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Limitations on the Application of a Ground-Based Spectral Technique for Determining Rain Forest Leaf Area Index

Red and photographic infrared spectral data were collected within a rain forest canopy under different irradiational conditions.

Introduction

Recent interest in global carbon cycling and, in particular, the contribution of tropical rain forests to the global phytomass, has resulted in numerous techniques for quantification of tropical rain forest condition, vigor, and extent. Mapping the areal extent of tropical rain forests is straightforward through conventional aircraft mapping procedures and other remote sensing methods. Determination of tropical rain forest condition and vigor, both of which are important to net primary productivity and carbon cycling, requires a different approach. One such approach involves the determination of green leaf area index (LAI). LAI is defined as the amount of leaf surface area per unit of ground area.

LAI measurements are an accepted method for quantifying the density of photosynthetically active vegetation present in plant canopies. Leaf area indices have been used to infer forest site fertility and vigor (Frier and Running, 1977). However, direct measurements of LAI are tedious and difficult to make, especially for dense vegetation canopies and even more so for tall dense canopies.

Several workers have reviewed various aspects of forest studies using Landsat data (Miller and Williams, 1978; Lackowski *et al.*, 1979; Nicols *et al.*, 1976; among others). However, none of these investigators addressed themselves directly to Landsat data/LAI relationship(s) for tropical forests. Satellite imagery by itself is of little value unless detailed ground control data is available to aid in the interpretation of the resulting imagery. The motivation behind this study, therefore, was to evaluate a ground-based spectral LAI estimation technique for the purpose of establishing a rapid and nondestructive method of tropical rain forest

Abstract: *A previously proposed spectral method for nondestructive leaf area index determination was evaluated under a wide variety of irradiational conditions in the Luquillo Rain Forest of Puerto Rico using a two channel hand-held radiometer filtered for red and photographic infrared wavelengths. Previously reported "normalization factors" for diurnal adjustment were found to degrade the data. Quantitative use of the method was found to be restricted to high sun elevations. Diurnal measurements taken under uniformly overcast conditions were of approximately the same variability as measurements made under clear skies. Care must be taken in any operational application of this technique to minimize irradiational variability and to sample adequately the spatial variability.*

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LAI determination. This would be beneficial not only for assisting with satellite image interpretation by establishing several ground control LAI points, but also would be useful *per se* in tropical rain forest ecological studies.

Previous Spectral-LAI Research

Numerous authors have shown strong relationships of various ratio combinations of red and photographic infrared spectral data to the condition of the photosynthetically active portions of various plant canopies (Colwell *et al.*, 1977; Tucker, 1979; Tucker *et al.*, 1980; Williams *et al.*, 1979; among others). Few investigators, however, have reported on spectral-LAI relationships. Holben *et al.* (1980) reported a strong green LAI correlation to ratios of red and photographic infrared spectral data for soybeans. Kimes *et al.* (1980) have reported a strong green LAI-spectral data relationship for corn. Odum *et al.* (1963) estimated LAI throughout a large area of a tropical rain forest by clipping the leaves from ten locations, then measuring LAI directly, correlating the ten clipped sites to optical density measured with silicon solar cells, and subsequently applying the LAI—optical density relationship to other sites throughout the rain forest. Jordan (1969) used the technique of ratioing photographic infrared light to red light as an index to forest canopy LAI. His technique was unique because he measured the transmitted light on the forest floor while other remote sensing investigators have measured the reflected light above the plant canopy (reviewed in Tucker, 1979). The same biophysical properties of plant leaves determine the spectral transmittance and spectral reflectance; therefore, a high correlation exists between spectral transmittance and spectral reflectance (Tucker and Garratt, 1977).

The photographic IR/RED radiance ratio exploits the spectral contrast of green leaves. Light in the photographic infrared region (~0.74-1.20 μm) is nearly equally transparent and reflective to plant leaves with little absorption. Red light (0.60-0.70 μm) is strongly absorbed by the chlorophyll pigments of leaves. Thus, a ratio of the photographic infrared radiance to red radiance is sensitive to the green leaf area index or green leaf biomass. The various ratio combinations used for these purposes contain spectral information about the chlorophyll concentration—leaf area index interaction (referred to herein as the green leaf area index interation) while simultaneously compensating for variations in solar intensity.

The objective of this study was to evaluate Jordan's (1969) technique under a variety of irradiational conditions in which the LAI was strictly controlled. The following points were examined: (1) the diurnal variation in the spectral ratio; (2) the effectiveness of proposed diurnal normalization factors; and (3) the effect of cloud cover on the spectral ratio.

Methods and Location

The experiment was conducted in cooperation with the Division of Terrestrial Ecology of the Center for Energy and Environment Research in San Juan, Puerto Rico. The study site was a 22m walkup tower located in the Luquillo National Forest 0.5 km southeast of the El Verde Field Station. The tower is situated on a 22° slope with an aspect of 11° measured clockwise from north. The top of the canopy is approximately 19.8m above the ground and generally forms a visually impenetrable layer between the ground and sky. The crown layer is fairly uniform and parallels the slope. The understory is very sparse, typically being comprised of shrubs and ferns. The walkup tower was completely enclosed by the forest canopy.

The tower is a walkup type with work platforms at ~2m intervals. The top of the tower emerges from the canopy. This facility provided an opportunity to study spectral quality distributions above, below, and within the canopy.

The instrument used for the study was a two-band, hand-held radiometer similar to that described by Pearson *et al.* (1976). The two bands were filtered for 0.65-0.70 μm (red) and 0.775-0.825 μm (photographic infrared) and exactly straddle the midpoints used by Jordan (1969) ten years earlier. The radiometer's portability and near instantaneous readout were a great advantage over previous units for fast and accurate data acquisition. Jordan's (1969) instrument (an ISCO spectroradiometer weighing 35 kg and carried in a back-pack) necessitated that a spectral band be "dialed in" before a reading could be made. Approximately 15 seconds were required to change bands, which is sufficient time for the irradiational conditions to change significantly due to the dynamic cloud environment of the Luquillo rain forest. Our two-band radiometer required less than one second to monitor both bands, thereby minimizing this source of error. In addition, the two-band radiometer weighed only 2 kg, enabling much greater mobility.

Preliminary attempts at data collection were similar to those used by Jordan (1969) where the sensor was pointed vertically at the canopy and the radiance and/or irradiance was observed and recorded. However, the variation in measured energy was substantial. Jordan (1969) minimized this by taking a large number of observations over a wide range of forest conditions and then calculating a simple average.

We reduced the wide variation in measured diffuse canopy light by measuring the radiance from a horizontal $BaSO_4$ reference panel with the sensor unit (instantaneous field-of-view or IFOV ≅ 20°) looking normal to the panel. This had the effect of integrating the incident light sources from all sectors of the forest canopy above the panel.

Three data pairs (photographic infrared and red radiance) were recorded at each position, usually in less than five seconds.

The forest study site was the immediate forest canopy surrounding the walkup tower. Data were collected initially at ground level and at each platform level, but the levels were later modified to ground level, 5.5, 12.8, 14.6, 16.5, and 21.9 metres under both clear sky and cloudy sky conditions. Data were taken hourly throughout the day and on the half hour at the ground locations. Sky conditions were observed and recorded from the top of the tower, which was above the rain forest canopy.

The radiance data pairs were ratioed (photographic infrared to red) to adjust for irradiational variability (Kriegler *et al.*, 1969). This transformation used by Jordan (1969) is simple and has been reported to be sensitive to low to high soybean LAI's (Holben *et al.*, 1980) and to green biomass from a variety of cover types (reviewed in Tucker, 1979).

Normalization Factors

Jordan (1969) proposed a normalization factor based on the orientation of the sun with respect to the horizontal vegetation canopy plane. This would alter the slant path length of the solar beam through the canopy as a function of the cosine of the solar zenith angle. This normalization factor assumed the forest canopy to be uniformly and horizontally distributed in space. In effect, this means the solar beam must penetrate more vegetation as the solar zenith angle increases.

Jordan (1969) used the following relationship to adjust his spectral data (SD):

$$SD_N = SD_o \cdot \cos Z \qquad (1)$$

where o = observed,
N = normalized, and
Z = Zenith Angle.

Jordan stated that the path length concept breaks down at large zenith angles.

Another normalization factor used for evaluation in this study was based on the same vegetational slant path length concept, but it is a function of the orientation of the canopy plane induced by the orientation of the land surface (slope and aspect). This relationship is written

$$SD_N = SD_o \cdot \cos i \qquad (2)$$

where i = incidence angle to the canopy plane.

Results and Discussion

Under clear sky conditions, the IR/RED radiance ratio decreased with an increase in height in the forest canopy, with variation induced in part by time of observations (Figure 1). A very rapid change in the spectral ratio occured between 12.8 and 16.5 meters and little change occurred from ground level to 12.8 meters. This response corresponded well with the earlier description of the canopy biomass distribution; that is, there was little change in the total green leaf biomass below 12.8 m, resulting in small attenuation of the spectral response in the red and photographic infrared bands.

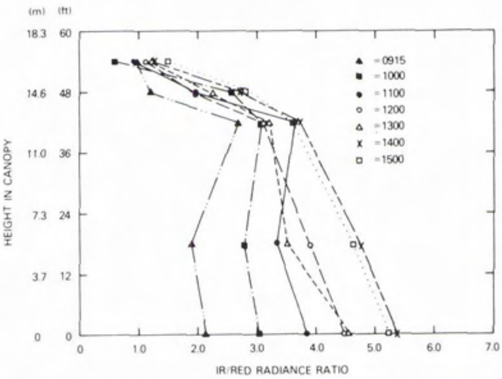

Fig. 1. The IR/RED radiance ratio was plotted against height in canopy for seven times a day on 11 February 1978. Note the temporal ordering of the ratio values according to time of observation of each level.

The curves in Figure 1 also demonstrated a temporal ordering in which the ratio values for each curve generally increased with time of day. Jordan (1969) attributed the temporal ordering to the effects of changing path length of the solar beam through the forest canopy. The radiance ratio increased with an increase in chlorophyll density and with forest green LAI. Therefore, Jordan (1969) hypothesized that, as the path length becomes longer, the quantity of chlorophyll and green leaves subtended by the solar beam increases, causing an increase in the IR/RED radiance ratio. Jordan (1969) normalized this effect by multiplying the ratio by the cosine of the solar zenith angle.

Least distinct temporal ordering of the spectral curves occurred near the canopy crown (16.5 m) (Figure 1). This may have been caused by an irregular green leaf biomass distribution, which was most apparent at the boundary layer of the canopy crown and the unobstructed sky immediately above.

Data Normalization Analysis

Two types of normalization factors were used in this analysis: the cosine of the solar zenith angle used by Jordan (1969) and the cosine of the solar incidence angle. These normalization factors were multiplied by the ratio values of each appropriate temporal curve for a data set under clear sky conditions. Theoretically, normalized temporal curves would be expected to lie on top of one another. Should this not occur, the separation between the family of curves would be increased

TABLE 1. EQUATIONS EXPRESSING HOW THE VARIANCE COMPONENTS α_X^2 CONTRIBUTED TO THE MEAN SQUARES (MS) CALCULATED IN A TWO-WAY MODEL II ANOVA WITH INTERACTION.

Source	E (MS)	Mean Square (MS)
T (time)	$\sigma^2 + \sigma^2_{T \times L} + l\sigma^2_T$	MS_T
L (Height in Canopy)	$\sigma^2 + \sigma^2_{T \times L} + t\sigma^2_L$	MS_L
T × L (Interaction)	$\sigma^2 + \sigma^2_{T \times L}$	MS_{TL}
Within Cell (error)	σ^2	MS_e

due to the correction factors. This would mean that the variability among the curves would not have been reduced (i.e., normalized).

Our analysis was divided into two types of radiation environments. A data set was collected on 11 February 1978 under cloudless skies with no visibly apparent haze, and another data set acquired on 10 February 1978 when sky conditions were uniformly overcast under a stratocumulus deck. Thus, a direct radiation environment and a diffuse radiation environment were analyzed.

DIRECT RADIATION ENVIRONMENT ANALYSIS

The family of diurnal curves presented in Figure 1 had a distinct temporal ordering, suggesting that the diurnal normalization techniques described earlier could be implemented. To test this concept, we examined the percentage variation due to time of observation for the raw and each normalized data set. A decrease in the percentage variation of the normalized data set relative to the raw data set would indicate that the normalization technique is useful for these data. The following analysis of variance (ANOVA) model was applied to the raw data set and each of the normalized data sets:

$$Y_{ijk} = \mu + T_i + L_j + TL_{ij} + e_{ijk} \qquad (3)$$

Y_{ijk} is the value for the k^{th} replicate at the i^{th} time of observation and the j^{th} height in the canopy; μ is the overall mean; T_i is the effect of the i^{th} time of observation; L_j is the effect of the j^{th} height in the canopy; TL_{ij} is the interaction effect of the i^{th} time of observation and the j^{th} height in the canopy; and e_{ijk} is the error term for the k^{th} observation in cell i,j. Since we are interested in the added variance component of each factor, time or height in the canopy, or their interaction, this is a model II ANOVA. The model for the mean square of each of the factors is given in Table 1. The ANOVA tables for the raw and each of the normalized data sets are presented in Table 2.

TABLE 2. ANOVA TABLES FOR THE RAW AND NORMALIZED DATA SETS. df = DEGREES OF FREEDOM, SS = SUMS OF SQUARES, MS = MEAN SQUARE, F = F RATIO STATISTIC. ns = F NOT SIGNIFICANT, * = F SIGNIFICANT AT α = 0.05, ** F SIGNIFICANT AT α = 0.01, *** = F SIGNIFICANT AT α = 0.001, **** = F SIGNIFICANT AT α = 0.0001 OR BETTER.

	Raw Data = IR/RED Radiance Ratio			
	df	*SS*	*MS*	*F*
Treatment	55	396.4668	7.2085	
T (Time)	6	71.4016	11.9003	6.65****
L (Level)	7	249.9255	35.7036	19.96****
L × T (Interaction)	42	75.1397	1.7890	125.99****
Error	112	1.5867	0.0142	
TOTAL	167	398.0535		
	Normalized Data (Z) = (IR/RED) * Cos (Z)			
	df	*SS*	*MS*	*F*
Treatment	55	256.5363	4.6643	
T (Time)	6	66.3088	11.0515	10.24****
L (Height in the Canopy)	7	114.8876	20.6982	19.17****
L × T (Interaction)	42	45.3400	1.0795	215.90****
Error	112	0.5635	0.0050	
TOTAL	167	257.0998		
	Normalized Data (i) = (IR/RED) * Cos (i)			
	df	*SS*	*MS*	*F*
Treatment	55	111.0312	2.0187	
T (Time)	6	25.7758	4.2960	8.86****
L (Height in the Canopy)	7	64.9028	9.2718	19.13****
L × T (Interaction)	42	20.3527	0.4846	210.70****
Error	112	0.2587	0.0023	
TOTAL	167	111.2899		

TABLE 3. VARIANCE COMPONENTS AND PERCENT OF THE TOTAL OF THE VARIANCE COMPONENT WERE CALCULATED FOR EACH TREATMENT OF THREE PROPOSED TIME NORMALIZING PROCEDURES INCLUDING NO NORMALIZATION FOR RATIOED SPECTRAL DATA TAKEN AT SEVEN TIMES OF DAY ON 10, FEBRUARY 1978. OF THE THREE NORMALIZING PROCEDURES, NO NORMALIZATION HAD THE SMALLEST PERCENT OF TOTAL M.S. FOR TIME INDICATING THAT THE PROPOSED TIME NORMALIZING PROCEDURES DID NOT REDUCE THE DEPENDENCE ON TIME.

	No Normalization	
Treatment	*Variance Component*	*Percent of Total*
Time × Height in Canopy	0.5916	19.91
Height in Canopy	1.8841	63.41
Time	0.4815	16.20
Error	0.0142	0.48
	Cosine Zenith angle Normalization	
Treatment	*Variance Component*	*Percent of Total*
Time × Height in Canopy	0.3582	18.58
Height in Canopy	1.0899	56.53
Time	0.4748	24.63
Error	0.0050	0.26
	Cosine Incidence Angle Normalization	
Treatment	*Variance Component*	*Percent of Total*
Time × Height in Canopy	0.1608	19.31
Height in Canopy	0.4882	58.62
Time	0.1815	21.79
Error	0.0023	0.28

It is clear that the raw and both normalized data sets had significant effects for time of observation, height in canopy, and time by height interaction. Using the equations in Table 1, one can solve for the variance terms σ^2, $\sigma^2_{T\times L}$, σ^2_L, and σ^2_T. From those terms, the percent of each variance term of the sum of the terms was calculated. Examination of these statistics (Table 3) showed that the normalization techniques did not decrease the percentage of the variance contributed by time; rather, they increased it. The percentage variance contributed by height in the canopy and the height-time interaction changed little between the raw and the normalized data sets. It is apparent that neither normalization technique produced the desired results; therefore, the raw data are better in this regard than the normalized data.

Several factors are suggested which may have reduced the usefulness of the normalization factors. First, any measurement procedure has inherent systematic and random errors in the system. We have minimized these errors by our data collection technique. Second, although the tower was erected in a forest canopy which was assumed to be uniformly distributed in the plane parallel to the slope, the horizontal distribution of the green leaf canopy was not entirely uniform, particularly near the crown. Third, the normalization factors required that the only light impinging the forest canopy was the direct solar beam which was invariant in quality, neither of which are necessarily true. Dave *et al.* (1975), modeling the cloudless sky diffuse component of solar irradiance at the bottom of the atmosphere, reported the contribution from the diffuse component ranged from 13 to 54 percent of the 0.535 μm global irradiance, depending on atmospheric composition and solar zenith angle. Gates (1966) and others have reported that the quality of the diffuse irradiance is richer in shorter wavelengths for clear non-hazy skies than for direct irradiance. The spectral radiances measured in this study possibly changed due to slight variations in the quality of the solar irradiance. These are variations for which the normalization factors could not account.

DIFFUSE CLOUD RADIATION ENVIRONMENT ANALYSIS

Mie scattering is caused by clouds, among other sources, and is largely wavelength independent. It

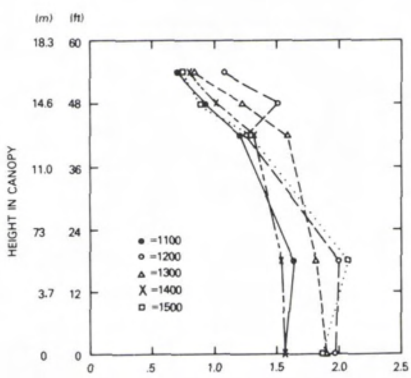

FIG. 2. Radiance data collected under uniformly overcast conditions was transformed to the IR/RED radiance ratio and plotted against height in canopy for five times of day on 10 February 1978. Observe the greater compaction of the family of curves relative to Figure 1.

TABLE 4. ANOVA TABLES FOR THE SUNNY AND CLOUDY DAYS DATA SETS. df = DEGREES OF FREEDOM, SS = SUM OF SQUARES, MS = MEAN SQUARE, F = F RATIO STATISTIC, ns = F NOT SIGNIFICANT, * = F SIGNIFICANT AT $\alpha = 0.05$, ** = F SIGNIFICANT AT $\alpha = 0.01$, *** = F SIGNIFICANT AT $\alpha = 0.001$, **** = F SIGNIFICANT AT $\alpha = 0.0001$ OR BETTER.

	Clear day IR/RED Radiance Ratio			
Source	*df*	*SS*	*MS*	*F*
Treatment	29	225.6330	7.7804	
T (Time)	4	15.4128	3.8532	9.92***
L (Height in the Canopy)	5	202.4524	40.4905	104.25****
T × L (Interaction)	20	7.7678	0.3884	36.99****
Error	60	0.6324	0.0105	
TOTAL	89	226.2655		
	Cloudy IR/RED Radiance Ratio			
Source	*df*	*SS*	*MS*	*F*
Treatment	29	15.7887	0.5444	
T (Time)	4	1.3500	0.3375	5.20**
L (Height in Canopy)	5	13.1404	2.6281	40.49****
T × L (Interaction)	20	1.2982	0.0649	4.16****
Error	60	0.9363	0.0156	
TOTAL	89	16.7250		

is, thus, hypothesized that the diffuse radiation from a uniform cloud layer (being of uniform quality throughout a day) having no directional component would provide a superior irradiational regime for spectral assessment of a forest leaf canopy over that of clear sky irradiance regimes. The data show that the diurnal family of spectral curves for overcast conditions were smoother and much closer together than the family of curves for the clear sky conditions, either normalized or not (Figure 2).

A balanced ANOVA using the model expressed in Equation 3 and Table 1 was used to assess the distribution of the percentage variance contributed by time of observation, height in the canopy, and time × height interaction for both a clear and cloudy day (Table 4).

Once again all of the effects, i.e., time, height in the canopy, and the time × height interaction, were significant regardless of direct sun or clouds. The percentage of the total of each variance component for both cloud and direct sun are presented in Table 5. With the exception of error, there was no significant effect on the distribution of the variance components. The percent of the variance components in the error term increases for overcast days.

Although these results did not recommend collecting spectral data under overcast conditions, the variations compared to the clear sky data set were slight. This suggested that similar LAI-spectral relationships are valid for cloudy sky as well as clear sky conditions. Because tropical rain forests were often enshrouded by clouds, spectral data collected under cloudy conditions may be the only practical alternative for quickly estimating the green LAI.

CONCLUSIONS

The applicability of a ground-based tropical rain forest leaf area index estimation technique using red and photographic infrared spectral data was

TABLE 5. VARIANCE COMPONENTS AND PERCENT OF THE TOTAL OF THE VARIANCE COMPONENTS WERE CALCULATED FOR EACH TREATMENT FROM RATIOED SPECTRAL DATA COLLECTED AT FIVE TIMES OF DAY DURING ONE DAY OF CLEAR SKY CONDITIONS AND ONE DAY OF CLOUDY SKY CONDITIONS. NOTE THE SMALL DIFFERENCES IN PERCENT OF TOTAL VARIANCE COMPONENTS OF TIME BETWEEN CLEAR AND CLOUDY SKY CONDITIONS.

	Clear Sky Conditions, 1100–1500, 11 Feb 78	
Treatment	*Variance Component*	*Percent of Total*
Time × Height in Canopy	0.1260	3.40
Height in Canopy	3.3418	90.09
Time	0.2310	6.23
Error	0.0105	0.28
	Cloudy Sky Conditions, 1100–1500, 10 Feb 78	
Treatment	*Variance Component*	*Percent of Total*
Time × Height in Canopy	0.0164	6.22
Height in Canopy	0.2136	80.98
Time	0.0182	6.90
Error	0.0156	5.91

found to be nearly equally sensitive under direct sunlight and uniformly cloudy conditions. Different numerical values were obtained, however, under these two very different irradiational regimes. Accordingly, any applications of this technique must be confined to periods of similar irradiational conditions.

Path length "normalization" factors did not reduce the diurnal variability. It was, thus, evident that sun-target-sensor geometry was rather complicated and that simple solar position models were not adequate for normalization purposes. Variability of the spectral irradiance combined with normal rain forest canopy variability necessitates the collection of several samples from each specific area in question.

We feel the technique evaluated herein is sufficiently promising to be evaluated further. This technique, if properly applied, offers the possibility of rapid and nondestructive estimation of forest canopy leaf area indices. The limitation(s) of current forest canopy leaf area index determination techniques needs no emphasis.

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