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SPATIAL AND TEMPORAL VARIATION IN THE DISTRIBUTION AND PARTITIONING OF SOLAR ENERGY IN A DECIDUOUS FOREST ECOSYSTEM

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SPATIAL AND TEMPORAL VARIATION IN THE DISTRIBUTION AND PARTITIONING OF SOLAR ENERGY IN A DECIDUOUS FOREST ECOSYSTEM (Subproject 50 and 51)

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Annual Report

Spatial and Temporal Variation in the Distribution and Partitioning of Solar Energy in a Deciduous Forest Ecosystem (Subprojects 50 and 51)

Atmospheric Turbulence and Diffusion Laboratory Contribution to the Eastern Deciduous Forest Biome of the International Biological Program at the Oak Ridge site.

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Introduction:

Energy flow can never become cyclic in a system despite the conservative nature of energy because of enthalpic and entropic processes that operate in all energy transformation phenomena which degrade energy into unusable forms. Therefore energy inputs are required for systems to function. In ecosystems, the functioning of the system is driven by incident solar radiation. Owing to the rotation of the earth upon its axis, this energy input is pulsed on a 24-hour period. This periodism is superimposed upon a further regular variation in energy input over the course of the year resulting from the tilt of the earth's axis of rotation. Irregular variation in energy supply over periods ranging from seconds to centuries are induced by changes in atmospheric turbidity, clouds, short-term climatic variations, and long-term climatic changes.

Despite these pulses and irregularities in energy supply an ecosystem functions continuously although the rates of some metabolic processes operating within the system vary according to the energy input. The ecosystem is able to function continuously, albeit with component processes operating at varying rates, only by virtue of the photosynthetic transformation of the kinetic energy of radiation to the potential energy of carbohydrates that can be stored over time. Accordingly the photosynthetic or primary production accurring within an ecosystem is an important factor governing the structure and function of that ecosystem.

It appears further that the physical structure of the primary producer component of the ecosystem has evolved so as to maximize the efficiency of the photosynthetic fixation of radiant energy received within the constraints offerred by physiologic characteristics, moisture conditions, nutrient flow, and intra- and inter-specific interactions (e.g. Horn, 1971). The understanding of the structure and function of ecosystems then implies the understanding of the feedback processes that have evolved between the geometry of the primary producers and the distribution of solar energy within the ecosystem.

The delineation of ecosystem structure and function further implies that the abiotic energy flow within an ecosystem must be understood as well as the biotic energy flow because of the relationship between abiotic energy flow and the moisture conditions of the leaves. The moisture conditions that obtain in leaves exert a profound effect upon the rates of photosynthesis that occur there. Since the amounts of solar energy that are partitioned into sensible and latent heat operate in concert with soil moisture conditions to define leaf water conditions, these components of the abiotic energy balance of an ecosystem must be determined.

The two studies discussed in this report represent an attempt to determine the distribution and disposition of solar energy in a deciduous forest ecosystem, to determine the effects of the forest structure and its temporal changes upon the distribution and disposition of solar energy, and to model the primary productivity of the ecosystem in terms of the structure and energy partitioning within the system.

Objectives:

The objective of these studies is to determine the partitioning of radiant energy in a Liriodendron tulipifera forest and to define the effects of forest structure and soil moisture regimes upon this partitioning. At this time only the distribution of solar energy and air temperature is being examined. Instrumentation is currently being installed to characterize the distribution of net short and long wave radiation in this forest and soil water potentials in the soil. Sensors for measurement of the distributions of air flow and atmospheric humidity are being selected. When the entire instrument system becomes operable we will be able to estimate the vertical fluxes of long and short wave radiation and sensible and latent heat through this forest during periods of negligible advection. By repeating these measurements over time, the temporal changes in this energy partitioning will be assessed and related to seasonal climatic differences and phenological changes in the forest.

Specifically the objectives of subproject 51, a study of spatial and temporal distributions of solar energy in a forest ecosystem, are:

1) to determine the variation of direct beam and diffuse solar radiation in a Liriodendron forest in space and time.
2) to relate this variation to the phenological changes that occur over time in the various forest strata and to the structure of the forest.
3) to evaluate the overall primary productivity of this forest in terms of the distribution of solar energy.
4) to test various models of the penetration of solar radiation into vegetative stands.

The objectives of subproject 50, energy partitioning in a deciduous forest, are:

1) to quantify the major components of the abiotic energy balance of a Liriodendron forest.
2) to relate the spatial and temporal changes in this partitioning of solar energy to forest structure and to temporal changes in incident solar radiation, soil moisture conditions, and forest phenology.
3) to relate the distribution and partitioning of solar energy in this forest to the primary productivity of the forest.
4) to provide a micormeteorological monitoring service to other scientists at the Oak Ridge site.

Methods:

The distribution of solar radiation within the Liriodendron forest is being determined using an array of Lintronic dome solarimeters which sense radiant energy in the spectral band 0.3 to 3 microns. No attempt is being made at present to determine the spectral quality of radiant energy in this forest.

Although the photosynthetic process seemingly does not distinguish between direct beam and diffuse radiation except as a result of differences in the spectral quality of these two components, the physical processes governing their penetration into vegetative stands differ greatly (Anderson, 1964b). Accordingly the determination of the effects of forest structure upon radiant energy distribution requires that these two components of forest radiation be measured. This is being done by measuring total incident radiation with open sensors and by measuring the diffuse component with sensors equipped with shadow-bands devised by Horowitz (1969). These shadow-bands are designed such that the sensor is shaded from the direct rays of the sun by an opaque band around the sensor along the solar path. Because the axis of rotation of the earth is not normal to the rays of the sun, the apparent solar path varies from day to day and the shadow-bands must be adjusted regularly to ensure that the sensor is indeed shaded from direct beam radiation. By subtraction then, total radiation-diffuse radiation = direct beam radiation.

Because of the extreme variability in the intensity of direct beam radiation penetrating a vegetative stand, relatively large numbers of measurements of direct beam intensities are required to obtain sample means with variances sufficiently small to be meaningful. In a deciduous forest in Connecticut, Reifsnyder, et al. (1972) found that to obtain instantaneous sample averages have standard errors of the mean of 0.010 cal. cm^{-2} min^{-1} or less required at least 18 sensors. Thirty minute time averages with a standard error of the same magnitude require 11 sensors. The variability of the diffuse component is much lower and in the study cited above, two shaded sensors were sufficient to adequately characterize this component for both instantaneous spatial averages and 30 minute time averages.

In the Liriodendron stand that I am studying, 12 open and 2 shaded sensors are randomly located at 6 inches above the forest floor and at 20 feet elevation. At 50 feet elevation, 11 open sensors and one shaded sensor are radomly located in horizontal space. In addition, 1 open and 1 shaded sensor are situated at 100 feet elevation, some 20 to 30 feet above the general level of the tops of the trees, so as to obtain a record of the intensites of the two radiative components incident upon the forest.

The output signals from these sensors are being scanned at 10 or 20 minute intervals on a continuous basis, converted to digital form, and recorded on punch paper tape. The scanning interval must unfortunately be varied because the maximum paper tape capacity of the data acquisition system is not sufficient to collect 24 hours of data at the 10 minute scanning interval. Thus a 20 minute scan interval must be used whenever the tape cannot be changed twice daily to ensure that no breaks in the coninuity of data collection occur.

Data reduction and summarization programs have been developed by Dr. Steve Shieh of the Physics Department, University of Tennessee. The raw data are read from the punch paper tape, converted to radiant intensities, edited, and recorded on magnetic tape. Dr. Shieh and a post-doctoral associate, Dr. Ken Borland, are reviewing theoretical models of radiant energy penetration into vegetative stands and will test the fit of data collected in this study to such models as well as to original models that they devise.

Quantification of forest structure and canopy geometry are limiting this modeling effort at present. Data collected by Dr. Blaine Dinger Ecological Sciences Division, ORNL, on the seasonal dynamics of the vertical and horizontal distribution of foliage in a yellow poplar forest (subproject 53) and by Fred Taylor, Ecological Sciences Division, ORNL, of the phenological development of selected understory species (subproject 94) will provide some data of use to this modeling effort. In addition I am planning to begin extensive measurements of leaf area, inclination, and orientation and the variation of these variables in space and time this coming spring.

Measurements will be made periodically by nondestructive methods throughout the growing season on major species within the overstory canopy, understory canopy, and shrub layer. These measurements will be supplanted with canopy closure data obtained from hemispherical canopy photographs taken periodically from the ground and from 20 and 50 foot elevations. All trees within the study area will be tallied by species, DBH, total height, and height to first branch. In addition, an attempt to extend Warren Wilson's (1960) inclined point quadrat technique to use in forests will be made. These measurements will be coordinated with the studies cited above by Dr. Dinger and Fred Taylor that are already underway.

To relate both the solar radiation distribution data and forest structure data to the primary productivity of the forest will require the cooperative efforts of Dr. Dinger, Dr. Shieh, and myself in evaluating these results in terms of Dr. Dinger's study of the rates of CO_2 exchange in the leaves of <u>Liriodendron tulipifera</u> (subproject 52).

The expansion of this study of radiant energy distribution to a determination of energy partitioning in this forest requires that other energy balance components be measured. Specifically, net and incoming all-wave radiation, net short wave (or solar) radiation, temperature, humidity, and air flow distributions must be monitored in addition to the distribution of solar radiation now under study. The flux of heat into or out of the soil, profiles of soil water potentials, and precipitation inputs must also be measured.

Accordingly a net-work of thermistors has been built and installed in the forest to provide a measure of the vertical and horizontal variation in air temperature. A system of humidity or dew point sensors is currently being designed by the Instrumentation and Controls Division of ORNL to obtain similar distributions of atmospheric humidity. Because of the expense of all-wave radiometers and of solarimeters capable of being inverted for determination of net solar radiation, I am unable to establish an instrument net sufficient to maintain adequate statistical control over the spatial variability of those varables. Instead an aerial tramway system is being designed to allow spatial sampling by single moving sensors at elevations of 3, 20, 50, and 100 feet above the forest floor. CSIRO Funk-type radiometers have been acquired for installation on this tramway system as well as Moll-Gorczynski solarimeters. One upright and one inverted solarimeter will be placed upon the trams at each of the four levels and net solar radiation will be obtained by subtracting outgoing radiation measured by the inverted sensor from the incoming radiation measured by the upright sensor. The soil heat flux is being monitored using Thornthwaite soil heat flux disks. The measurements are replicated three times. Soil water potentials are monitored using Wescor thermocouple psychrometers. The psychrometers have been placed in the soil at depths of 4 feet, 2 feet, 1 foot, 6 inches, 2 inches and just beneath the soil surface. The lower three depths are replicated three times. The upper three depths are replicated four times. Precipitation is measured with a remote recording rain gage mounted at 100-foot elevation. Two additional gages are situated on the forest floor to obtain an estimate of throughfall. Intercepted precipitation can be derived by subtracting throughfall from the total precipitation recorded above the stand. Table one summarizes the instrument net that is planned and indicates the location of all sensors.

At this time there is no possible way to estimate advective transfers of sensible or of latent heat to or from this forest. Thus the determination of energy partitioning in the forest by measurement of the major components of the energy balance will only be valid during periods which have negligible advective energy transfer. Because of this constraint, the periods for which data are to be analyzed for determination of the energy partitioning must be carefully selected. Data from periods having strong winds and high turbulent mixing cannot be used. Data from night periods having strong gravity flow in the air layers near the ground cannot be analyzed. Since this instrument system will also serve as a micrometeorological monitoring service to other IBP scientists, data will be collected continuously even though not all the data can be used for determination of energy partitioning.

Since the number of sensors in this expanded system will exceed the capacity of the data acquisition system now in operation, an additional system is being acquired. Signals from the various sensors will be scanned at preselected intervals on a continuous basis, converted to digital form, and recorded on punch paper tape. In addition both the existing data acquisition system and the system now being assembled will be hardwired into a computing facility being acquired by the Ecological Sciences Division, ORNL. This computer will be programmed such that data summaries from the instrument array within the Liriodendron forest of interest to other scientists will be computed, recorded, and filed on a routine basis.

The forest structure data to be collected as described previously will be used in the development of models of the influence of forest structure upon energy partitioning and of the relationship between energy partitioning and of the relationship between energy partitioning and photosynthetic activity.

Results to Date and Discussion:

Table 1 and the section on methods in this report summarize the current status of instrument acquisition and installation. Solar radiation data collection began August 2, 1971, about 6 months behind schedule owing to a design error by the manufacturer of the data acquisition system. The Instrumentation and Controls Division of ORNL was able to rectify this error thus making the system operable but the time required to do this resulted in the loss of data throughout most of the current years' growing season. Since August 2, the system has been in continuous operation with only minor breaks in data continuity because of equipment failure. Continuing installation of other instrumentation throughout the fall of 1971 has precluded any analysis of the radiation data currently being collected.

Preliminary data on the distribution of solar radiation in this forest was collected in the spring of 1969. These data are currently being analyzed and the results to date are summarized here.

During the spring of 1969, solar radiation was measured using Lintronic dome solarimeters on loan from the Yale University School of Forestry. Sensors were randomly located at 6 inches above the forest floor (17 open + 2 shaded) and non-randomly located at mid-canopy (3 open + 2 shaded) and in the upper canopy (3 open + 2 shaded). Random location of elevated sensors was precluded by limited numbers of towers. Additional sensors would be needed at both mid-canopy (approximately 42 feet elevation) and upper canopy (approximately 64 feet elevation) to obtain spatial means having tolerable standard errors. Because of this instanteneous mean values from these two levels are highly questionable. Despite this limitation however, the trends exhibited by data from these levels as well as the daily averages of there data should be realistic.

In 1969, the walk-up tower in this forest did not extend above the forest canopy. Hence no record of incident solar radiation upon the forest could be obtained. For this reason, data was collected only on relatively cloud-free days in order that the radiation record from the NOAA weather station in Oak Ridge (townsite station), some 8 miles to the north, could be taken as a measure of the total radiation incident upon the forest.

Data were collected on 13 days throughout the spring and early summer of 1969. Of these 13 days, 3 developed partly cloudy conditions soon after the system was turned on. Data from these days have been deleted from this summary. In addition, May 15 became totally overcast slightly before solar noon; hence morning data only is included for this day. Owing to the lack of automatic data acquisition facilities, this system had to be turned on and off manually. Since access to this forest is restricted, this condition resulted in great variability in the daily lengths of data records. To allow comparison of data from different days, only the data from the 6 hour period centered on solar noon is included in these analyses.

Figure 1 shows in diagrammatic form, a qualitative assessment of the structure of this forest and the placement of sensors in relation to this structure. Qualitative records of the phenological development of the canopy cover were also made and are summarized here. April 12 was the first clear day on which data was collected. By this date bud break had already occurred in the *Liriodendron tulipifera* of the overstory canopy. However, the first leaf was not yet unfolded. In the understory canopy, the *Cersis canadensis* and *Cornus florida* were in full bloom but no leaves had yet become visible. Between April 12 and 21, leaves in the overstory canopy rapidly opened and expanded. Leaves in the understory canopy were visible on April 21, but had not yet unfolded. By the end of April, Liriodendron leaves in the area of crown closure in the upper canopy had become larger than those above. In the understory, leaf expansion had proceeded very rapidly and although some leaf expansion occurred well into May, the appearance of the understory canopy changed little after April 30. Leaf expansion in the overstory canopy continued through May but much more slowly than in April. Data collected in 1971 by Dr. Blaine Dinger indicate that leaf expansion in the overstory reaches a maximum about 10 weeks after the onset of growth in the spring. Assuming that neither 1969 nor 1971 were atypical years, this would indicate that the upper canopy reached maximum development in 1969 early in June.

The average radiant intensities for the 6 hour mid-day period centered on solar noon are shown in figure 2. It appears that in terms of direct beam radiation reaching the forest floor, this forest was essentially fully leafed by May 7. Only slight decreases in this quantity occurred after May 7.

In constrast, the average intensities of the diffuse component show only slight variation from day to day throughout April and then a gradual decrease throughout May.

At mid-canopy, the average direct beam intensities were nearly constant during April indicating that the shade created by the rapidly expanding leaves above was off set by the increasing amounts of radiation incident upon the forest by virtue of the increasing solar elevation which reaches a maximum at the summer solstice (June 21-22). In May however, shade effects obscure the effects of increasing solar elevations and the average direct beam intensities decreased gradually. I cannot explain the high value of direct beam intensity at this level on May 15. Average intensities of the diffuse component of solar radiation are quite variable throughout the spring but no trend in these data are apparent.

On both April 21 and May 15, average diffuse component intensities at mid-canopy are shown to exceed those in the upper canopy, an impossible situation. Because of time limitations, I was not able to adjust the shadow bands on these dates and thus the shaded sensors actually sensed some direct beam radiation as well. Thus the indicated diffuse intensities are high and the direct beam intensities derived by subtraction are somewhat lower than were actually present.

In the upper canopy, the average daily direct beam intensities increase until late April indicating that the effects of increasing solar elevation upon radiation received exceed those of leaf expansion during this time. In late April however, direct beam intensities begin to decrease as further leaf expansion creates shade sufficient to off set the effect of continuing increases in solar elevation. Average intensities of the diffuse component in the upper canopy, as at mid-canopy, show no seasonal trend but exhibit great variability from day to day.

From this figure it appears that the overstory canopy exerts a more powerful effect upon both the extenction of direct beam and diffuse radiant intensities during the latter half of April than does the understory canopy. Later in the season however, the understory canopy reduces intensities proportionally more than does the overstory canopy. This indicates that my qualitative assessment of more rapid leaf expansion in the overstory canopy in the early spring is accurate. These data also support Horn's (1971) conclusion that species having more nearly horizontal leaves distributed in a single layer cast denser shade than species having leaves inclined more vertically and distributed in many layers. The Cornus and Cercis leaves present a strikingly impenetrable appearance from above by virtue of their near horizontal inclination and their ordered distribution over the upper surface of the crown much like shingles on a roof. Liriodendron leaves, on the other hand, tend to be inclined more vertically. This tendency becomes more pronounced with height in the overstory canopy. The leaves are distributed throughout the crown volume. The visual appearance of Liriodendron crowns from above is much more chaotic than those of predominant species in the understory canopy.

Because of the increasing amounts of radiation incident upon the forest in the spring resulting from increasing solar elevations, changing radiation conditions within the forest reflect both forest phenological changes and changing radiation climate. Even on cloud free days, radiant intensities reaching the forest are further varied over time periods shorter than the solar day by the apparent solar path symmetric about solar noon and by changing atmospheric turbuidity (Anderson, 1964b). Variability in radiation received induced by changing solar position and elevation as well as by atmospheric turbidity can be eliminated by normalizing radiation within the forest by that incident upon the forest. The remaining variability can then be ascribed to phenological changes in the forest structure. Since the physical processes governing the distribution of direct beam and diffuse radiation are quite different, this normalization is best effected using the intensities of the two radiant energy components received at the top of the stand. Unfortunately only total radiation is recorded at the townsite station. Hence normalization of each radiation component by that component above the stand was not possible. This deficiency has been corrected in the present study.

The 1969 data was normalized by the total incident radiation and the resulting penetration rates are shown in figures 3 and 4. This procedure eliminates the variation induced by changes in the earth-sun geometry but does not eliminate variability induced by changing atmospheric turbidity.

From Figure 3, it is apparent that the fraction of total radiation incident upon the forest that penetrates to the forest floor as diffuse radiation decreases throughout the duration of this preliminary study. At mid-canopy, no such trend is evident. The penetration of diffuse radiation to this level is relatively constant. Similarly in the upper canopy no seasonal trend in the penetration rate of diffuse radiation is evident although the day to day variation in penetration rates is somewhat greater than at mid-canopy.

This lack of seasonal trends in the penetration of diffuse radiation is not surprising. Anderson's (1964a) analysis of canopy photographs led her to conclude that most of the diffuse radiation penetrating a forest comes from near the zenith since canopy closure is least there. Further, since the data presented here are for the mid-day periods only when the sun is high in the sky, the sky brightness at the zenith is maximal. I expect that seasonal trends are present in diffuse radiation penetration rates averaged over the full solar day. Data now being collected will enable me to verify whether or not the expectation is actually true.

Figure 4 shows the penetration rates of the direct beam component to each of the three levels in the forest. At the forest floor the direct beam component is reduced sharply throughout April and only slightly thereafter. Thus the forest is essentially fully leafed by early May in terms of both actual amounts of direct beam radiation reaching the forest floor and in turns of direct beam penetration rates. At mid-canopy the direct beam penetration is reduced over time similarly to that on the forest floor. However the period of reduction extends to late May at this level. In the upper canopy the fraction of total radiation above received at this level as direct beam is relatively constant until late April whne the penetration rate begins to decrease quite rapidly in response to continued leaf expansion.

Salisbury (1916) was apparently the first to try to quantify the difference in light conditions in a diciduous forest between the light phase when the trees are bare of leaves and the shade phase when the trees have leaves. Anderson's (1964b) more recent work indicates that the time and duration of leaf expansion also greatly affects the seasonal change in light conditions in diciduous forests from winter to summer. This finding led her to define absolute light and shade phases beyond the relative phases of Salibury. The results shown here in figures 3 and 4 are especially significant in these terms because these figures indicate that beyond absolute phases, elevational differences in a forest are also present owing to differing rates of phenological change in the forest strata. The absolute shade phase in this forest begins considerably earlier on the forest floor than at higher levels in the forest.

While spatial and temporal averaging of radiant intensities is a convenient means of assessing the distribution of radiation within a forest, such averages are not particularly relevant to primary productivity because of the nonlinear response of photosynthesis to radiant intensity. For this reason I am further analyzing these data in terms of the frequency distribution of radiant intensities measured by the sensors at each level. In plotting these distributions for the six-hour mid-day period centered on solar noon, it became apparent that the shapes of the distribution curves measured in April were quite different from those measured later in the season. Thus separate plots were made for April and for May and July data.

Figures 5 and 6 show the intensity distribution of the diffuse component on the forest floor on April dates and on May and July dates respectively. Modal intensity values on April dates are quite similar as are the general shapes of the daily curves indicating similar variation about the mode. In May and July, modal values are reduced considerably and the distributions are much more variable from day to day. Variation about the daily modes are similar in May and July and are somewhat reduced from that found in April.

Similar trends are exhibited at mid-canopy as indicated by figures 7 and 8. Modal intensities in April occur at somewhat higher values at mid-canopy than on the forest floor and variation about the modes is greater at mid-canopy as evidenced by the broader base of the frequency diagram. In May and July, modal intensities exhibit little change from those of April except for the May 26 data for which I have no explanation. The bimodality of the distributions is more pronounced in May and July data and the distributions are skewed to lower radiant intensities than in April.

The distributions of diffuse radiant intensities in the upper canopy are plotted in figures 9 and 10. Day to day variation is great and no obvious differences between April and later data are exhibited.

The changes in direct beam intensity distributions are much more pronounced at all levels in the forest than are the distribution of diffuse intensities. (Note that the scale of the abacissa in figures 11 through 16 are reduced by a factor of 5 from the previous plots of diffuse intensity distributions.)

Figures 11 and 12 show the distributions of direct beam intensities in April and in May and July respectively. Modal intensities are quite low in April and are reduced still further as the season progresses. April distributions are skewed to somewhat higher intensities but this skewness becomes negligible as the season progresses. This reflects the great reduction in the sizes and numbers of sunflects on the forest floor as the leaves expand in the canopy above.

At mid-canopy the distribution of direct beam intensities approaches ~~apprches~~ a rectangular distribution in April (figure 13) although variability is great.

No pronounced modes are exhibited on any April dates. The May and July distributions shown on figure 14 exhibit well defined modes at quite low intensities however. These modal intensities are only slightly greater than those existant on the forest floor as shown in figure 12. The May and July distributions in the mid-canopy are also skewed somewhat more strongly to higher intensities indicating more frequent sunflects reaching this level than the forest floor.

The distribution of intensities in the upper canopy on April days is shown on figure 15. The modal intensities are quite high and the curves are strongly skewed to lower intensities. In May and July however, while peak intensities at the high value ends of the curves are reduced only slightly, the frequency of occurrence of mid-scale intensities is much reduced. Further, a second peak develops at quite low radiant intensities. Thus the distribution of direct beam intensity on clear days during the first half of the growing season are indicated to be strongly biomodal.

A major portion of the primary productivity of this forest occurs within the overstory canopy. This is also the forest stratum in which radiant intensities depart most strongly from Gaussian on relatively clear days. Thus the use of linear model of photosynthetic response to radiant intensities must be suspect. However, since cloud free days are rather uncommon during the growing season of east Tennessee, these data may not be truly indicative of the radiant energy conditions that predominate in this forest throughout the growing season. With data now being collected, these analyses will be carried out for all days within the growing season to assess the significance of the results reported here.

Summary:

The distribution of solar radiation in space and time in a deciduous forest is currently being measured. Instrumentation for determination of other components of the abiatic energy balance in this forest is now being acquired and installed. Preliminary data collected in the spring of 1969 incate that the varying structure and phenology of the forest strata strongly influence the penetration of solar radiation through these strata. The tendency for radiant intensity distributions within and below the overstory canopy to be bimodal and strongly skewed indicate that the use of average radiation intensities in the calculation of photosynthetic response may yield misleading results. Further investigation of this aspect of forest primary productivity is planned.

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Table 1

Liriodendron Forest Micrometeorological Monitoring System:

Sensor	Variable Measured	Variable Derived	Sensor Location
Lintronic dome solarimeters (in operation)	total incident radiation in band 0.3 to 3.0μ		12 on ground 12 at 20 feet 11 at 50 feet 1 at 100 feet
Lintronic dome solarimeters with shadow bands (in operation)	diffuse component of radiation 0.3 to 3.0μ	total - diffuse = direct beam component	2 on ground 2 at 20 feet 1 at 50 feet 1 at 100 feet
CSIRO net radiometers (on hand - to be installed)	net all wave radiation 0.3 to 60.0μ	net all wave - net short wave = net long wave	1 on trolley at 3' 1 on trolley at 20' 1 on trolley at 50' 1 on trolley at 100'
CSIRO net radiometer with bottom shielded	incoming all wave radiation 0.3 to 60μ	incoming - net = outgoing all wave radiation	1 on trolley at 3' 1 on trolley at 100'
Moll-Gorczynski solarimeters (on hand - to be installed)	upright - incoming solar inverted - reflected solar 0.3 to 2μ	incoming reflected = net solar radiation	1 upright + 1 inverted at 3' 1 upright + 1 inverted at 20' 1 upright + 1 inverted at 50' 1 upright + 1 inverted at 100'

Sensor	Variable Measured	Variable Derived	Sensor Location
Eppley precision pyranometer with RG-8 filter (on hand - to be installed)	incoming radiation in 0.7 to 3μ (near IR)	incoming all wave- (incoming solar & incoming near IR) = incoming far I.R	1 at 100 feet
Thermistors (50 now in operation 22 more to be purchased)	temperature (soil or air)		For Fred Taylor's phenology work 10 profiles at 0, 1, & 4.5 feet systematically located in valley above cesium forest. For NOAA energy studies 2 profiles in soil at 0, 2", 6", 1', & 2" depths. Distribution in forest: 2 at 1'; 5 at 3'; 2 at 10' 5 at 20'; 2 at 30'; 2 at 40'; 5 at 50'; 2 at 60', 70', & 80'; 3 at 100'.
Soil heat flux disks (in operation)	Soil heat flux		3 at soil surface
Thermocouple Phychrometers (in operation)	Soil water potential		3 profiles 0, 2", 6", 1', 2', 4' 1 profile 0, 2", 6"

Sensor	Variable Measured	Variable Derived	Sensor Location
Dew cells (to be selected and purchased)	Dew point temperature	relative humidity, absolute humidity, vapor pressure, etc. from dew point and air temp.	2 at 1'; 3 at 3'; 2 10'; 3 at 20'; 2 at 30' and 40'; 3 at 50'; 2 at 60', 70', & 80'; 3 at 100'.
Synopic wind system (to be purchased)	Wind speed and direction		anemometer and vane at 100'
Omnidirectional Anemometers (to be selected and purchased)	Total horizontal wind speed in forest		2 profiles at 3, 20, 50, & 70 feet
Recording Rain Gages (in operation)	Total precip & Throughfall	Total - throughfall = interception	1 - 100' 2 - Ground

Figure 1: Qualitative Assessment of Structure of Liriodendron Forest

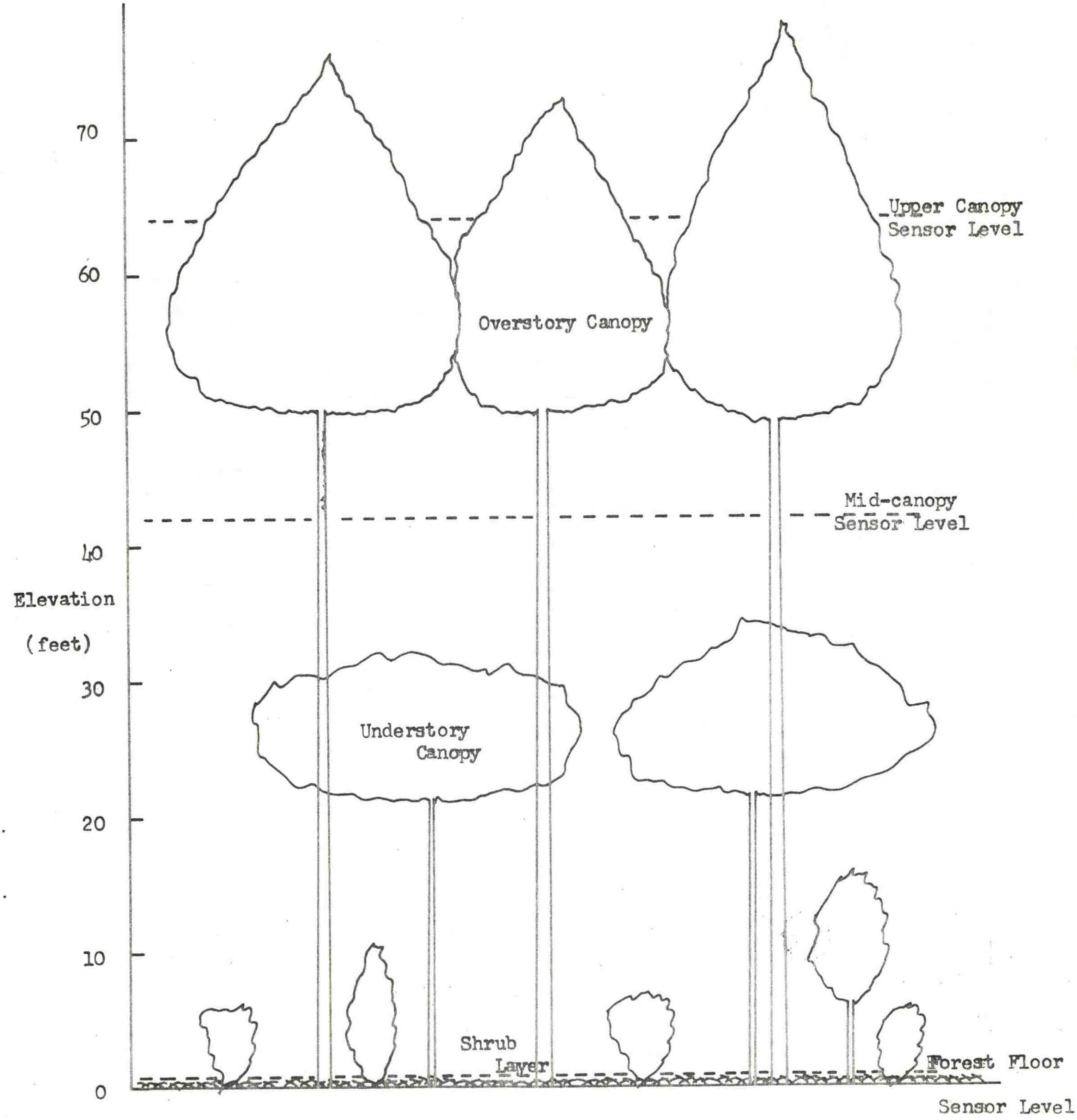

Figure 2: Average Radiant Intensity in Liriodendron Forest for Period Solar Noon ± 3 Hours

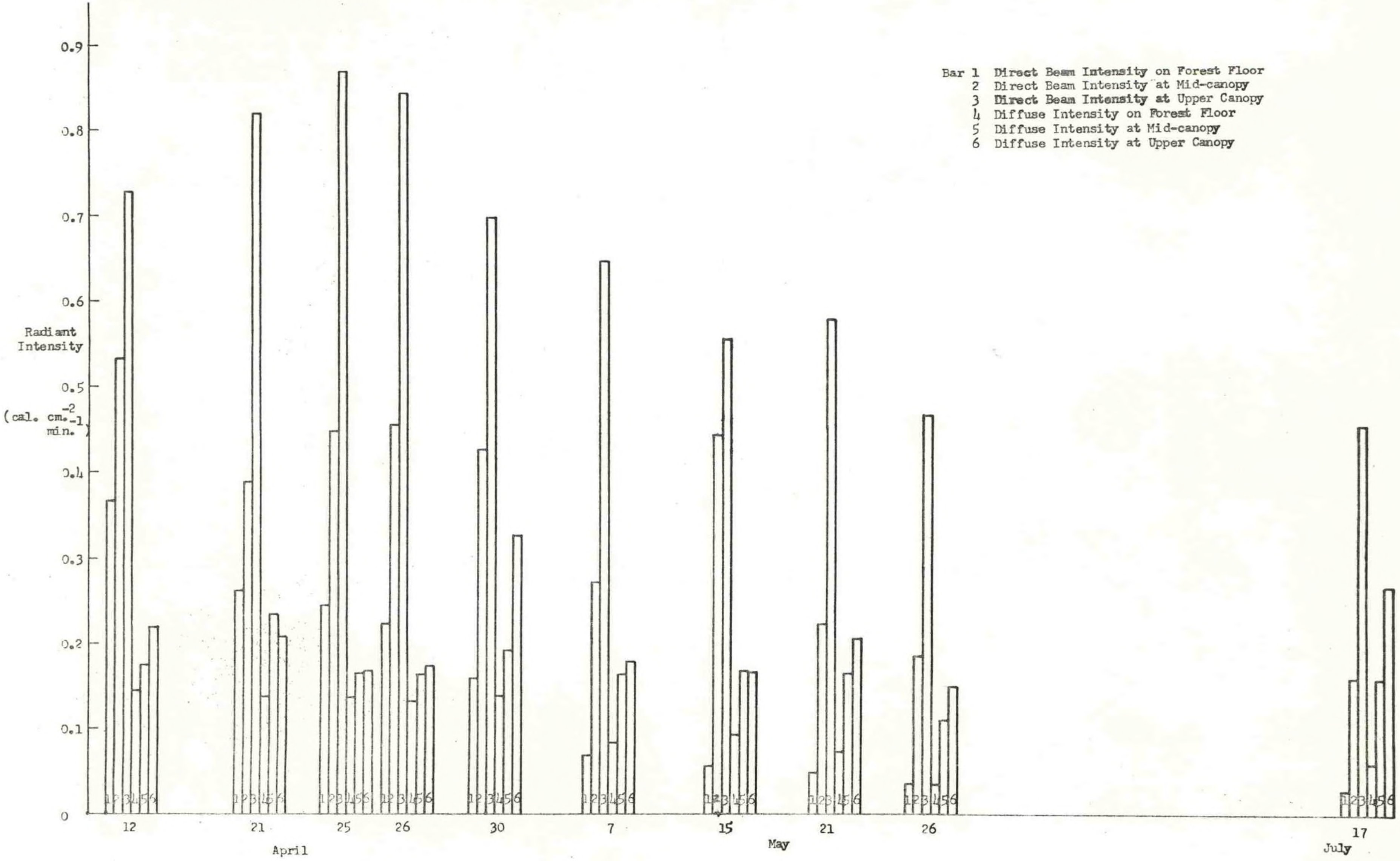

Figure 3: Average Penetration of Diffuse Radiation Into Forest for Period Solar Noon ±3 Hours

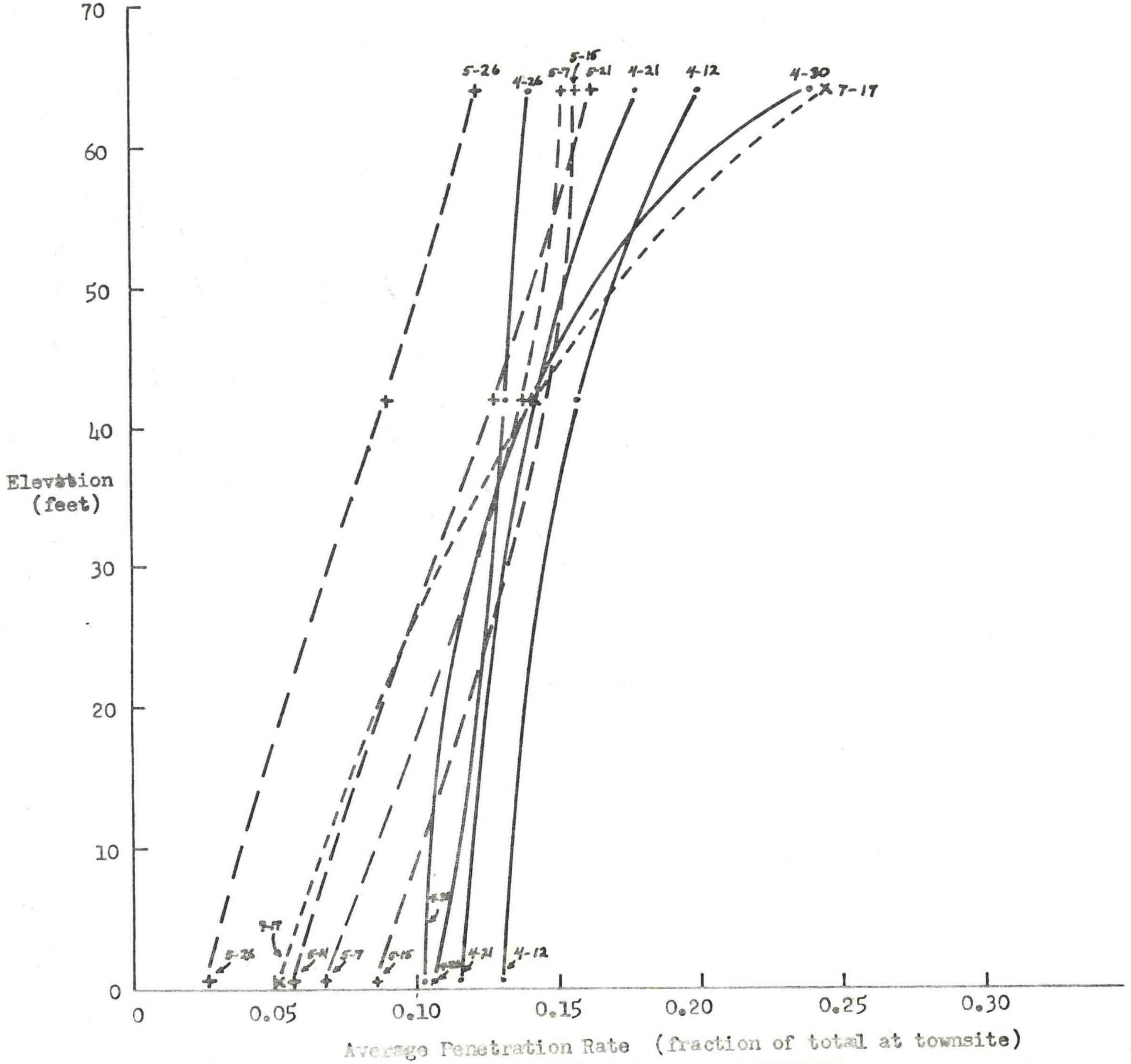

Figure 4: Average Penetration of Direct Beam Radiation Into Forest For Period Solar Noon ±3 Hours

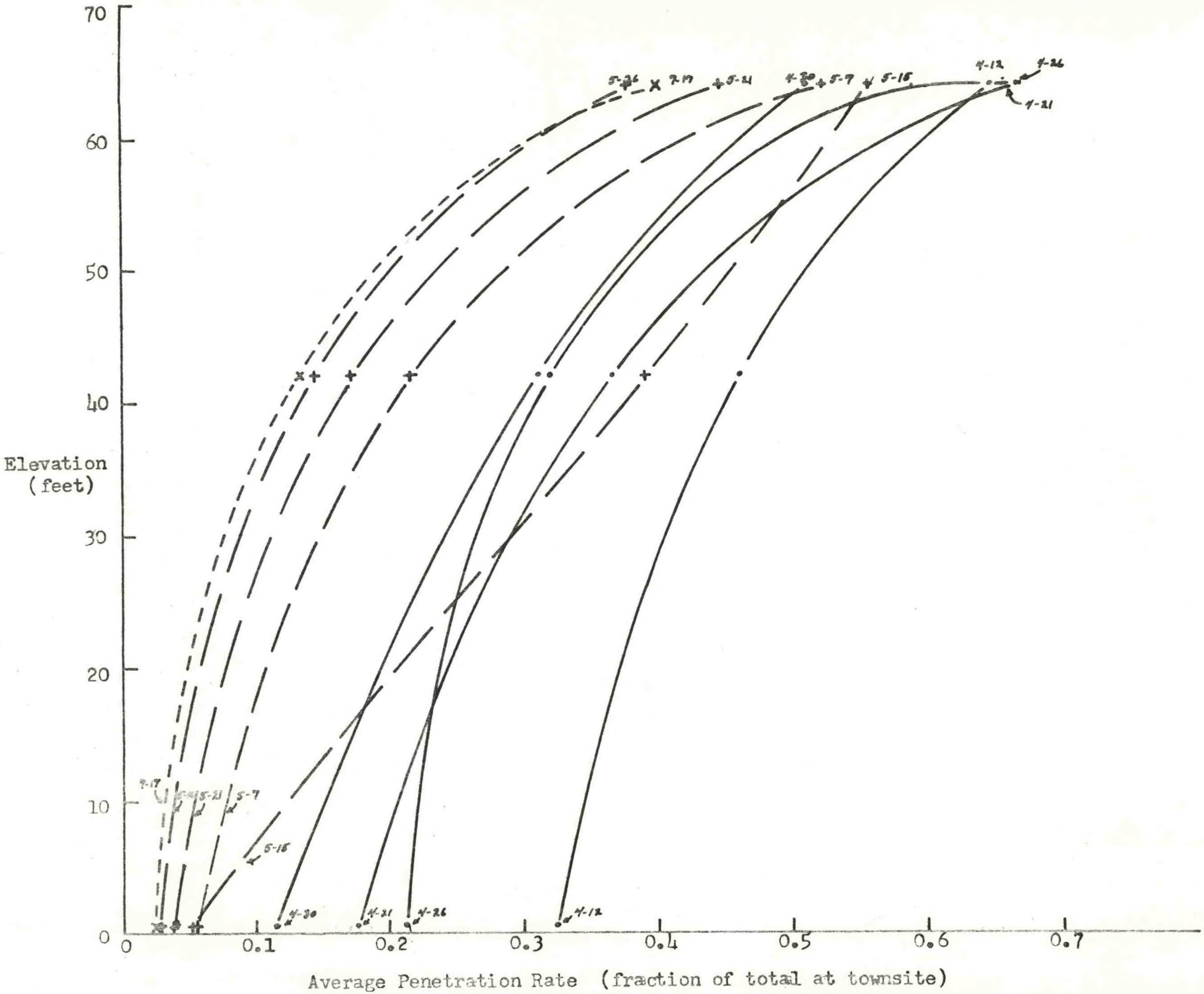

Figure 5: Distribution of Diffuse Radiant Intensity on Forest Floor for Period Solar Noon ±3 Hours

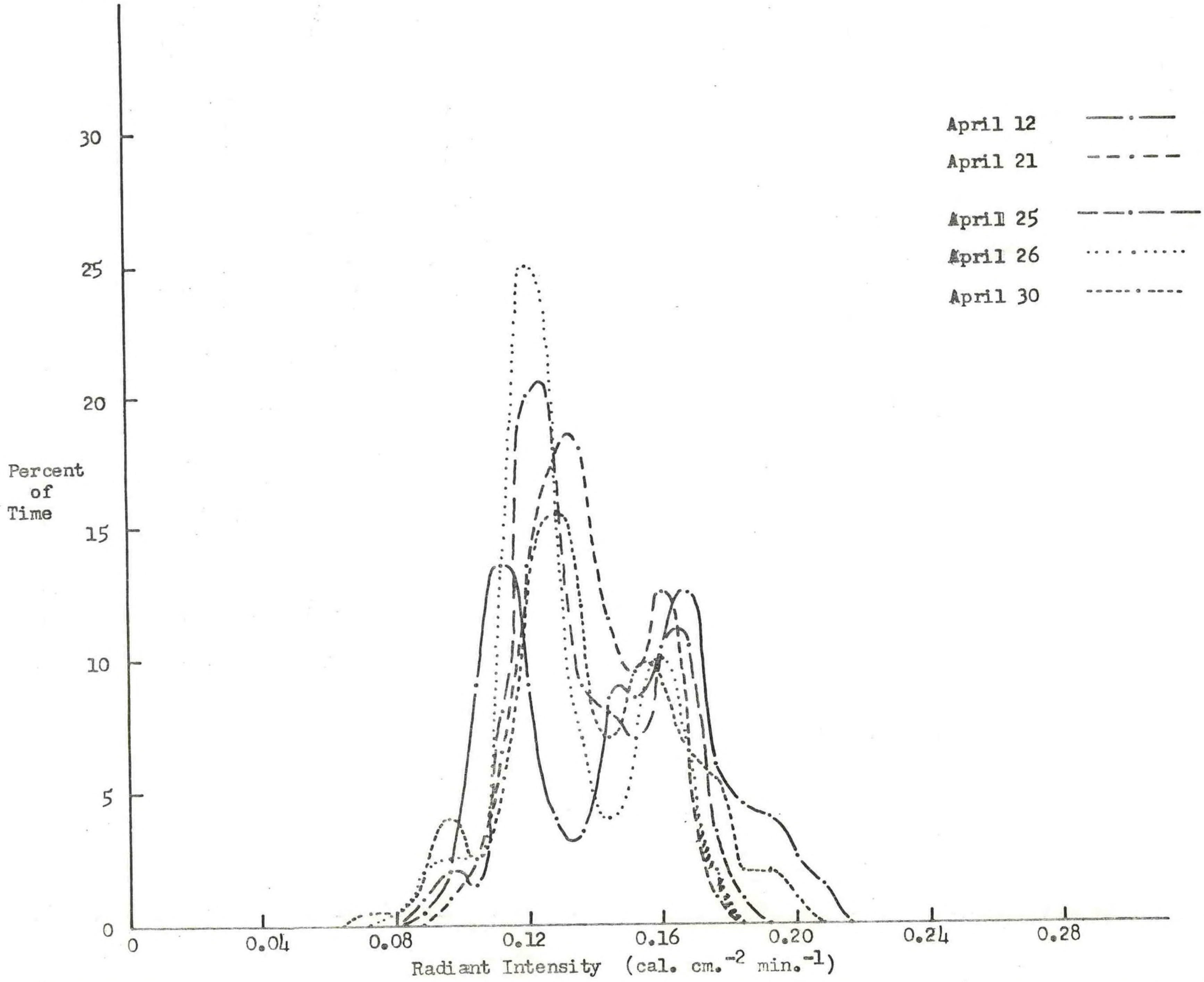

Figure 6: Distribution of Diffuse Radiant Intensity on Forest Floor for Period Solar Noon ±3 Hours

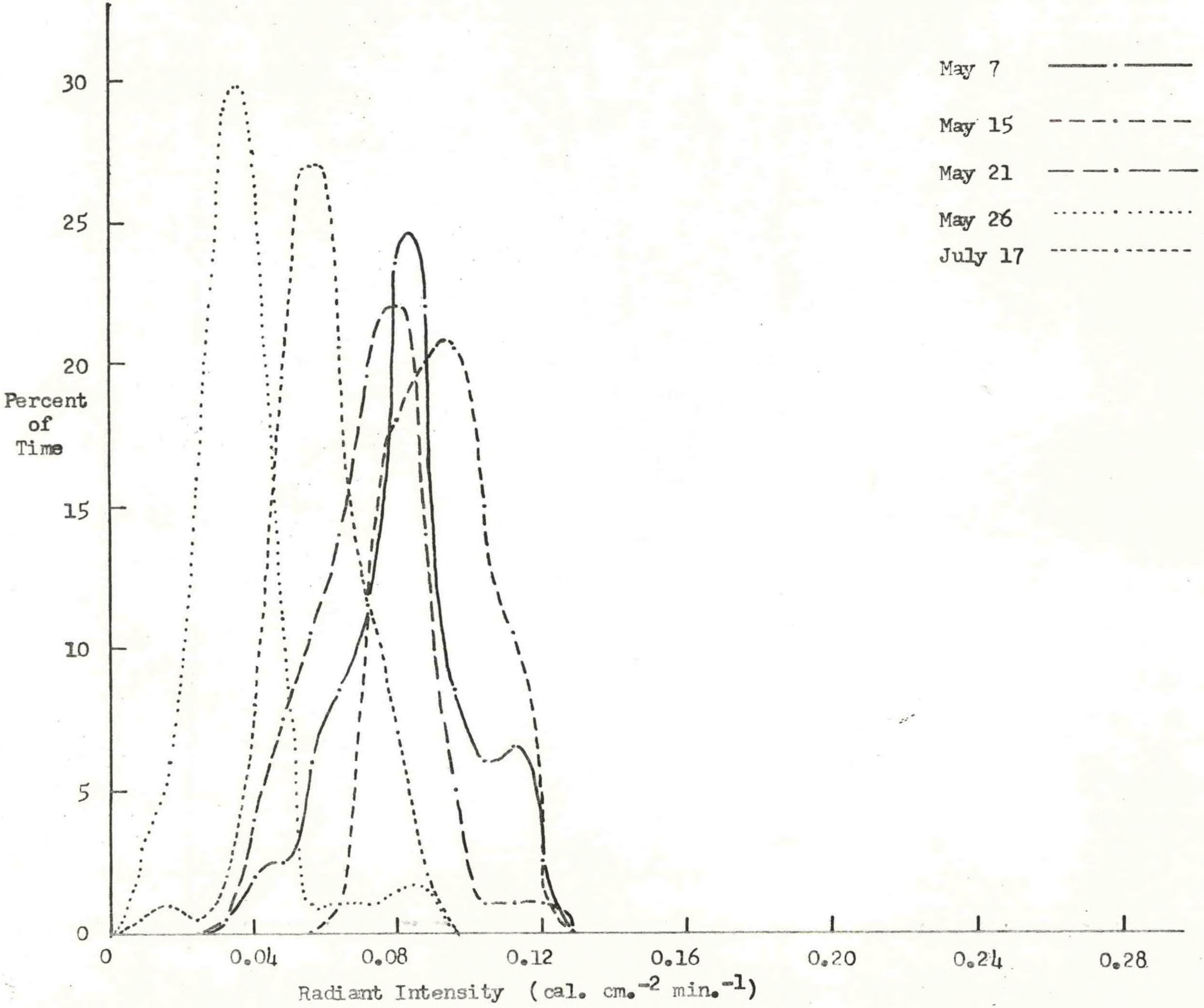

Figure 7: Distribution of Diffuse Radiant Intensity at Mid-canopy for Period Solar Noon ± 3 Hours

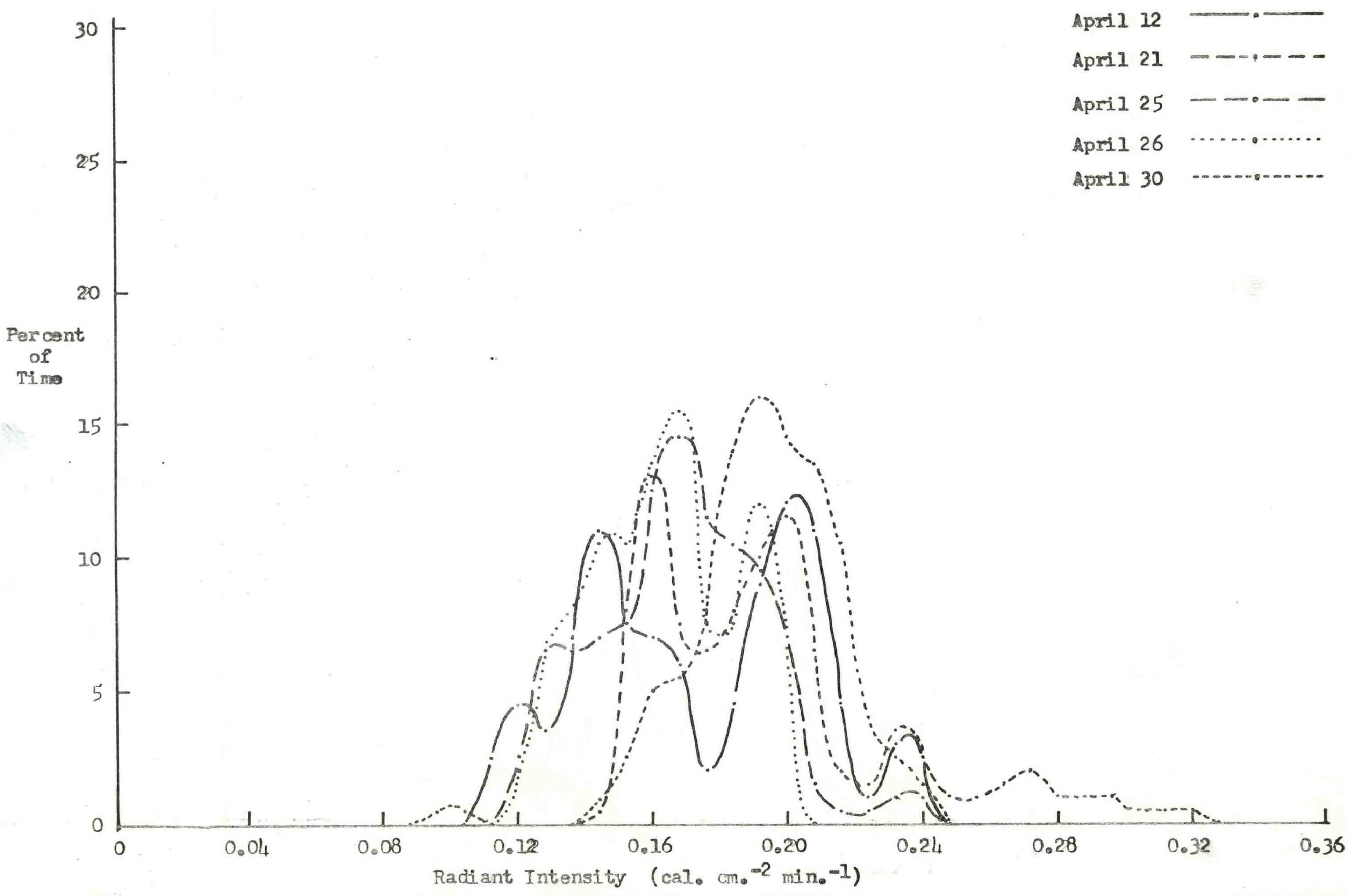

Figure 8: Distribution of Diffuse Radiant Intensity at Mid-canopy for Period Solar Noon ± 3 Hours

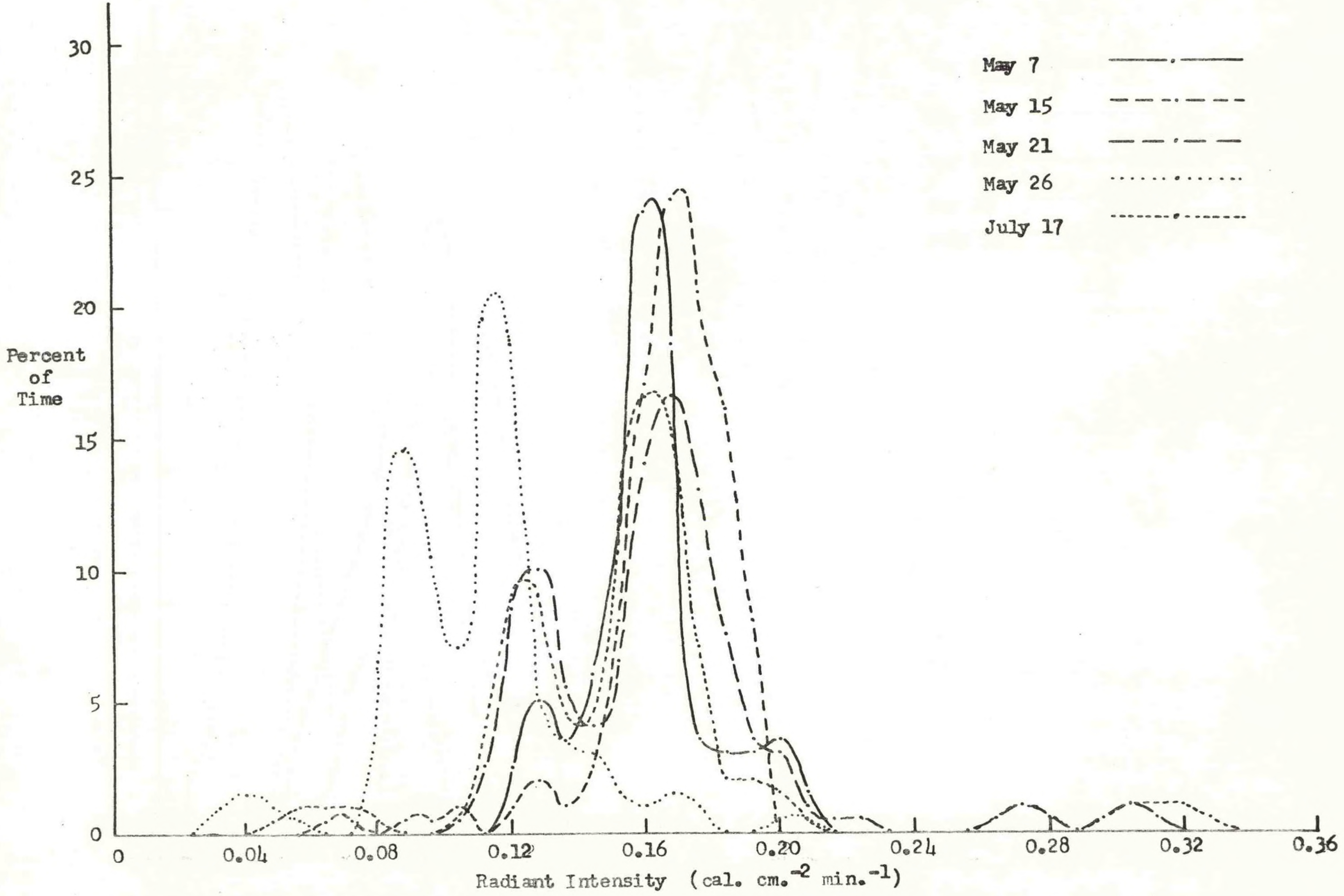

Figure 9: Distribution of Diffuse Radiant Intensity at Upper Canopy for Period Solar Moon ± 3 Hours

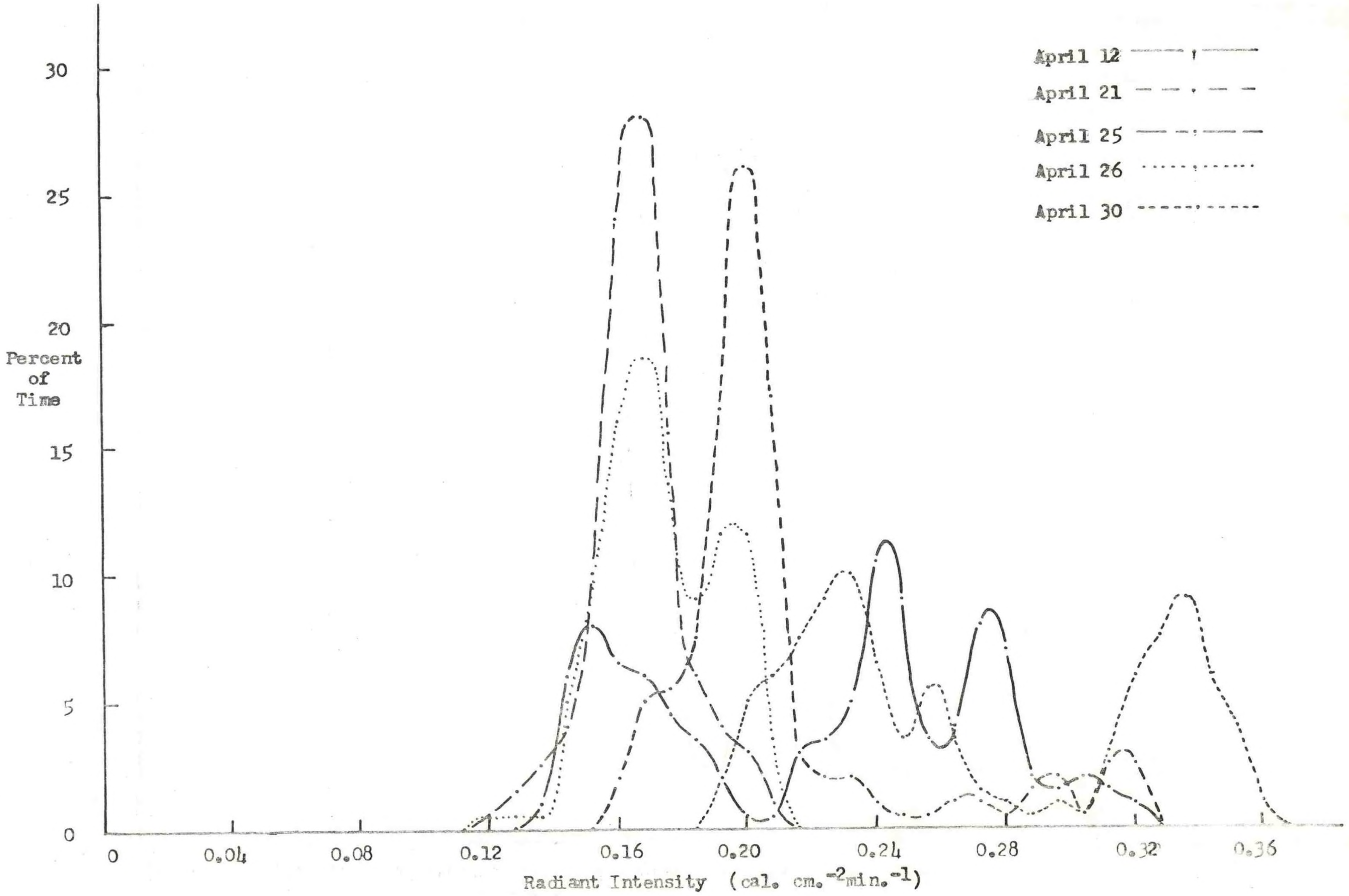

Figure 10: Distribution of Diffuse Radiant Intensity at Upper Canopy for Period Solar Noon ± 3 Hours

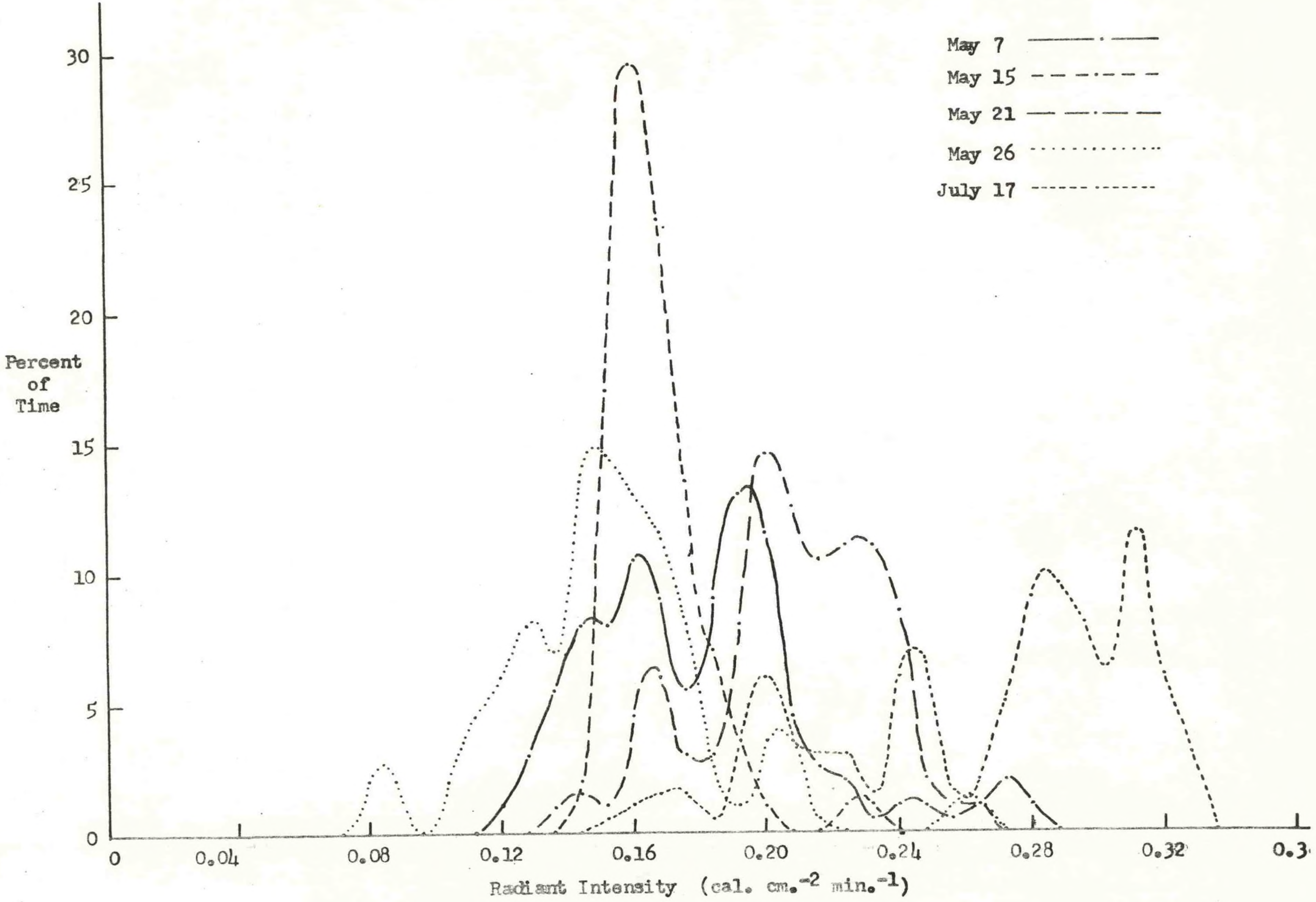

Figure 11: Distribution of Direct Beam Radiant Intensity on Forest Floor for Period Solar Noon ± 3 Hours

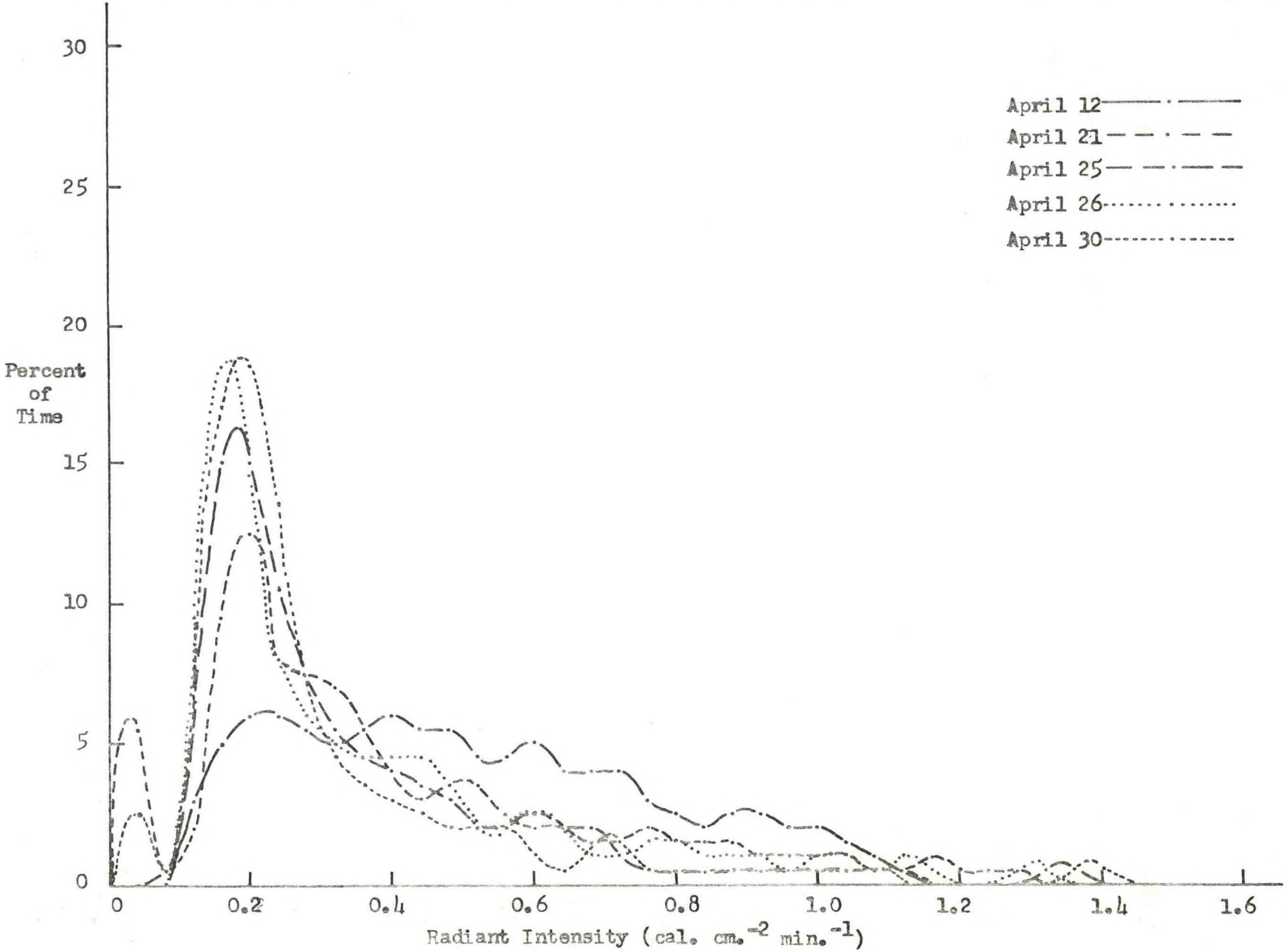

Figure 12: Distribution of Direct Beam Radiant Intensity on Forest Floor for Period Solar Noon ±3 Hours

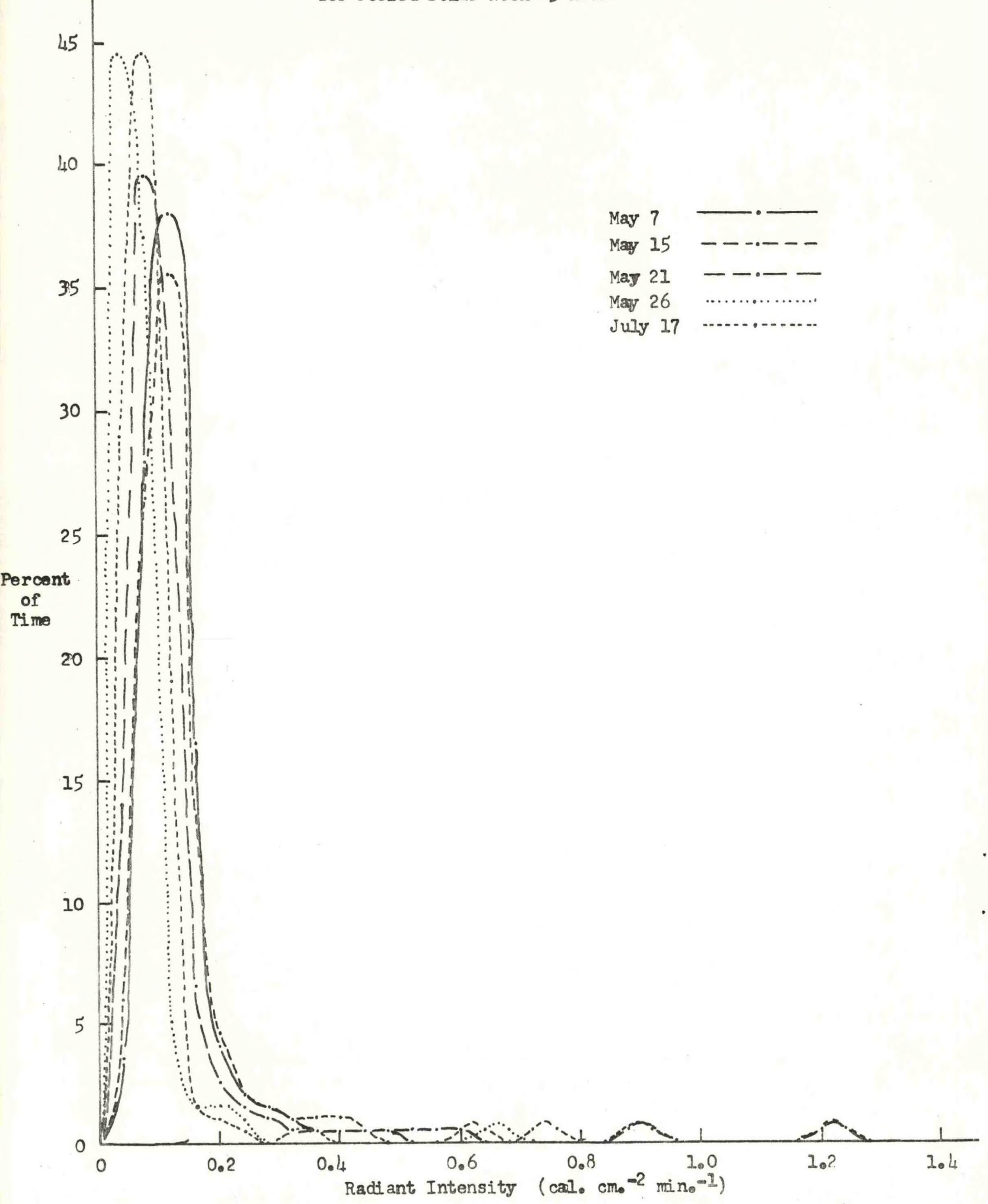

Figure 13: Distribution of Direct Beam Radiant Intensity at Mid-canopy for Period Solar Noon ± 3 Hours

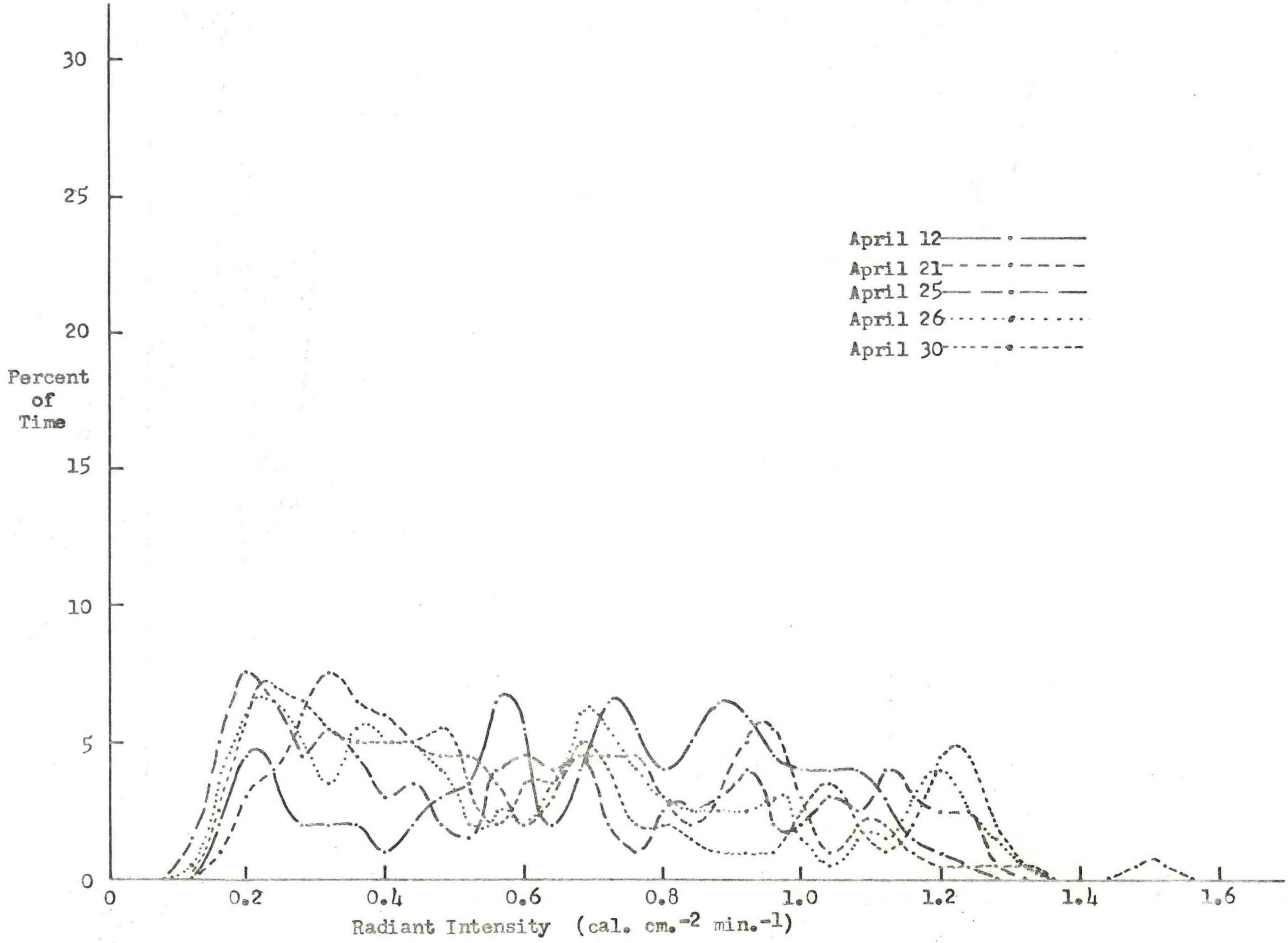

Figure 14: Distribution of Direct Beam Radiant Intensity at Mid-canopy for Period Solar Noon ± 3 Hours

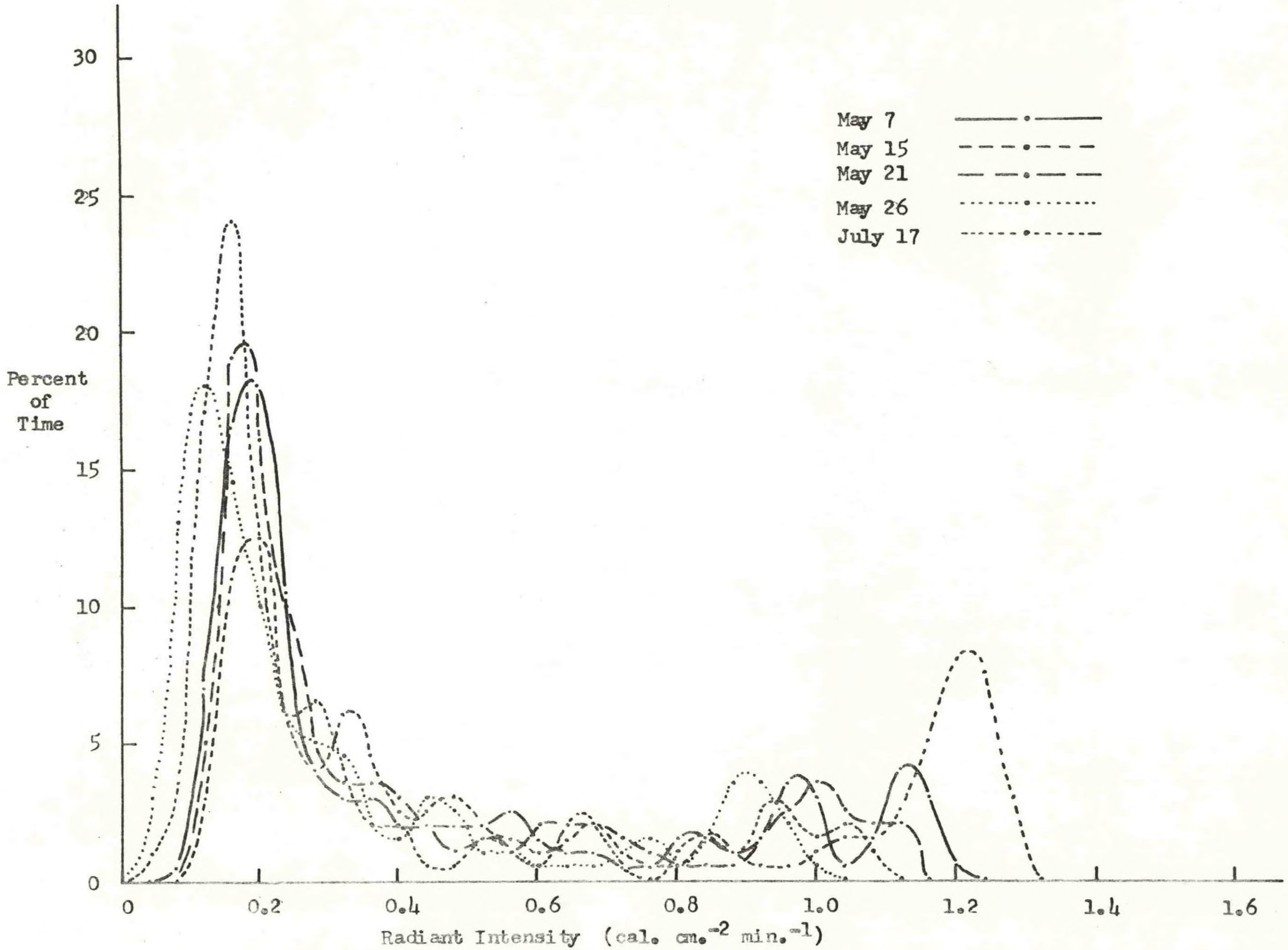

Figure 15: Distribution of Direct Beam Radiant Intensity at Upper Canopy for Period Solar Noon ±3 Hours

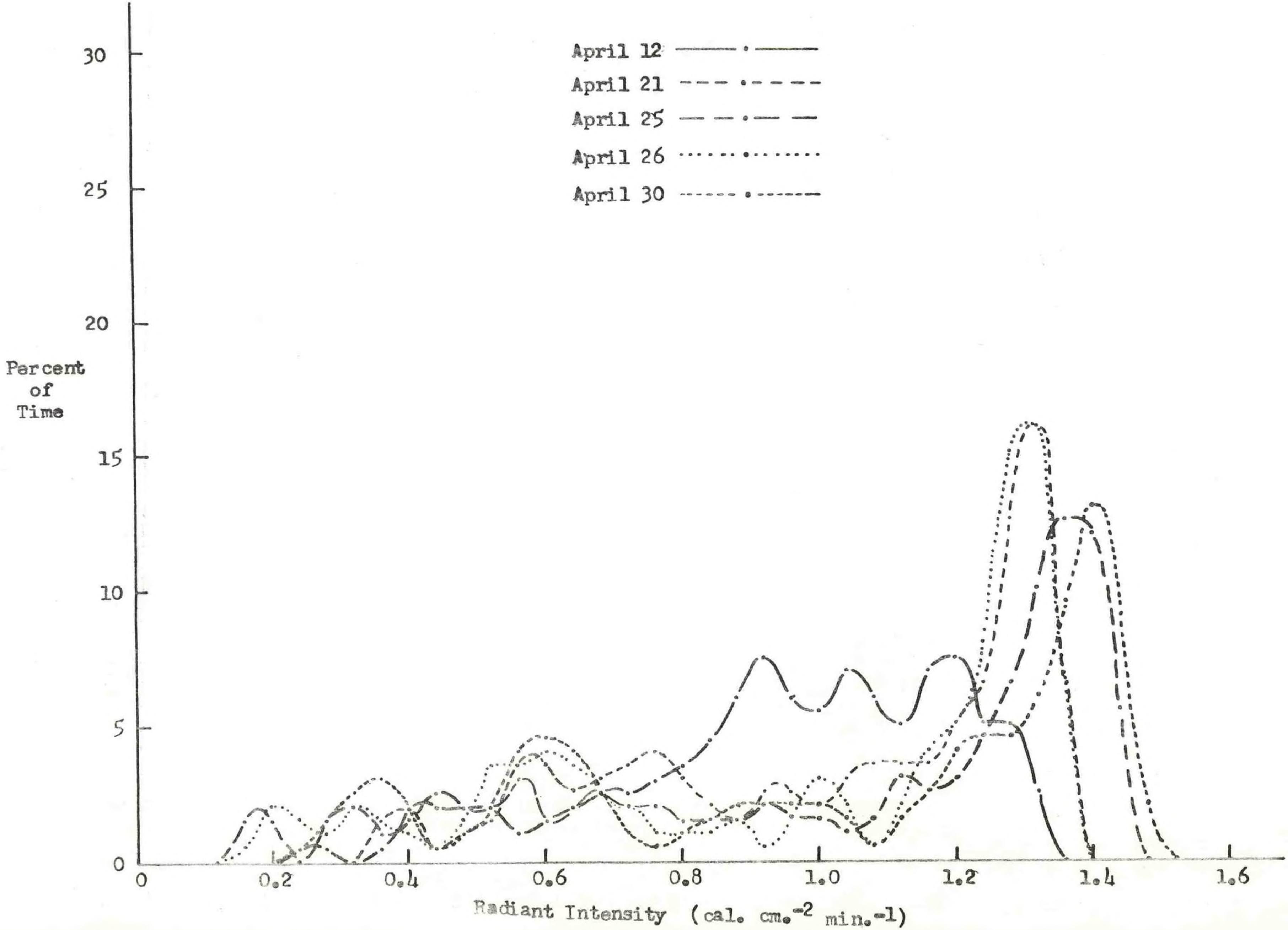

Figure 16: Distribution of Direct Beam Radiant Intensity at Upper Canopy for Period Solar Noon ± 3 Hours