson (1966), for example, indicates that the range of moisture found for Transect 3 on July 21 will cause a variation in the rate of spread of about 21 percent for a no wind condition. Studies by Fons[3] show that with a 6 mi/h wind the range in moisture for Transect 5 on July 29 would cause a 47 percent change in spread rate, and a 31 percent change would be caused by the moisture variation on Transect 6 on July 31. Because the probability of ignition increases rapidly with decreasing moisture content (Brown and Davis 1973), the likelihood of a firebrand starting a fire if falling on an area that has been exposed to solar radiation can be much greater than for continuously shaded areas. Changes in moisture as small as 0.5 percent are considered as significant in rate of fire spread, fire intensity, and fire ignition in fire danger rating (Deeming and others 1972).

The variations in fuel moisture are closely related to the amount and intensity of the solar radiation reaching the litter surface through openings in the crown canopy, and the effect that the openings have on cooling of the litter by radiation at night. Consequently, any influence affecting the radiation received or lost, such as latitude, time of day and year, stand characteristics, atmospheric conditions, and topographic configurations, will also affect the moisture variation patterns of the litter.

The data collected indicate that litter even briefly exposed to direct sunlight can become substantially lower in moisture than areas not exposed, and that the lower moisture level will persist after the litter is again shaded. The history of the exposure of an area to solar radiation is thus more important in determining the litter moisture at any given time than are the exposure conditions at that time.

Because of the exploratory nature of the study, the specific results probably apply directly only to the areas in which the data were collected. However, the strong relationships found between litter moisture and radiation heating and cooling have several important and widespread implications. The large spatial variations in surface fuel moisture found in the ponderosa pine stands are likely to exist in many other wildland vegetation types

[3] Office report on file at the Forest Fire Laboratory, Riverside, California.

too. Deciduous forests, for example, have large seasonal variations in the degree of crown shading of surface fuels, and other types of coniferous forests have crown openings similar to those of ponderosa pine. Brush and other low-growing vegetation vary widely in crown density and in the amount of shading they provide to the surface litter and the protection they afford from nighttime cooling. High moisture content can result from dew formation in openings in the timber stand, and it is possible that the moisture in at least part of such openings may remain higher than surrounding areas throughout the day. These considerations can significantly affect prescribed burning procedures — such as burning slash in clearcut blocks. The moisture content of dead fuel is a key factor in the inception and behavior of wildland fire. Consequently radiation heating and cooling are important considerations in the design of moisture sampling procedures for studies of fire behavior and for the application of fire behavior information in fire danger rating, firefighting, prescribed fire, and other field activities where fuel moisture is significant.

The results of the study indicate a need for more sophisticated investigations of radiation heating and cooling in various wildland vegetative types and situations, with the object of developing area classification systems and measurement techniques whereby realistic estimates of fuel moisture can be made. Instrumentation for measuring solar radiation and radiation cooling in the wildland situation may need to be developed. However, measuring reflected light intensity from the litter with a photographic exposure meter, as was done nearly 50 years ago in this study, proved to be a highly effective and low-cost means of determining solar radiation intensity. In light of today's technology, development of means to measure solar radiation and radiation losses and determining the effects of radiation on wildland fuel moisture should not be formidable.

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