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THE USE OF HIGH SPECTRAL RESOLUTION BANDS FOR ESTIMATING ABSORBED PHOTOSYNTHETICALLY ACTIVE RADIATION (A_{par})

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ABSTRACT

Most remote sensing estimations of vegetation variables such as leaf area index (LAI), absorbed photosynthetically active radiation (A_{par}), and phytomass are made using broad band sensors with a bandwidth of approximately 100 nm. However, high resolution spectrometers are available and have not been fully exploited for the purpose of improving estimates of vegetation variables. The study was directed to investigate the use of high spectral resolution spectroscopy for remote sensing estimates of A_{par} in vegetation canopies in the presence of nonphotosynthetic background materials such as soil and leaf litter. A high spectral resolution method defined as the chlorophyll absorption ratio index (CARI) was developed for minimizing the effects of nonphotosynthetic materials in the remote estimates of A_{par}. CARI utilizes three bands at 550, 670, and 700 nm with bandwidth of 10 nm. Simulated canopy reflectance of a range of leaf area index (LAI) were generated with the SAIL model using measurements of 42 different soil types as canopy background. CARI obtained from the simulated canopy reflectance was compared with these broad band vegetation indices (normalized difference vegetation index (NDVI), soil adjusted vegetation index (SAVI), and simple ratio (SR)). CARI reduced the effect of nonphotosynthetic background materials in the assessment of vegetation canopy A_{par} more effectively than broad band vegetation indices.

KEY WORDS: A_{par}, CARI, SAIL MODEL, NDVI, SAVI, SR, VEGETATION INDICES

1. INTRODUCTION

Current remote sensing estimates of vegetation variables such as green biomass, leaf area index (LAI), and A_{par} are made with broad band sensors with bandwidths of approximately 100 nm. These broad band vegetation indices have been shown to suffer from a sensitivity and the reflectance of nonphotosynthetic background materials (Choudhury, 1987, Huete, 1989, Goward et al., 1992).

Although recent advances in technology have allowed the use of high resolution spectroscopy for remote sensing, this technology has not been fully exploited for characterization of the atmosphere-plant-soil complex. Only a few researchers, to this time, have worked with narrow spectral band reflectance as a means of eliminating the effects of nonphotosynthetic background materials in vegetation canopy reflectance. The ratio analysis of reflectance spectra (RARS) by Chappelle et al. (1992) showed that ratios of reflectance in narrow bands correlated well with leaf pigment concentration, and they suggested that photosynthetic pigments may be remotely estimated with high accuracy from narrow band reflectance. The use of second derivative spectra has shown promise for reducing the effects of nonphotosynthetic background materials in vegetation canopies (Hall et al., 1990; Demetriades-Shah et al., 1990).

Canopy reflectance is an integrated function of leaf optical properties, plant structure, background reflectance, and solar illumination and view angles. Canopy reflectance models have provided tools to; 1) assess the effect of different canopy characteristic on reflectance; 2) evaluate plant canopy reflectance under varying

observation conditions; and 3) explore relationships between biophysical properties (i.e., LAI, A_{par}) and canopy reflectance (Suits, 1972; Kimes et al., 1984; Verhoef, 1984).

Photosynthetically active radiation (PAR) absorbed by plant pigments is the energy source for photosynthesis. The pigments making the greatest contribution to light absorption and photosynthesis are chlorophyll *a*, chlorophyll *b*, and carotenoids (Fig 1). Both chlorophylls *a* and *b* have absorption maxima in the 640 nm-690 nm region and in the 440 nm-470 nm region. Also β-carotene has an absorption maximum at 470 nm region and minimum absorption beyond 530 nm. Both chlorophylls and β-carotene have minimal absorbance at 550 nm region and beyond 700 nm. One of the canopy reflectance characteristics that directly governs the amount of light absorption and reflectance is the quantity of these photosynthetic pigments in the plant leaves. Also, the amount of exposed nonphotosynthetic materials including soil, leaf litter, and woody biomass such as twigs, stems, and trunks have been shown to be important factors in canopy reflectance.

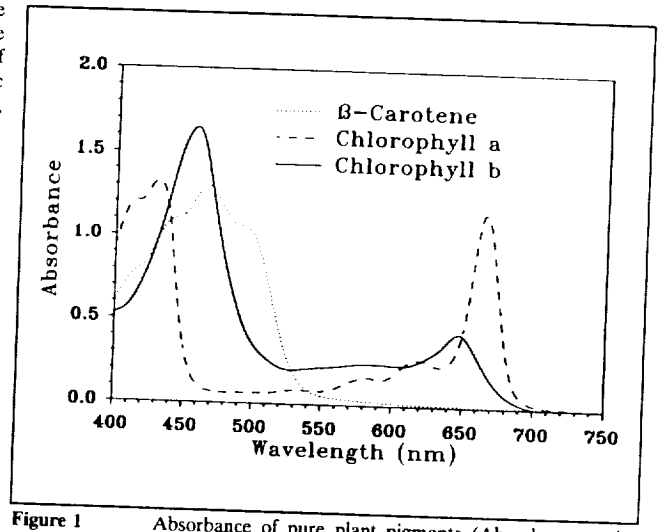

Figure 1 Absorbance of pure plant pigments (Absorbance = log (I_0/I), I_0 = incident, I = transmitted light)

The main objective of this research is to investigate the use of narrow reflectance bands in remote estimates of canopy A_{par}. The research concentrated toward reducing the variability in the A_{par} estimates due to the presents of diverse nonphotosynthetic materials. This technique utilized narrow spectral bands with bandwidth of approximately 10 nm. For evaluating the proposed narrow band method, the SAIL (scattering from arbitrarily inclined leaves; Verhoef, 1984) canopy model was used; 1) for simulating vegetation canopy reflectance as a mixture of green biomass and background material components; and 2) to derive A_{par}. This model has been used successfully in similar applications (Goward et al., 1992, Hall et al., 1990).

2. DEVELOPMENT OF NARROW BAND METHOD

2.1 Leaf level Reflectance

TABLE 1. Correlations (r^2) between soybean leaf reflectance (n = 50) bands. Reflectance measurements were acquired using LI-COR 1800 spectroradiometer and integrating sphere.

Wave (nm)	550	670	690	700	710	750	800
550	1.000	0.786	0.930	0.992	0.981	0.000	0.062
670	0.786	1.000	0.914	0.802	0.710	0.005	0.083
690	0.930	0.914	1.000	0.955	0.871	0.001	0.075
700	0.992	0.802	0.955	1.000	0.973	0.000	0.059
710	0.981	0.710	0.871	0.973	1.000	0.008	0.034
750	0.000	0.005	0.001	0.000	0.008	1.000	0.903
800	0.062	0.083	0.075	0.059	0.034	0.903	1.000

Greenhouse grown soybean leaves were used for the leaf level reflectance measurements. The plants were grown in perlite with varying nitrogen nutrient solutions applied (0 % to 100 % of optimal growth rate). These varying nitrogen concentrations produced a range of nitrogen deficiency stress that resulted in a wide range of leaf pigment concentrations and a range of reflectance spectra (Fig. 3 (I)). Reflectance measurements of 50 leaves were acquired with a LI-COR 1800 spectroradiometer and integrating sphere (LI-COR, Inc. Lincoln, Nebraska).

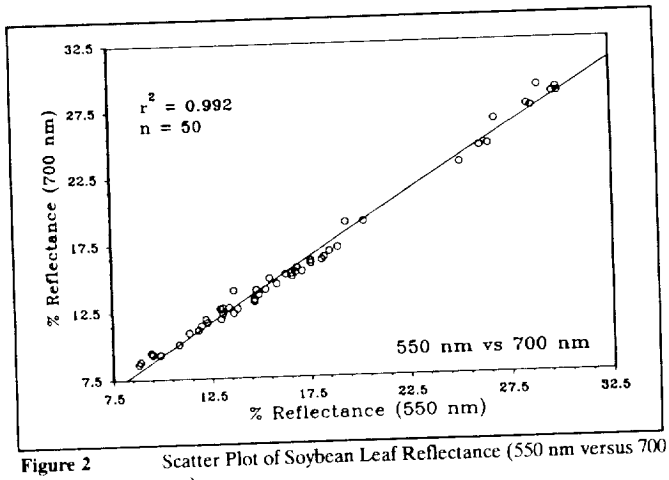

Figure 2 Scatter Plot of Soybean Leaf Reflectance (550 nm versus 700 nm)

2.1.1 *Significance of 550 and 700 nm bands*

The reflectance bands of the soybean leaf reflectance spectra were correlated with each other (Table 1). Most of the bands in the PAR region correlate highly with each other. It appears that the 550 nm and 700 nm bands have the highest correlation (r^2 = 0.992). This relationship is visible in the absorption of the pure pigments (Fig. 1) in which the 550 nm and 700 nm bands correspond to the minimum absorption of the photosynthetic pigments. The significance of this relationship is such that in leaf level reflectance, a ratio of the 550 nm and 700 nm bands is constant regardless of the differences in chlorophyll concentrations. When the 550 nm bands are plotted against the 700 nm reflectance bands of the soybean leaves with varying leaf pigment concentrations, this relationship is well illustrated (Fig. 2). It is observed that beyond 700 nm where absorption due to the pigments is minimal, the correlation with the 550 nm band drops. This is possibly due to the dominance of the effect of leaf structure on vegetative reflectance beyond 700 nm.

The 700 nm band is located at the boundary of the region where reflectance is dominated by pigments and at the beginning portion of the Near Infra-Red (NIR) rising slope (red edge) which is due to the structural characteristics. Thus, the transition from the dominant effect of the pigment absorption to NIR vegetative characteristics (i.e., scattering) occurs in this region.

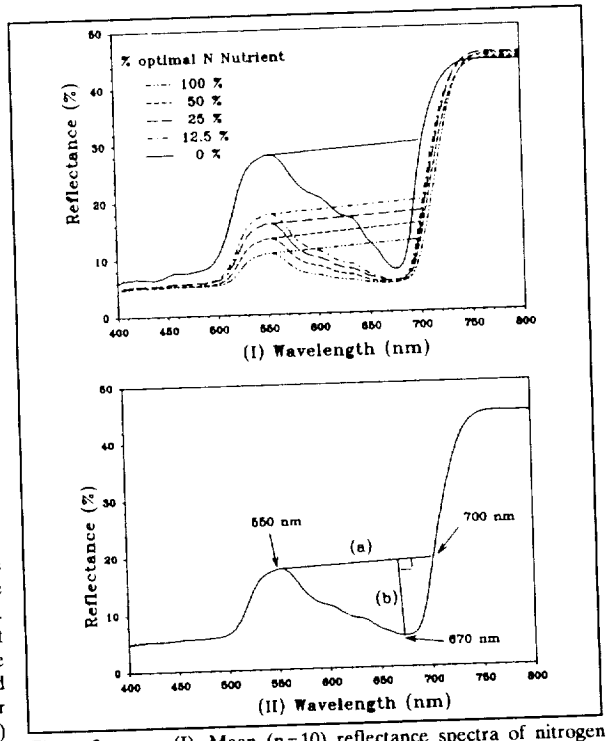

Figure 3 (I). Mean (n=10) reflectance spectra of nitrogen treated soybean leaves. (II). (a) is a chlorophyll absorption minima line, (b) is defined as CAR

2.1.2 *Definition of the Chlorophyll Absorption in Reflectance (CAR)*

Utilizing the properties of the 550 nm and 700 nm bands in conjunction with the 670 nm chlorophyll *a* absorption maximum band led to the definition of the chlorophyll absorption in reflectance (CAR). The line (a) in Fig. 3 (II) which was drawn from the 700 nm to 550 nm band forms the base line to measure the depth of the chlorophyll absorption. The slopes of this 550 nm-700 nm lines for the 50 soybean leaf level reflectance spectra are a constant. The distance (b) in Fig. 3 (II) from the 670 nm band perpendicular to the 550-700 nm line (absorption minima) can be quantified and defined as CAR. Thus, CAR is the shortest distance from the 670 nm band to the 550 nm-700 nm line.

The calculation of the CAR utilizes an orthogonal projection on a 2-dimensional *x-y* plane using wavelength as x and the percent reflectance as y coordinates, respectively. By definition, the orthogonal projection *p* from a point to a vector spanned from the origin is given by

$$p = \frac{a^T b}{a^T a} \propto a, \qquad \text{where } a^T = (x_{700nm-550nm}\ y_{700nm-550nm}),\ a = \begin{pmatrix} x_{700nm-550nm} \\ y_{700nm-550nm} \end{pmatrix},\ b = \begin{pmatrix} x_{670nm-550nm} \\ y_{670nm-550nm} \end{pmatrix}.$$

Note that the wavelength and the reflectance coordinates are linearly transformed so that x_{550nm} and y_{550nm} become the origin of the *x-y* plane. Thus, the 550 nm-700 nm line is the vector spanned from the origin. The distance (CAR) of the projection from the point (670 nm) to the *p* is quantified as

$$CAR^2 = \left\| b - \frac{a^T b}{a^T a} \propto a \right\|^2 = \frac{(b^T b) \propto (a^T a) - (a^T b)^2}{(a^T a)} \quad \text{then,} \qquad CAR = \sqrt{\frac{(b^T b) \propto (a^T a) - (a^T b)^2}{(a^T a)}}.$$

CAR calculated on the reflectance spectra of 50 soybean leaves plotted against the chlorophyll *a* concentrations are shown in figure 4. There is a strong inverse-linear relationship with a regression r^2 of 0.964 demonstrating the values of CAR as an accurate measurement of leaf level chlorophyll absorption.

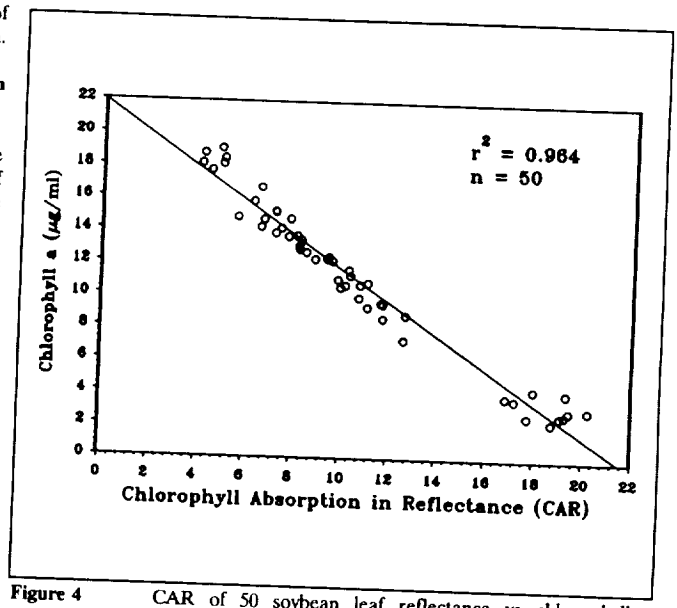

Figure 4 CAR of 50 soybean leaf reflectance vs chlorophyll *a* concentration of the same leaves

2.2 Characteristics of CAR in canopy reflectance

Soybean canopy reflectance spectra, leaf area index (LAI) of 1.0, were simulated using the SAIL model for dark, yellow, and soil high in iron contents as background materials. Since the LAI for the canopy is 1.0, the simulated spectra contain identical green biomass and the only differences among the spectra are the effects of reflectance characteristics of the soils. Figure 5 illustrates the resulting spectral variabilities in the canopy reflectance due to the different background reflectances, and that the slopes of 550 nm-700 nm lines of CAR vary as a result of the effects of the reflectance of nonphotosynthetic materials. The variations in canopy reflectance are recognized in the differences between the 700 nm to 550 nm band ratios which are 1.35, 1.44, and 1.70 for the dark, yellow, and iron soil, respectively.

2.3 Development of the chlorophyll absorption ratio index (CARI)

Although CAR appears to be a suitable method for estimating absorption from leaf level reflectance spectra, it was found to be an inadequate model for estimating A_{par} at the canopy level. Canopy level CAR is a function of absorption due to green biomass and reflectance characteristics of background materials. Thus, the behavior of CAR is such that changes in the 550-700 nm slope in the canopy reflectance results changes the value of CAR.

The canopy level CAR was modified to compensate for the effects of background reflectance. A multiplication of the reflectance band ratio of 700 nm and 670 nm with CAR, was defined as the chlorophyll absorption ratio index (CARI = $CAR_{Canopy} \cdot (R_{700}/R_{670})$).

We believe that the ratio of the 700 nm and 670 nm bands counteracts the effects of background reflectance. This ratio is the slope of background materials when the canopy contains no green biomass. At 670 nm, chlorophyll *a* in vegetation has an absorption maximum absorption which minimizes the background reflectance. The 700 nm band where chlorophyll *a* absorption becomes minimum is a band where the background reflectance becomes relatively significant. In the case of partial canopy closure, this ratio would depict the combined effects of the background reflectance as well as the fraction of nonphotosynthetic to photosynthetic materials.

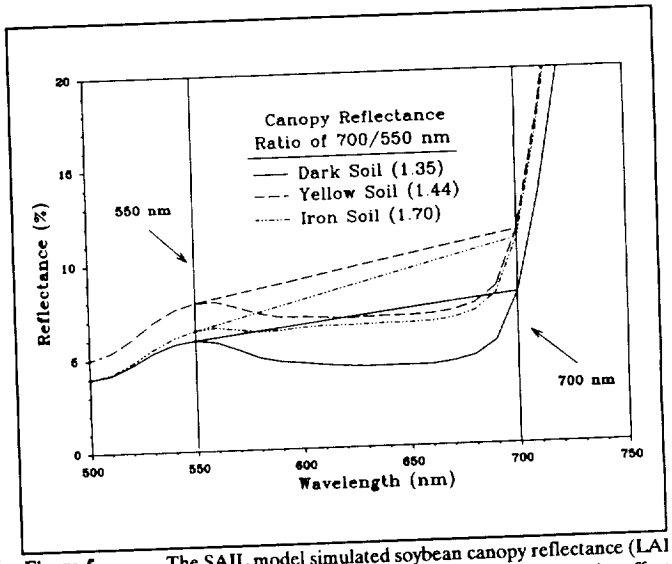

Figure 5 The SAIL model simulated soybean canopy reflectance (LAI = 1.0). The ratio of 700/550 nm differences are the effect of reflectance characteristics of the background materials.

3. ASSESSMENT OF CHLOROPHYLL ABSORPTION RATIO INDEX

Soybean canopy reflectance at 10 nm spectral resolution at 550, 670, 700 nm, and 600-690 nm and 750-850 nm bands were simulated using the SAIL model. Table 2 lists the optical properties of soybean leaf and parameters used for the simulation. Reflectance of soils obtained from National Soil Erosion Research Laboratory described

TABLE 2. Soybean leaf reflectance and transmittance plus other input parameters used for the SAIL model simulation of soybean canopy reflectance.

Waveband	% Refl.	% Trans.	TIME	11:00
550 ± 5 nm	12.88	18.03	SOLAR DECLINATION ANGLE	23.50°
670 ± 5 nm	5.83	3.18	SOLAR ZENITH ANGLE	20.79°
700 ± 5 nm	14.80	20.23	LATITUDE	40.00°
RED (600-690 nm)	6.87	6.98	VIEW ZENITH ANGLE	0.00°
NIR (750-850 nm)	45.85	52.47	VIEW AZIMUTH ANGLE	0.00°

by Daughtry et al., (1993) were used as background materials in the simulation of canopy reflectance. A total of 840 canopy reflectance, 20 levels of LAI ranging from 0.1 to 4.5 (0.1 to 1.0 in 0.1 interval, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 3, 3.5, 4, and 4.5), with 42 different soils as background were simulated. In conjunction with these reflectance spectra, the fraction of absorbed photosynthetically active radiation (Fa_{par} = [A_{par}/Incident PAR]) were simulated.

Figure 6 is a presentation of vegetation indices plotted against Fa_{par}. These vegetation indices were calculated using the results from the SAIL model simulation. The normalized difference vegetation index (NDVI) was calculated using (NIR - RED)/(NIR + RED). For the calculation of the soil adjusted vegetation index (SAVI; Huete, 1988), a soil isoline factor of 0.5 resulted in the smallest variation for canopies with LAI less than or equal to 2. Thus, SAVI was calculated as [(NIR - RED)/(NIR + RED + 0.5)] X (1.5). the ratio of (750-850 nm and 600-690 nm were used for the SR. Before full canopy closure, NDVI (Fig. 6(a)) and SR (Fig. 6(b)) are highly variable in the assessment of Fa_{par} due to the variations in the soil background reflectance. The effects of soil backgrounds were significantly reduced by SAVI (Fig. 6(c)) and CARI (Fig. 6(d)).

In order to compare variability of these vegetation indices at lower LAI, canopy reflectance were simulated at LAI ranging from 0.05 to 2.0 in 0.05 interval, and the vegetation indices were calculated. The parameters used for this simulation were the same as the previous simulation. The statistical procedure Student-Newman-Kuels mean test was conducted to these vegetation indices. Table 3 is a presentation of the test results, where means

TABLE 3. Student-Newman-Kuels test for variables, means with the same letter are not significantly different at a significance level of 1 % (α = 0.01).

LAI	SNK (CARI)	SNK (NDVI)	SNK (SAVI)	SNK (SR)
2.00	A	A	A	A
1.95	B A	A	B A	B A
1.90	B	B A	B A C	B C
1.85	C	B A	B D A C	D C
1.80	D	B A C	B D E C	D E
1.75	E	B A C	D E C	F E
1.70	F	B D A C	F D E	F G
1.65	G	B D A C	F E G	H G
1.60	H	E B D A C	F H G	H I
1.55	I	E B D A C F	I H G	J I
1.50	J	E B D C F	I H J	J K
1.45	K	E D G C F	I K J	L K
1.40	L	E H D G F	K J	L M
1.35	M	E H G F	L K	N M
1.30	N	H G I F	L M	N O
1.25	O	H J G I	N M	P O
1.20	P	H J K I	N O	P Q
1.15	Q	J K I	P O	R Q
1.10	R	L J K	P Q	R S
1.05	S	L K M	R Q	T S
1.00	T	L N M	R S	T U
0.95	U	N M	T S	V U
0.90	V	O N	T U	V W
0.85	W	O P	V U	X W
0.80	X	Q P	W	X Y
0.75	Y	Q R	X	Z Y
0.70	Z	S R	Y	Z A
0.65	A	S T	Z	B A
0.60	B	U T	A	B C
0.55	C	U V	B	D C
0.50	D	V	C	D E
0.45	E	W	D	F E
0.40	F	X	E	F G
0.35	G	Y	F	H G
0.30	H	Z	G	H I
0.25	I	A	H	J I
0.20	J	B	I	J I K
0.15	K	C	J	J L K
0.10	L	D	K	L K
0.05	M	E		L

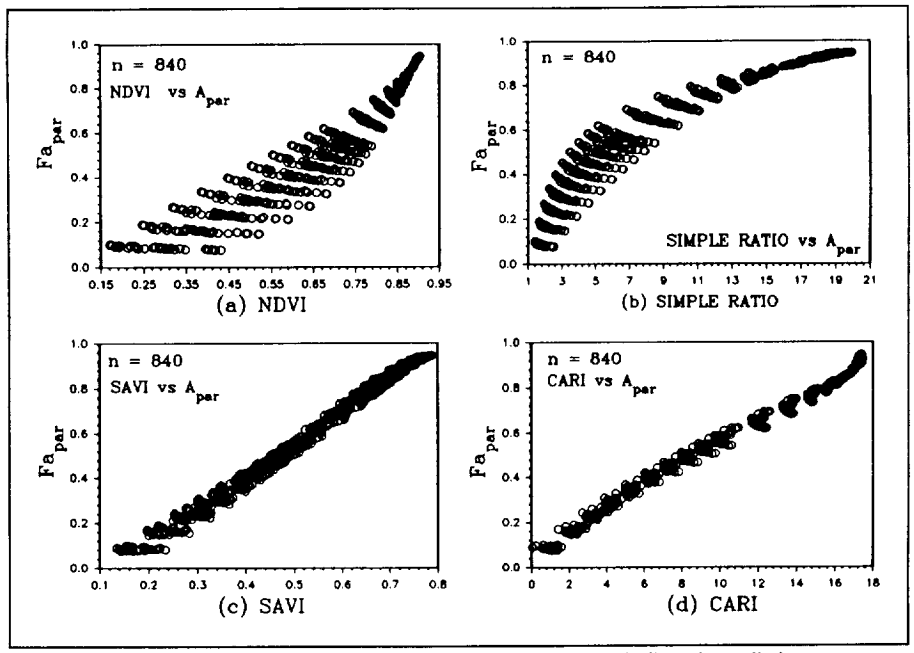

Figure 6 Vegetation indices vs fraction of absorbed photosynthetically active radiation

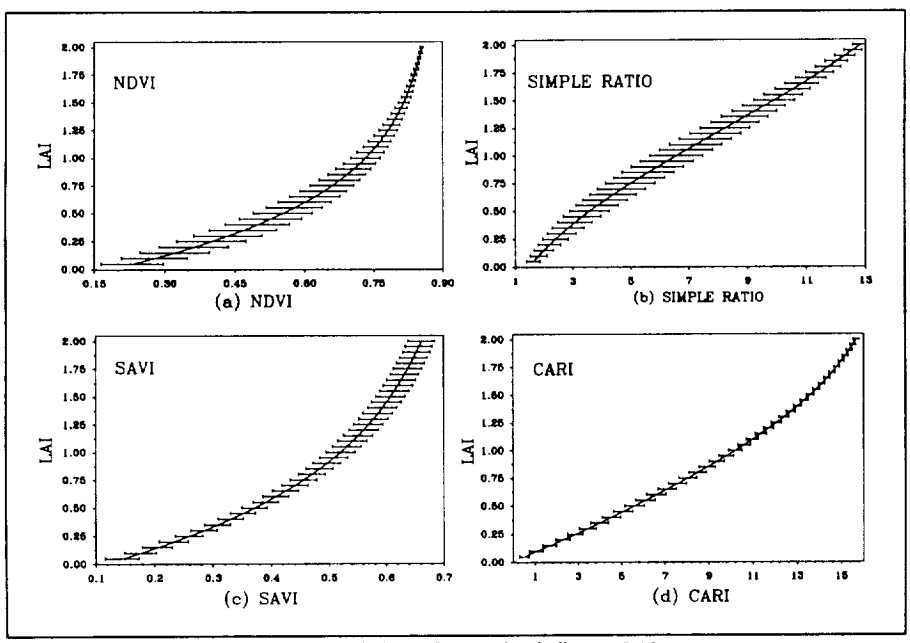

Figure 7 Means and standard deviations of vegetation indices vs LAI

with different letters indicate that the means can be separated at a significance level of 1 % (α = 0.01). The result indicates that the CARI performs better than other broad band indices in separating the means at LAI differences of 0.05. Figure 7 is an illustration of the means and standard deviations of these vegetation indices plotted against LAI. This figure summarizes that the CARI reduces effects of nonphotosynthetic materials in the assessment of vegetation canopy A_{par} more effectively than broad band vegetation indices.

4. CONCLUSIONS

These investigations demonstrate the potential utility of narrow reflectance bands for assessing biophysical properties of vegetation canopy. The variability of broad band techniques due to background reflectance characteristics are significantly reduced by CARI. It should be stressed that these conclusions are based solely upon the results obtained with simulated canopy reflectances and that the SAIL model does not consider all the natural phenomena in a vegetation canopy such as spectral variability due to woody biomass. Field experiments are planned to evaluate, and further enhance the utility of CARI.

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