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Effect of Forest Canopy Closure on Incoming Solar Radiance

by

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16. Abstract

A previous investigation into the utility of Landsat multispectral scanner (MSS) data for detecting gypsy moth defoliation has met with limited success. The ability to separate healthy and moderate defoliation is confounded by spectral similarity and topographic effects. In order to better understand the physical processes involved in defoliation assessment from remotely sensed data, a field study was designed to investigate the effect of forest canopy closure and other environmental variables on incoming solar radiation. Diffuse radiation measurements were recorded in red, infrared, and middle infrared wavelengths using the Mark II Three Band Field Radiometer. Results to date indicate that the percent canopy closure is the single most important variable affecting incoming solar radiation. In the visible and near infrared regions, interaction between time of day and date (defined later as solar zenith angle) also affect radiometric response. Aspect has only limited influence on radiance response. These same variables do not influence middle infrared response, however. Uniformity of the forest canopy appears to be more important. These results are compared to Landsat MSS classification results of gypsy moth defoliation.

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A previous investigation into the utility of Landsat multispectral scanner (MSS) data for detecting gypsy moth defoliation has met with limited success. The ability to separate healthy and moderate defoliation is confounded by spectral similarity and topographic effects. In order to better understand the physical processes involved in defoliation assessment from remotely sensed data, a field study was designed to investigate the effect of forest canopy closure and other environmental variables on incoming solar radiation. Diffuse radiation measurements were recorded in red, infrared, and middle infrared wavelengths using the Mark II Three Band Field Radiometer. Results to date indicate that the percent canopy closure is the single most important variable affecting incoming solar radiation. In the visible and near infrared regions, interaction between time of day and date (defined later as solar zenith angle) also affect radiometric response. Aspect has only limited influence on radiance response. These same variables do not influence middle infrared response, however. Uniformity of the forest canopy appears to be more important. These results are compared to Landsat MSS classification results of gypsy moth defoliation.

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EFFECT OF FOREST CANOPY CLOSURE ON INCOMING SOLAR RADIANCE

INTRODUCTION

Over the last several years, personnel at NASA's Goddard Space Flight Center (GSFC) have been examining the use of Landsat Multispectral Scanner (MSS) data to detect and monitor insect defoliation of hardwood forests. Initial results indicated that defoliated areas were spectrally similar to selected agricultural fields in the study area. Detection of defoliation by the gypsy moth caterpillar was later improved using multitemporal data sets (Williams and Stauffer, 1978). Landsat data collected over a given forest prior to insect infestation was classified using computer-aided analysis techniques to identify the extent of forest cover versus non-forest cover. A second data set, collected over the same area after defoliation occurred was then digitally overlaid onto the forest/non-forest classification map. Forested areas were isolated on the image exhibiting insect defoliation and subsequent analysis was limited to those areas only.

Several processing techniques were applied to the defoliated imagery in an attempt to discriminate various levels of insect damage (Williams et al., 1979). In addition to maximum likelihood procedures, vegetation indices which relate the Landsat spectral measurements to various vegetation density indicators such as green leaf biomass were applied to the MSS data. Each procedure separated healthy forest from heavily defoliated stands. However, the ability to separate healthy forest from moderate defoliation (30-60% canopy removed) proved to be more difficult because the two cover types have nearly identical spectral responses (Nelson, 1981). This problem was further compounded by slope and aspect. Whereas some moderate defoliation was separable from healthy and heavily defoliated forest on southeastern slopes, the same level of defoliation was usually not identified on northwestern slopes.

In order to better understand why certain levels of defoliation were not separable using Landsat data, a field study was designed to investigate the radiometric properties of forests under varying crown densities. The objectives of this investigation were to determine the degree of change in forest canopy cover detectable by radiometric measurements and to determine what other sources of variation contributed to the radiance measured. The experiment was carried out using a Mark II 3-band Radiometer developed at Goddard (Tucker et al., 1981). The instrument was designed to measure energy in three wavelength regions that correspond to Landsat D's Thematic Mapper band TM3 (0.63 - 0.69 μm), TM4 (0.76 - 0.90 μm) and TM5 (1.55 - 1.75 μm).

Several investigators have used similar radiometers to examine the in situ spectral properties of agricultural crops (Kimes, et al., 1980; Tucker et al., 1980). Recently, Holben et al. (1980) used the radiometer to evaluate a spectral method for nondestructive leaf area index determination in a tropical forest by recording diffuse radiance at the forest floor and within the forest canopy. This sampling procedure was particularly valuable for studying forest radiometric properties because the investigators were not hindered by the difficulties associated with collecting reflectance measurements over the forest canopy.

COLLECTION OF FIELD DATA

Diffuse radiance was measured under the forest canopy at 48 sample plots along Doubling Gap Mountain near Carlisle, PA. Measurements were made throughout the gypsy moth summer feeding cycle in 1980 (May, June, and July). Doubling Gap is covered by mature hardwood forest consisting of oak (*Quercus* sp), hickory (*Carya* sp), and maple (*Acer* sp). The mountain is part of the ridge and valley physiographic region of the Appalachians, and is subject to gypsy moth attack.

Eight 300m x 300m blocks were randomly selected along the Mountain; four on the north facing slope and four on the south facing slope. Within each block, six plots, 100m x 100m, were chosen at random. Stand age, species composition, and basal area were recorded at each plot center. Radiance measurements were taken on cloud free, low haze days, using the Mark II 3-band radiometer. A 30cm x 30cm barium sulfate plate was placed on the ground at the center point of the plot and levelled. Holding the radiometer approximately 45cm above the plate, radiance measurements were taken over 5 randomly selected points on the plate (See Figure 1). By measuring light reflected from the barium sulphate plate, diffuse incoming radiation was recorded in each of the three wavelength regions (TM3, TM4, TM5). The date and time of day were noted. These measurements were used in subsequent statistical analyses.

Following the radiometer readings, a 35mm camera with a 28mm lens was placed at the plot center point looking directly up at the forest canopy Photographs were taken of the forest canopy and were later examined to estimate percent sky versus canopy cover. In the laboratory, a 16 dot per square inch grid was overlain onto each photo. Dots falling within open sky were counted and divided by the total number of dots covering the photo to determine percent open sky. The uniformity of the canopy (i.e., uniformly dispersed or large holes within canopy) was also interpreted from the nadir viewing photos.

After all the field data were collected and photographs interpreted, the data were analyzed with linear regression and analysis of covariance using the 1979 Statistical Analysis System (SAS).

Although heavy defoliation was expected within almost all the sample blocks, only one received substantial insect damage. Consequently, the complete range of canopy closures was not sampled throughout this exercise. Radiometric measurements were obtained for crown closures ranging between 60 and 97 percent and at 0 percent only. Therefore, the results of this experiment can only be expressed as expected tendencies which need to be further substantiated by additional field studies.

GENERAL LINEAR MODEL

Simple linear regressions were used to examine the effect of canopy closure on incoming solar radiance. Since statistical analyses require that populations be normally distributed, an arcsine transformation was applied to the percent canopy closure to normalize these data. The transformation was performed using the following formula:

$$P_t = \text{Arcsin} \sqrt{P_a}$$

where,

P_t = transformed percent canopy closure value

P_a = actual percent canopy closure value

The regression lines calculated for each wavelength band are plotted in Figures 2, 3, and 4. The general linear model for each line is defined as:

$$y_x = \alpha + \beta P_t + \epsilon$$

where,

y = predicted radiance value for band x

α = intercept

β = coefficient

P_t = transformed percent canopy closure value

ϵ = error term

The moderately high r^2 values (.71, .67, .53) are indicative of the strong correlation between canopy closure and incoming solar radiance. However, there still remains considerable variability not accounted for by the model. In fact, variability tends to increase within the mid-ranges of canopy closure. Although a direct correlation between the field radiance values and Landsat MSS reflectance values cannot be made, the field data analyses give several indicators which are useful to Landsat based studies of insect defoliation. For example, moderate defoliation (30–60% canopy removed) may have such high spectral variability that the class cannot be identified, even with higher spectral resolution, unless other environmental variables are considered. In view of this indicator, analyses of covariance were used to examine the effects of other variables on incoming solar radiance.

ANALYSIS OF COVARIANCE

Environmental variables, such as aspect, canopy uniformity, and time and date of radiance measurement, were selected as covariates in the general linear model to examine the effect of these variables on incoming solar radiance. Analyses of covariance for each wavelength band was performed using the following model:

$$y_x = \alpha + \beta_1 P_t + \beta_2 A + \beta_3 T + \beta_4 D + \beta_5 C + \beta_6 P_t{*}A + \beta_7 P_t{*}A + \beta_8 P_t{*}T +$$
$$\beta_8 P_t{*}D + \beta_9 P_t{*}C + \beta_{10} A{*}T + \beta_{11} A{*}D + \beta_{12} A{*}C + \beta_{13} T{*}D +$$
$$\beta_{14} T{*}C + \beta_{15} D{*}C + \epsilon$$

where,

y = predicted radiance value for band x

α = intercept

β_i = coefficient

P_t = transformed percent canopy value

A = aspect

T = time of measurement

D = date of measurement

C = canopy distribution (i.e., uniformly dispersed or having large holes within canopy)

ϵ = error term

The results of these analyses are given in Tables 1, 2, and 3. The sums of squares listed in the tables are those which are calculated for the particular variable being added to the model last. The values do not reflect incremental sums of squares for the model. The subsequent PR>F value is a more appropriate measure of the variable significance.

In each wavelength region, no singular variable appears to influence radiance response. However, the interactions of several variables do affect response. For example, the interactions of aspect with date and with time are particularly significant for TM3 and TM4 (red and reflective infrared wavelengths, respectively). Further observation shows the date * time interaction to be significant for TM3 and of lesser importance for TM4. These interactive variables are indicative of the effect of incident solar angle on radiance -- a response which is also evident from Landsat MSS investigations (Justice et al., 1980; Hoffer et al., 1975; Holben and Justice, 1979). Another series of statistical analyses using solar zenith angle in lieu of date and time will be discussed in a following section.

Two additional observations from the analyses of covariance are worthy of comment. The percent of canopy closure showed no influence on radiance when used in conjunction with other environmental variables. This illustrates the ability of other variables to mask out the effect of what would initially appear to be the more dominant variable. In subsequent analyses the importance of canopy closure will again become evident.

Finally, the response of TM5 to the general linear model is contrary to both TM3 and TM4. This middle infrared wavelength band does not appear to be influenced by any of the interactions noted previously, nor by any singular variable. Only the date * distribution interaction is significant, indicating that this wavelength region may be unique in its radiometric characteristics.

ANALYSIS OF COVARIANCE USING SOLAR ZENITH ANGLE

Following the initial analyses of covariance, additional analyses were run on the radiance measurements replacing the date and time variables with solar zenith angle. Tables 4, 5, and 6 list the analysis results for each wavelength band, using the general model:

$$y_x = \alpha + \beta_1 P_t + \beta_2 A + \beta_3 Z + \beta_4 C + \beta_5 P_t{*}A + \beta_6 P_t{*}Z + \beta_7 P_t{*}C + C + \beta_8 A{*}Z + \beta_9 A{*}C + \beta_{10} Z{*}C + \epsilon$$

where,

y_x = predicted radiance value for band

β_i = coefficient

P_t = transformed percent canopy closure value

A = aspect

Z = solar zenith angle

C = canopy distribution

The importance of percent canopy closure, solar zenith angle, and the distribution of the forest canopy to radiance response in TM3 and TM4 is readily apparent from the covariance tables (Table 4 and 5). These variables and their interactions are highly significant. The results indicate that when using remotely sensed data to monitor forest canopy condition, solar zenith angle should be accounted for to make optimum use of radiance (or reflectance) measurements. Interestingly, the effect of aspect, seen previously, is not evident when zenith angle is accounted for.

In the middle infrared wavelength region (TM5), solar zenith angle does not appear to influence incoming solar radiance (See Table 6). In contrast, the distribution of the forest canopy is the most significant variable followed by the Arcsin * Aspect and Arcsin * Distribution interactions. The relatively low r^2 value of 0.59 is indicative of the absence of relevant variables which account for much of the variability in radiance response for middle infrared wavelengths. This again points to the uniqueness of this spectral region.

CONCLUSIONS

The technique employed in this study enabled the investigator to examine the radiometric properties of several different forest conditions. Diffuse solar radiance measured at the forest floor revealed responses to forest cover that were comparable to results obtained from previous Landsat studies. Several conclusions were reached, based on this study:

1. Percent canopy closure is the single most important variable affecting radiance within a forest stand.
2. Solar zenith angle, expressed as a date * time interaction or as incident angle, influences radiance response in visible (red) and near infrared wavelength regions.
3. A topographic effect, attributed to aspect, alone, in previous gypsy moth studies, was not evident in this study.
4. Percent canopy closure and solar zenith angle did not appear to have significant influence on the middle infrared wavelength region examined. The uniformity of the forest canopy appeared most important.

The conclusions reached through the results of this project are in need of further research and evaluation. Anticipated research efforts will involve a summer 1981 field radiometer study as well as a spectral reflectance investigation to begin in the spring of 1981.

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Mr. Kevin Ingrams .... Field Data Collection

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of Environmental Resources) .... Field Support and Data Collection

Ms. Robin Mohr .... Manuscript Preparation

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Table 1
Analysis of Covariance for TM3 ($r^2 = 0.92$)

Source	Degrees of Freedom	Type IV Sum of Squares	F Value	PR>F
Arcsin of Percent Canopy	1	0.63	1.19	0.2798
Aspect	1	0.23	0.44	0.5091
Date	2	0.28	0.26	0.7685
Time	15	9.13	1.15	0.3305
Canopy Distribution	1	1.06	2.02	0.1603
Arcsin * Aspect	1	0.49	0.92	0.3397
Arcsin * Date	2	0.16	0.15	0.8579
Arcsin * Time	15	7.22	1.05	0.4153
Arcsin * Distribution	1	1.40	2.65	0.1085
Aspect * Date	2	7.51	7.11	0.0016+
Aspect * Time	14	10.61	1.83	0.0666+
Aspect * Distribution	1	1.20	2.26	0.1371
Date * Time	17	15.35	1.82	0.0471+
Date * Distribution	2	1.36	1.28	0.2840
Time * Distribution	13	6.03	0.88	0.5799

+Significant Effect

Table 2
Analysis of Covariance for TM4 ($r^2 = 0.91$)

Source	Degrees of Freedom	Type IV Sum of Squares	F Value	PR>F
Arcsin of Percent Canopy	1	1.94	0.82	0.3675
Aspect	1	1.54	0.66	0.4209
Date	2	1.94	0.41	0.6637
Time	15	37.48	1.06	0.4069
Canopy Distribution	1	3.34	1.42	0.2379
Arcsin * Aspect	1	2.95	1.25	0.2669
Arcsin * Date	2	1.27	0.27	0.7644
Arcsin * Time	15	31.07	1.02	0.4466
Arcsin * Distribution	1	4.43	1.88	0.1747
Aspect * Date	2	29.16	6.20	0.0034+
Aspect * Time	14	43.61	1.69	0.0954+
Aspect * Distribution	1	8.78	3.73	0.0575+
Date * Time	17	58.93	1.57	0.1032
Date * Distribution	2	5.09	1.08	0.3443
Time * Distribution	13	31.83	1.04	0.4246

+Significant Effect

Table 3
Analysis of Covariance for TM5 ($r^2 = 0.82$)

Source	Degrees of Freedom	Type IV Sum of Squares	F Value	PR>F
Arcsin of Percent Canopy	1	0.21	0.85	0.3609
Aspect	1	0.18	0.72	0.3989
Date	2	0.17	0.35	0.7072
Time	15	2.79	0.76	0.7129
Canopy Distribution	1	0.20	0.83	0.2785
Arcsin * Aspect	1	0.29	1.19	0.3642
Arcsin * Date	2	0.19	0.40	0.6743
Arcsin * Time	15	2.12	0.67	0.7856
Arcsin * Distribution	1	0.30	1.24	0.2690
Aspect * Date	2	0.45	0.93	0.4008
Aspect * Time	14	2.28	0.85	0.5915
Aspect * Distribution	1	0.02	0.10	0.7562
Date * Time	17	4.54	1.16	0.3188
Date * Distribution	2	1.96	4.04	0.0221+
Time * Distribution	13	3.98	1.25	0.2623

+Significant Effect

Table 4
Analysis of Covariance for TM3 using solar zenith angle in place of date and time
($r^2 = 0.80$)

Source	Degrees of Freedom	Type IV Sum of Squares	F Value	PR>F
Arcsin of Percent Canopy	1	8.58	14.54	0.0002+
Zenith Angle	1	8.30	14.07	0.0003+
Aspect	1	0.17	0.28	0.5972
Canopy Distribution	1	6.36	10.77	0.0013+
Arcsin * Angle	1	2.99	5.07	0.0258+
Arcsin * Aspect	1	0.58	0.99	0.3216
Arcsin * Distribution	1	4.20	7.11	0.0085+
Angle * Aspect	1	1.50	2.54	0.1132
Angle * Distribution	1	3.42	5.79	0.0174+
Aspect * Distribution	1	0.49	0.83	0.3643

+Significant Effect

Table 5
Analysis of Covariance for TM4 using solar zenith angle in place of date and time
($r^2 = 0.77$)

Source	Degrees of Freedom	Type IV Sum of Squares	F Value	PR>F
Arcsin of Percent Canopy	1	20.11	7.45	0.0071+
Zenith Angle	1	19.33	7.16	0.0083+
Aspect	1	0.23	0.09	0.7710
Canopy Distribution	1	26.35	9.76	0.0022+
Arcsin * Angle	1	2.08	0.77	0.3814
Arcsin * Aspect	1	5.07	1.88	0.1726
Arcsin * Distribution	1	16.19	6.00	0.0155+
Angle * Aspect	1	4.72	1.75	0.1880
Angle * Distribution	1	18.85	6.98	0.0091+
Aspect * Distribution	1	4.03	1.49	0.2239

+Significant Effect

Table 6
Analysis of Covariance for TM5 using solar zenith angle in place of date and time
($r^2 = 0.59$)

Source	Degrees of Freedom	Type IV Sum of Squares	F Value	PR>F
Arcsin of Percent Canopy	1	0.52	1.98	0.1617
Zenith Angle	1	0.13	0.50	0.4824
Aspect	1	0.18	0.71	0.4014
Canopy Distribution	1	1.21	4.63	0.0330+
Arcsin * Angle	1	0.001	0.00	0.9465
Arcsin * Aspect	1	1.18	4.52	0.0352+
Arcsin * Distribution	1	0.93	3.56	0.0613+
Angle * Aspect	1	0.07	0.26	0.6076
Angle * Distribution	1	0.44	1.68	0.1967
Aspect * Distribution	1	0.01	0.05	0.8276

+Significant Effect

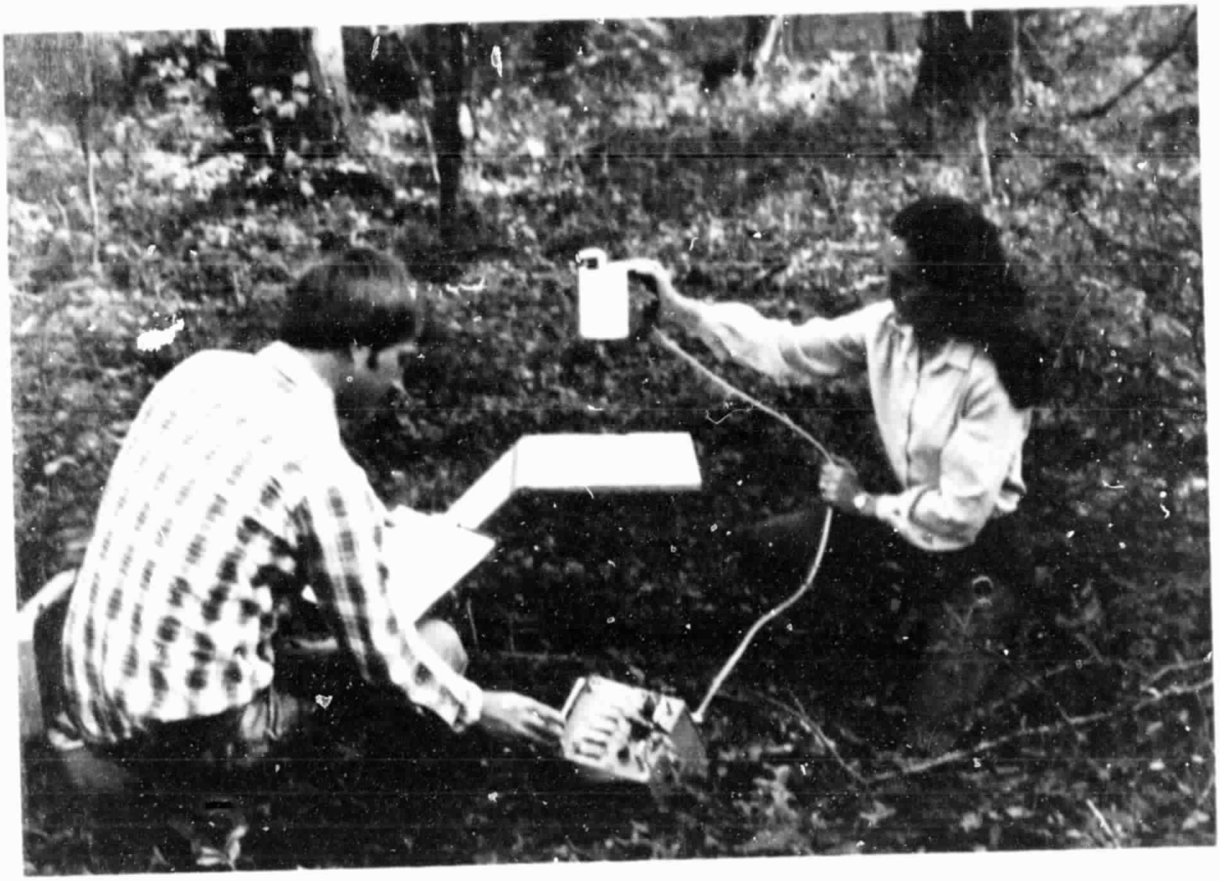

Figure 1. Diffuse radiance was measured at the forest floor using the Mark II 3-Band Radiometer held over a barium sulfate plate.

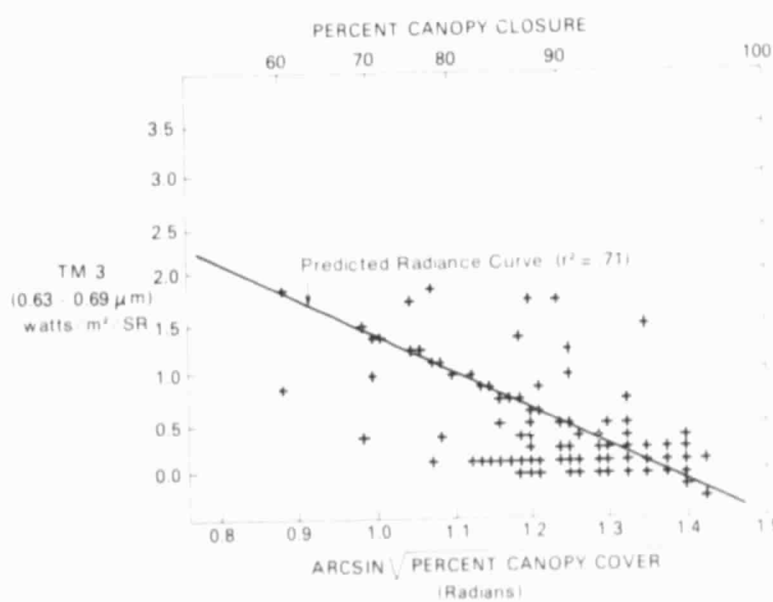

Figure 2. Predicted radiance curve for canopy closures greater than 60 percent (0.63 – 0.69 μm).

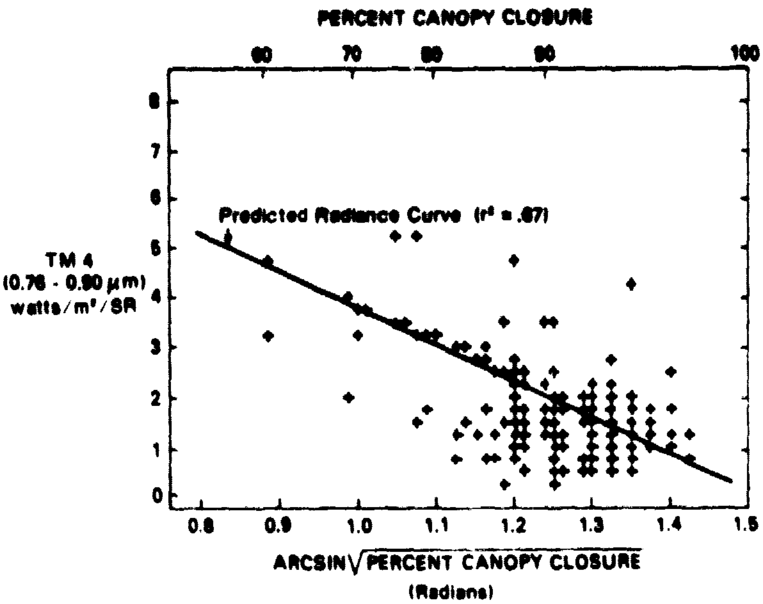

Figure 3. Predicted radiance curve for canopy closures greater than 60 percent (0.76 – 0.90 μm).

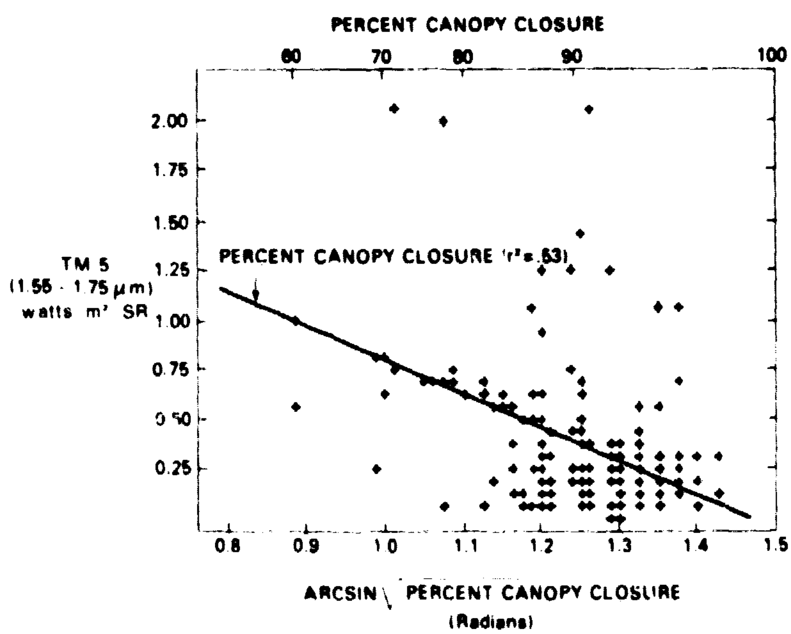

Figure 4. Predicted radiance curve for canopy closures greater than 60 percent (1.55 – 1.75 μm).