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Spectral Assessment of Soybean Leaf Area and Leaf Biomass

The most significant correlations were found to exist between the spectral data and green leaf area index and/or green leaf biomass.

Astract: *Red and photographic infrared spectral radiance have been correlated with soybean total leaf area index, green leaf area index, chlorotic leaf area index, green leaf biomass, chlorotic leaf biomass, and total biomass. The most significant correlations were found to exist between the spectral data and green leaf area index and/or green leaf biomass. These findings demonstrate that ground based remote sensing data can supply information basic to soybean canopy growth, development, and status by non-destructive determination of the green leaf area or green leaf biomass.*

Introduction and Review

Previous research has reported that linear combinations of red and photographic infrared spectral data were significantly correlated with the green or photosynthetically active portions of plant canopies for a variety of cover types (e.g., Jordan, 1969; Colwell *et al.*, 1977; Deering, 1978; Tucker, 1979). In addition, other workers have applied Landsat red and near infrared data (MSS 5 and MSS 6 or MSS 7) to a variety of vegetation analyses (e.g., Kriegler *et al.*, 1969; Rouse *et al.*, 1974; Carneggie *et al.*, 1974; Blair and Baumgardner, 1977; Ashley and Rea, 1975; Maxwell, 1976; Richardson and Wiegand, 1977; Wiegand *et al.*, 1979).

These successful applications of red and photographic infrared linear combination data to a variety of vegetation situations strongly supports the contention that these data are sensitive to basic biotic properties of vegetated surfaces. We now report on an experiment in which red and photographic infrared spectral data were collected from soybean plots and were correlated with leaf area, leaf biomass, and total biomass.

Experimental Methods

A soybean field (*Glycine max* (L. Merr.) on Elinsboro sandy loam soil located on the USDA Beltsville Agricultural Research Center, Maryland was selected for study. The soybeans were planted on 20 May 1978, and had a row spacing of 76 cm and a 5-cm spacing within the row. The crop emerged in early June and reached 100 percent canopy cover in early August. The first freeze occurred on 11 October 1978 after which most green leaves became chlorotic.

Four 50-cm diameter plots were randomly selected for sampling each week of the 15 week growing season. Prior to canopy closure each plot contained varying proportions of green vegetation and bare soil. Four pairs of red (0.63-0.69 μm) and photographic infrared (0.775-0.825 μm) spectral data were collected for each plot with a nadir pointing

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hand-held radiometer similar to Pearson *et al.* (1976). The instrument was positioned over the canopy such that the full angle field of view (FOV) exactly registered with the diameter of the plot at the top of the canopy. Concurrent agronomic data pertaining to crop development, visually estimated canopy cover, number of leaves, and plant height were recorded before each of the plots was harvested. All of the above ground vegetation was clipped at ground level and the total wet biomass was determined. Subsequently, the total wet biomass was stratified into wet green leaf biomass, wet chlorotic leaf biomass, and wet stem biomass. A leaf was visually classified as chlorotic if >50 percent of the leaf area was yellow or the greenness of a photosynthetically active leaf had uniformly faded to a yellow shade. The wet green and wet chlorotic leaf biomasses were immediately run through an automatic leaf area meter to determine the green leaf area and chlorotic leaf area. The wet biomass fractions were then force-air dried at 60°C for 48 hours before the dry green leaf biomass, dry chlorotic leaf biomass, and dry stem biomass determinations were made. The stem biomass determinations included reproductive organs.

The spectral radiance data were collected at approximately one week intervals and were collected in direct sunlight under cloudless or partly cloudy skies between the hours of 1030 and 1430 EDT. Atmospheric conditions varied from very clear with low humidity, to hazy with high humidity. A reference reading was taken from a $BaSO_4$ panel prior to measuring each plot with the hand-held radiometer. Radiance data were used in the analysis because the two bands in question (0.63 to 0.69 and 0.775 to 0.825 μm) are spectrally close together and have similar atmospheric transmission characteristics.

The radiance data were used to form the IR/red radiance ratio and the normalized difference (ND), (IR-red)/IR + red), (Kriegler, 1969). All radiance data were averaged for each plot (i.e., the mean of the four observations) and the averaged values used thereafter in the statistical analysis. The data analysis correlated and regressed the red

TABLE 1. LINEAR CORRELATION COEFFICIENTS BETWEEN THE FOUR SPECTRAL VARIABLES AND THE PLANT CANOPY VARIABLES AND THE RANGE OF THE PLANT CANOPY VARIABLES MEASURED. THE SAMPLE SIZES ARE NOTED IN BRACKETS.

Canopy Variable	Range	Red	IR	IR/Red	ND
Green LAI [52]	0.05 – 7.61	−0.75	0.75	0.92	0.81
Green Wet Leaf Biomass (g/m^2) [60]	0.0 – 1262.4	−0.67	0.79	0.93	0.82
Green Dry Leaf Biomass (g/m^2) [60]	0.0 – 292.8	−0.68	0.75	0.92	0.83
Chlorotic LAI [40]	0.0 – 1.22	0.02	−0.14	−0.30	0.07
Chlorotic Wet Leaf Biomass (g/m^2) [42]	0.0 – 182.4	0.01	−0.12	−0.29	0.07
Chlorotic Dry Leaf Biomass (g/m^2) [40]	0.0 – 47.0	0.03	−0.20	−0.34	0.05
Total LAI [40]	0.0 – 7.95	−0.84	0.85	0.89	0.84
Total Wet Leaf Biomass (g/m^2) [42]	0.0 – 1310.4	−0.82	0.85	0.90	0.82
Total Dry Leaf Biomass (g/m^2) [40]	0.0 – 301.0	−0.84	0.82	0.88	0.83
Wet Stem Biomass (g/m^2) [60]	76.8 – 4749.6	−0.32	0.00	0.05	0.35
Dry Stem Biomass (g/m^2) [40]	110.4 – 1070.4	0.55	−0.74	−0.74	−0.54
Total Wet Biomass (g/m^2) [60]	48.0 – 5121.6	−0.73	0.31	0.65	0.71
Total Dry Biomass (g/m^2) [60]	4.8 – 1209.6	−0.58	−0.14	0.26	0.36
Estimated Crop Cover (%) [60]	5 – 100	−0.93	0.48	0.79	0.87

radiance, the photographic IR-radiance, IR/red radiance ratio, and the normalized difference with respect to the various plant canopy variables measured (Table 1).

Results and Discussion

The analyses showed conclusively that red and photographic infrared spectral data were highly related to the green leaf area index (LAI) and the green leaf wet and dry biomass (Table 1, Figure 1). The IR/red radiance ratio was the spectral variable most highly correlated with the green LAI and the green leaf biomass and had a generally linear trend with respect to these canopy variables, (Figure 1c). The ND, by comparison, was nonlinear with respect to the same canopy variables (Figure 1d). This difference in nonlinearity for red and photographic infrared variables has previously been reported for moderate to high green leaf biomass situations (Colwell *et al.*, 1977; Tucker *et al.*, 1980). The asymptotic nature of the ND curve restricts its usefulness for high leaf biomass situations.

The discussion of our results henceforth focuses principally upon the IR/red radiance ratio because it was found to be the variable most highly and linearly correlated with the green biomass and green LAI (Table 1 and Figure 1). The red and photographic infrared radiances, while useful in some regards, did not compensate for differences in the spectral irradiance at the times of data collection (i.e., they are proportional to the instantaneous incident spectral irradiance). We, therefore, will deal with the ratioed data which minimizes this variation in the spectral data.

The IR/red radiance ratio was more highly correlated with the green LAI than were the total LAI or the chlorotic LAI (Figure 1c and 2; Table 1). These same relationships existed between the IR/red radiance ratio and the green leaf biomass, chlorotic leaf biomass,

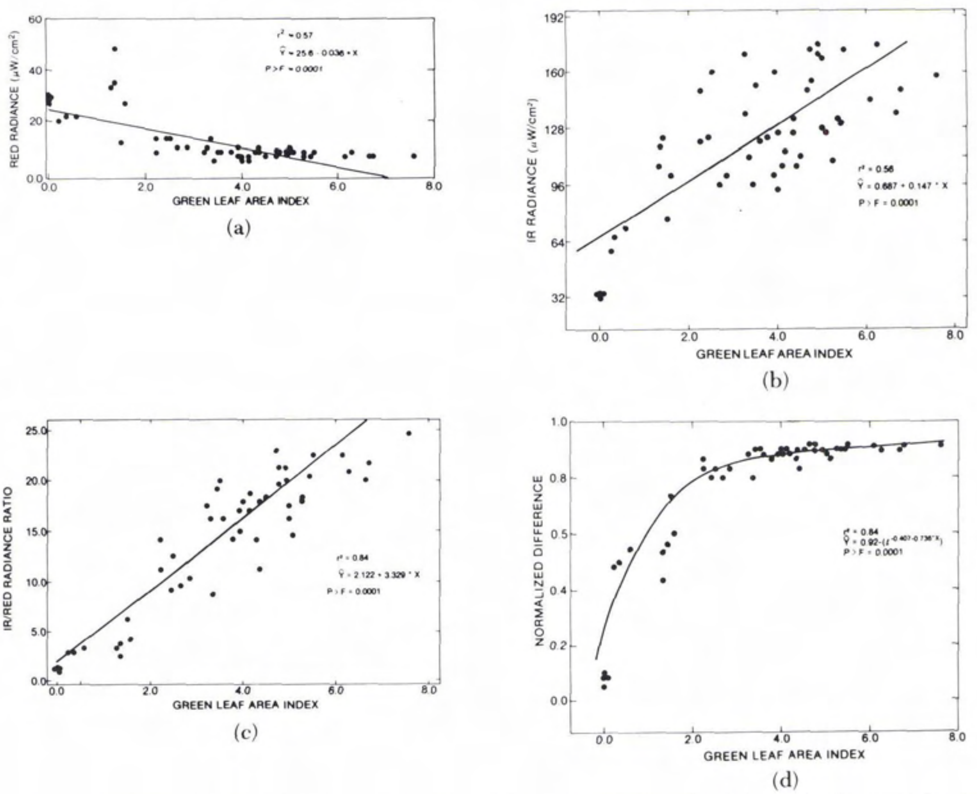

FIG. 1. The green leaf area index versus (a) red radiance, (b) photographic infrared radiance, (c) IR/red radiance ratio, and (d) the normalized difference (IR − red)/(IR + red). The red radiance remains nearly constant for green LAI greater than 3 while the photographic infrared increases with increasing green LAI. The high variability in (b) is due to differing irradiational conditions at the times of observation. Note also the superiority of the IR/red radiance ratio for predicting the green leaf area index.

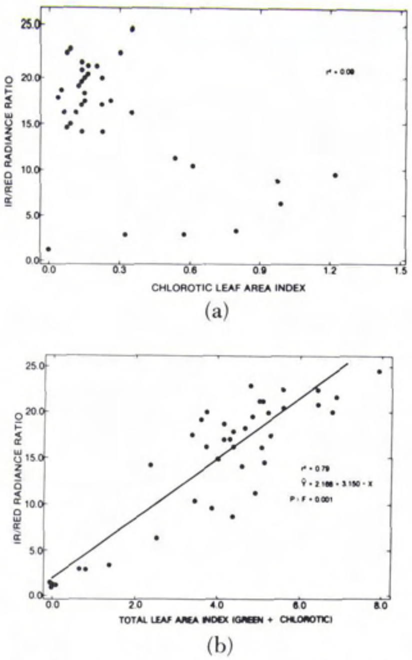

FIG. 2. The IR/red radiance ratio versus (a) the chlorotic leaf area index and (b) the total leaf area index (green + chlorotic). See also Figure 1c.

and total leaf biomass (wet and dry, for all three cases), respectively. The IR/red radiance ratio was not highly correlated with any of the "chlorotic" variables, the total wet biomass or total dry biomass, or the wet stem biomass. This further established that the IR/red radiance ratio was most useful for accurate nondestructive estimations of projected *in situ* soybean green leaf area or biomass.

Our study has also shown that total, chlorotic, and green leaf area index determinations were highly related to their respective wet and dry leaf biomass determinations (Figure 3). This could, depending on crop type, reduce much of the field effort involved in relating spectral data to quantitative canopy variables by replacing the time consuming LAI measurements with leaf biomass determinations. Similar findings for winter wheat have been reported by Aase (1978).

Green or photosynthetically active LAI data is one of the basic state or system level variables for primary production modeling (Wiegand *et al.,* 1979). This dynamic biotic entity, which responds rapidly to abiotic and/or biotic influences, in effect integrates the various conditions affecting plant growth and development. The green LAI also represents the potential for primary productivity at a given point of time. Because photosynthesis occurs principally in green leaves, the green LAI is highly related to net primary production. Remote sensing can thus supply information about the potential for plant growth and development. These data, monitored through time and combined with other types of data (soil water, climate, etc.), offer the potential to nondestructively monitor vegetation growth and development *in situ*.

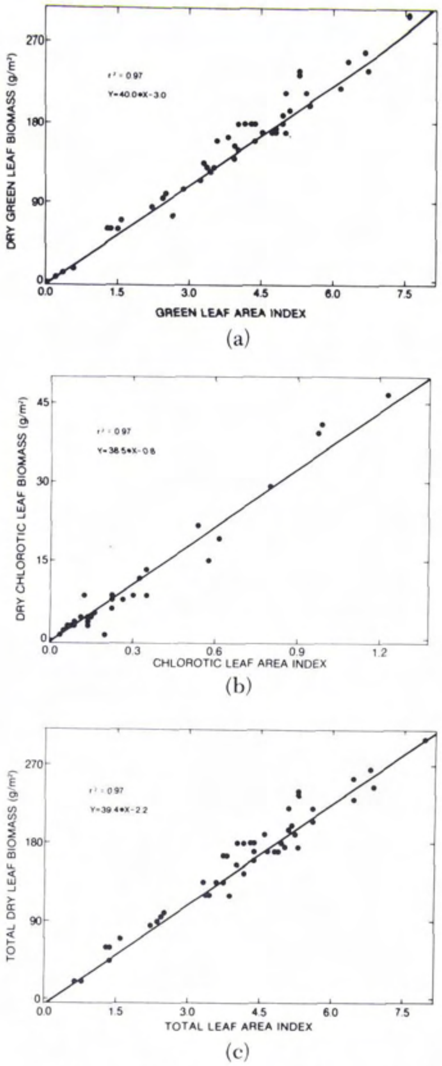

FIG. 3. The high correlations between the leaf canopy biomass and their respective leaf area indices: (a) Dry green leaf biomass (g/m²) vs green LAI, (b) Dry chlorotic leaf biomass (g/m²) vs chlorotic LAI, and (c) dry total leaf biomass vs total LAI.

The commonly recorded agronomic variable "estimated crop cover" has been considered an important indicator of crop canopy condition. We evaluated the relationship of the spectral data to estimated crop cover in a high leaf density situation. There were poor relationships between estimated crop cover and both the IR/red radiance ratio and the green LAI (Figure 4). Once canopy closure occurred (i.e., 100 percent crop cover), the estimated crop cover by definition could not increase although the soybean plants continued to produce green leaves. The green LAI, however, quantified the increase in leaf production and the IR/red radiance ratio was sensitive to it. It is, thus, apparent that estimated crop cover is a poor choice for quantifying *in situ* canopy condition for a soybean crop.

Conclusions

- The IR/red radiance ratio and normalized difference responded principally to changes in the green leaf variables.
- The IR/red radiance ratio was linearly and highly correlated to the green leaf variables.
- The normalized difference was exponentially related to the green leaf variables. The asymptotic nature of this relationship limited the use of the normalized difference for estimating these plant canopy variables in high leaf density vegetation canopies.
- The dry leaf weight variables may be substituted for their corresponding LAI variables for this investigation.
- Estimated crop cover was poorly related to either spectral data or green leaf variables for high leaf density canopies.
- Spectral monitoring of plant canopies by red and photographic infrared linear combinations could provide a significant and direct input to terrestrial primary productivity and evapotranspiration models.

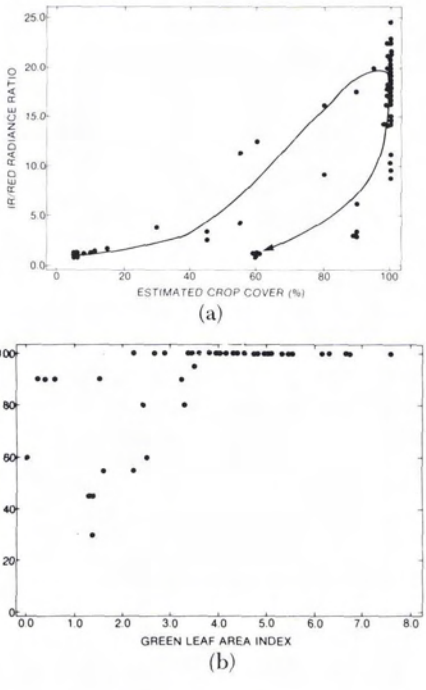

FIG. 4. The relationship between estimated crop cover and (a) the IR/red radiance ratio and (b) the green leaf area index. The arrow in (a) tracks the data through time. Note how the IR/red radiance ratio and green LAI change while the estimated crop cover remains at 100 percent. The high estimated crop cover at green LAI's of less than one occurred after the first frost when nearly all of the leaves had become chlorotic yet had not senesced.

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References

Aase, J. K., 1978. Relationship between leaf area and dry matter in winter wheat, *Agron. J.* 70:563-565.

Ashley, M. D., and J. Rea, 1975. Seasonal vegetation differences from ERTS imagery, *Photogram. Engr. and Remote Sensing* 41:713-719.

Blair, B. O., and M. F. Baumgardner, 1977. Detection of the green and brown wave in hardwood canopy covers using multidate multispectral data from Landsat-1, *Agron. J.* 69:808-811.

Carneggie, D. M., S. D. de Gloria, and R. M. Colwell, 1974. *Usefulness of ERTS-1 and supporting aircraft data for monitoring plant development and range conditions in California's annual grasslands,* Bureau of Land Management Final Report 53500-CT3-266 (N).

Colwell, J. E., D. P. Rice, and R. F. Nalepka, 1977. Wheat yield forecasts using Landsat data. In *Proc. of the 11th International Symposium on Remote Sensing of Environment,* University of Michigan, Ann Arbor, pp. 1245-1254.

Deering, D. W., 1978. *Rangeland reflectance characteristics measured by aircraft and space craft sensors.* Ph.D. dissertation. Texas A & M University, College Station, 338 p.

Jordan, C. F., 1969. Derivation of leaf area index from quality of light on the forest floor, *Ecology* 50(4):663-666.

Kriegler, F. J., W. A. Malila, R. F. Nalepka, and W. Richardson, 1969. Preprocessing transformations and their effects on multispectral recognition. In *Proc. of the Sixth Intern'l. Symposium on Remote Sensing of Environment,* Univ. of Mich. Ann Arbor, pp. 97-109.

Maxwell, E. L., 1976. Multivariate system analysis of multispectral imagery, *Photogram. Engr. and Remote Sensing* 42(9):1173-1186.

Pearson, R. L., L. D. Miller, and C. J. Tucker, 1976. Hand-held radiometer to measure graminous biomass, *Appl. Optics* 16(3):416-418.

Richardson, A. J., and C. L. Wiegand, 1977. Distinguishing vegetation from soil background information, *Photogram. Engr. and Remote Sensing* 43(12):1541-1552.

Tucker, C. J., 1979. Red and photographic infrared linear combinations for monitoring vegetation, *Remote Sensing of Environment* 8(2):127-150.

Tucker, C. J., J. H. Elgin, and J. E. McMurtrey, 1980. Relationship of red and photographic infrared spectral data to alfalfa biomass, canopy cover, and drought stress, *International J. of Remote Sensing* 1(1):(in press).

Wiegand, C. L., A. J. Richardson, and E. T. Kanemasu, 1979. Leaf area index estimates for wheat from Landsat and their implications for evapotranspiration and crop modeling, *Agron. J.* 71:336-342.

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