Diurnal Patterns of Wheat Spectral Reflectances

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Abstract—Spectral reflectances of Produra wheat were measured at 13 different times of the day at Phoenix, Arizona, on April 14, 1979 using a nadir-oriented hand-held 4-band radiometer which had bandpass characteristics similar to those on current LANDSAT satellites. Different sun altitude and azimuth angles caused significant diurnal changes in radiant return in both visible and near-IR regions of the spectrum and in several vegetation indices derived from them. The magnitude of these changes were related to different canopy architecture, percent cover, and green leaf area conditions. Spectral measurements taken at each time period were well correlated with green leaf area index but the nature of the relationship changed significantly with time of day. Thus a significant bias in the estimation of green leaf area index (GLAI) from remotely sensed spectral data could occur if sun angles are not properly accounted for.

I. Introduction

RECENT developments in hand-held radiometry [1] have paved the way for the rapid collection of broad waveband spectral data over experimental agricultural plots. Such data are essential to develop and understand the relationships between spectral and agronomic data, such as leaf area index (LAI), biomass and yield. In turn, these relationships should provide needed information to improve the interpretation of satellite data and provide inputs toward the design of future satellite instrumentation and orbital characteristics. Ground-based and aircraft-collected spectral data are not limited to a specific time-of-day acquisition, as are present LANDSAT satellite data. Instead, they are controlled by other constraints, such as those imposed by weather, personnel and equipment availability. Although most researchers limit data collection to several hours before and after solar noon, the time involved for a sequence of measurements over widely spaced fields is often substantial. The bidirectional reflectance properties of plant canopies are complex [2] and not well understood. As a result, spectral data are usually not adjusted for diurnal or seasonal changes in sun angle; a factor which can lead to serious errors or misinterpretation of results.

In an earlier paper [3], we presented spectral data for wheat plots that were hand planted to a high density within rows and approaching a hedgerow type configuration. At the time of our observations all plants were in the same phenological stage. We discussed the complex interactions of sun angles with row orientation, geometry and light reflectance, and concluded that changing sun angles due to time-of-day were sufficient to obscure apparent spectral differences which might have been attributed to varietal characteristics. Because those results appeared to contradict earlier findings of Lemme and Westin [4], we decided that the effect of changing sun angles warranted more extensive investigation under field conditions. As a consequence, the following report describes a series of hand-held spectral measurements made at 13 times during a single day over differentially water-stressed wheat plots in three different growth stages. Our specific objectives were three-fold: first, to document the diurnal pattern of several widely used vegetation indices derived from several visible and infrared wavebands; second, to determine whether an optimum time-of-day exists for extracting agronomic information from these spectral data; and third, to assess the relative magnitudes of errors in scene interpretation which may arise when canopy geometry and changing sun angle configuration, due to time of day, seasonal or latitudinal effects, are not properly accounted for.

II. Experimental Approach

A. Agronomic Methods

In 1978 we initiated a "serial cereal" experiment at Phoenix, Arizona (112 W longitude, 33 N latitude). Three plots of wheat (*Triticum durum* Desf. var. Produra) were planted sequentially, the first on November 1, 1978, the second on December 15, 1978 and the third on February 13, 1979. Seeds were machine-planted in N-S oriented rows that were 18 cm apart. Each planting was divided into four 12 × 13 m plots for differential irrigation purposes. Although winter rains prevented the early initiation of differential stress on the first two plantings, by April 14, 1979, the day diurnal spectral measurements were made, significant water stress was evident in at least one plot within each planting date.

The agronomic data were estimated from 5 to 6 twice-weekly samples centered around the April 14th measurement period. Each sample consisted of 6 randomly chosen plants. Green leaf area index (GLAI) was determined using an optically integrating leaf area meter. It is defined here as a dimensionless ratio of the green leaf area (m^2) to the surface area of the soil supporting it (m^2). Fraction green was the ratio of green LAI to total LAI. Grain yield and plant density were determined for the spectral target areas in each plot at harvest during May. Percent green cover was estimated by a dot grid analysis of vertical photographs of the target areas.

B. Spectral Measurements

Observations were made using an Exotech Model 100 A "LANDSAT Groundtruth Radiometer" with 15° field-of-view lenses. The spectral bandpasses for this radiometer are similar

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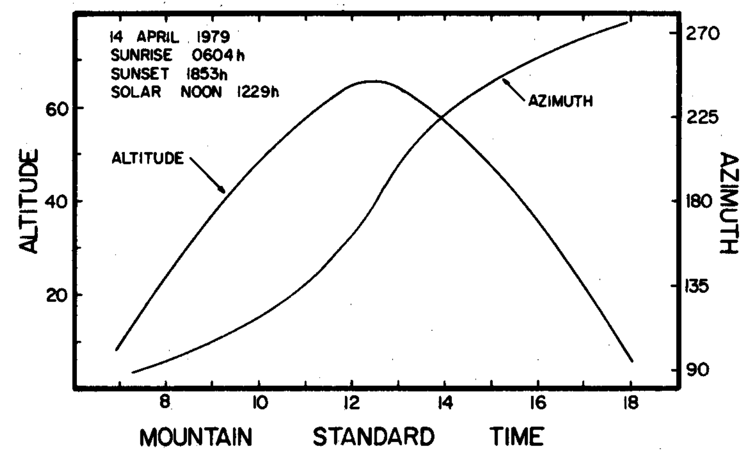


Fig. 1. Sun altitude (degrees above the horizon) and azimuth (degrees clockwise from north) angles for Phoenix, Arizona, on April 14, 1979.

to those of LANDSAT satellites, i.e., MSS4 (0.5 to 0.6 μm), MSS5 (0.6 to 0.7 μm), MSS6 (0.7 to 0.8 μm), and MSS7 (0.8 to 1.1 μm).[1] The radiometer was nadir oriented and hand-held about 2 m above the soil surface. It was used in conjunction with a microprocessor-based portable data acquisition system that allows simultaneous recording of measurements from each band and subsequent direct output to a computer [5]. Data collection began by recording four readings from a $BaSO_4$ reflectance plate, six readings from designated target zones within each of three wheat subplots, four readings of the plate, six readings each from three wheat subplots, etc., until all twelve subplots were measured. This sequence, requiring about 6 min to complete, was carried out at thirteen times on April 14, 1979, beginning at 0753 h and ending at 1758 h MST.

TABLE I
AGRONOMIC CHARACTERISTICS OF EXPERIMENTAL PRODURA WHEAT FIELDS AT PHOENIX, ARIZONA ON APRIL 14, 1979

Plot	Stage [6]	Plant Density (m^2)	Height (cm)	Green LAI	Fraction Green	% Green Cover	Total Dry Biomass (kg/ha)	Total Water[1/] Applied (cm)	Grain[2/] Yield (kg/ha)
1A	11.1	117	100	2.8	.60	81	17420	50.6	6010
1B	11.1-11.2	120	100	0.5	.40	48	14930	38.6	3530
1C	11.1	118	105	1.5	.51	50	15680	52.7	4000
1D	11.1	121	102	3.7	.72	86	19690	65.6	5630
2A	10.6	95	86	1.4	.67	59	9080	36.0	2290
2B	10.6	117	97	3.2	.84	80	11590	47.5	3040
2C	10.6	98	97	2.9	.85	89	9650	58.6	3650
2D	10.5-10.6	98	96	4.1	.85	88	8220	74.4	5680
3A	7	66	46	1.3	.98	51	1210	41.7	1550
3B	7	85	46	2.0	.99	71	1760	60.4	3240
3C	7	92	45	1.8	.99	73	1830	34.4	860
3D	7	85	42	1.6	.96	66	2040	21.1	690

[1/] Includes rainfall and irrigations from planting until harvest.

[2/] Grain yield at harvest, on a dry weight basis.

III. RESULTS AND DISCUSSION

A. Weather and Sun Angles

Meteorological conditions on April 14th were characterized by clear skies and relatively low levels of haze throughout the day. Wind conditions remained calm except during the 1538-h and 1634-h measurement period, when light winds were sufficient to cause the leaves to move slightly. Sun altitude changed markedly during the measurements from 22.5° at 0753 h to a maximum of 65.6° at solar noon, and then dropped to 7.2° at 1758 h MST. Sun azimuth varied from 94° to 276° (Fig. 1).

B. Agronomic Information

Table I presents agronomic data for the experimental wheat plots on the day measurements were made, total water received over the growing season and final grain yield on a dry-weight basis. The plots which have the "1" designation, i.e., 1A, 1B, 1C, and 1D, were phenologically most advanced with kernel development in the milky ripe stage [6]. The green leaf area had passed its peak and was declining. Plot 1B senescenced most rapidly and most of its canopy was brown because of insufficient water. Although the lower canopy elements in plots 1A and 1D were also brown, the upper canopy, flag leaves, heads and awns remained green and effectively obscured the soil and brown leaves from an overhead nadir view. A slight amount of lodging was present in 1A and 1D. A maximum yield of 6010 kg/ha was recorded in 1A.

The plots with the "2" designation were planted six weeks later. Plant density was slightly less than in the "1" plots due to different environmental conditions during germination and emergence. By mid April, these plots had headed and were just past the flowering stage with kernels partially formed. With the exception of 2A, which had some dying of leaves due to limited amount of water, these plots were mostly green, the leaves were oriented vertically and percent green cover was 80-90 percent. Yields from these plots ranged from 2290 to 5680 kg/ha.

Plants in the "3" plots were in stage 7 (second node formed and the next to the last leaf just visible). A few brown leaves were present in these canopies, but inasmuch as green cover ranged from 51 to 73 percent, substantial amounts of soil were viewed by the nadir-looking radiometer. Plots 3C and 3D had

[1] LANDSAT spectral data are expected to follow trends similar to Exotech radiometer data, however, absolute values will undoubtedly be different due to calibration differences and atmospheric attenuation. It should be pointed out that radiance data from the LANDSAT MSS7 is quantitized into 63 different levels instead of the 127 levels used in the other three bands. Thus calculations involving digital data from LANDSAT must be scaled appropriately before any direct comparisons between the two data sets can be made.

yields less than 1000 kg/ha. This was caused primarily by drought stress imposed after the diurnal sequence of radiometric measurements in mid April. Plot 3B was irrigated one day prior to measurements, and thus the surface soils were wet throughout the study.

C. Diurnal Changes in Crop Spectral Reflectances

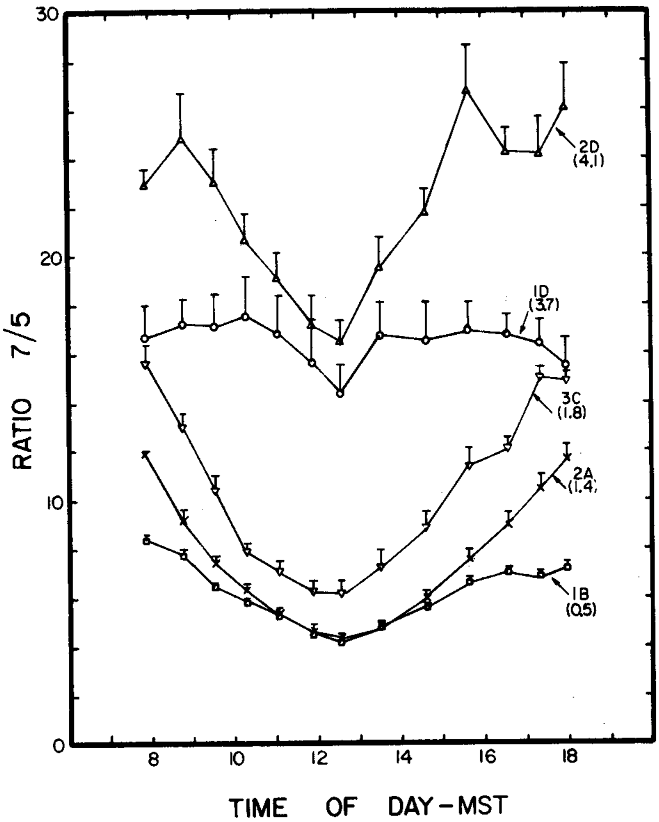
a) Ratio and ND indices: A number of indices derived from radiometric measurements have been proposed to characterize various agronomic parameters such as plant cover, leaf area index, biomass, and yield [7]. Usually incorporating data from several wavebands, these indices exploit the fact that as the density of the photosythetically active biomass increases, there is a concomitant increase in near-infrared reflectance and a decrease in visible reflectance. For illustration, we have chosen two such indices that utilize band ratioing techniques which make them relatively independent of illumination intensity and eliminate the irradiance measurements required for the calculation of reflectances. The ratioing of waveband radiances instead of reflectances also circumvents errors in irradiance estimates which are introduced by the nonLambertian response of $BaSO_4$ reference panels at low sun angles [8].

Fig. 2 shows the ratio of radiances in MSS7 to MSS5 and the Normalized Difference parameter,[2] ND = (MSS7 - MSS5)/(MSS7 + MSS5), as a function of time of day for five of our experimental fields which represent a range of canopy conditions. The standard error bars show that these indices changed significantly during the day for each vegetated field. They were roughly symmetrical about solar noon and attained their lowest values at that time. We observed the greatest diurnal changes when the green LAI was low and substantial amounts of sunlit soil (fields 2A and 3C) or brown leaves (field 1B) were viewed by the radiometer. Note that field 2A had three times the green LAI of 1B and although their spectral data were statistically separable at low sun angles, they were almost identical from 1000 to 1500 h. We found the opposite to be true for fields 1D and 3C. Despite two-fold differences in GLAI, they were statistically indistinguishable before 0800 h or after 1700 h; yet at midday they remained well separated because sunlight penetrated to the soil in 3C. Such examples underscore the complexities of relating single scene multispectral data to agronomic variables without preliminary knowledge of sun angles and canopy configuration.

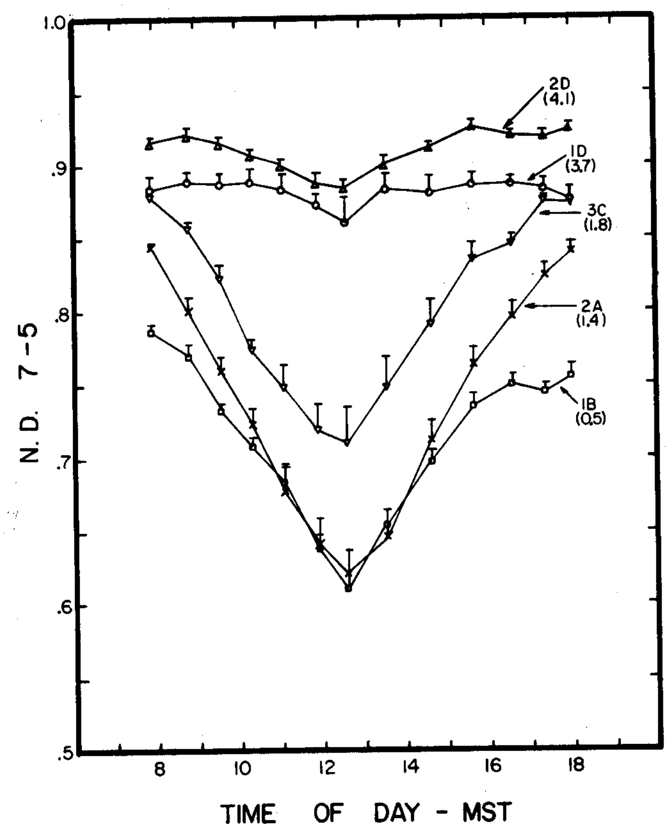
b) Visible and near-IR light: The diurnal patterns illustrated in Fig. 2 can best be explained by examining the interaction of incident light in the visible (MSS5) and near-IR (MSS7) wavebands with canopy architecture and the changing proportions of soil and green or brown canopy elements. First, consider the behavior of visible light when it strikes a canopy (Fig. 3(a)). We found that its reflectance[3] was relatively uniform throughout the day for canopies with LAI $\geqslant 3$. The same was true in field 3B (not shown in Fig. 3 (a)) where soils were wet from a

[2] ND was originally referred to as the Vegetation Index or VI [9].

[3] The Lambertian response of the $BaSO_4$ reference panel was unknown and thus not corrected for. Data presented by Kimes and Kirchner [8] indicate that this will result in an overestimation of target reflectance factors at low sun altitudes.



(a)



(b)

Fig. 2. Diurnal changes in two vegetation indices derived from spectral radiances in MSS5 and MSS7 for five selected Produra wheat fields on April 14, 1979 at Phoenix, Arizona. Vertical bars define +1 standard error. Green LAI is shown in parenthesis. (a) Radiance ratio of MSS7 to MSS5. (b) Radiance normalized difference parameter.

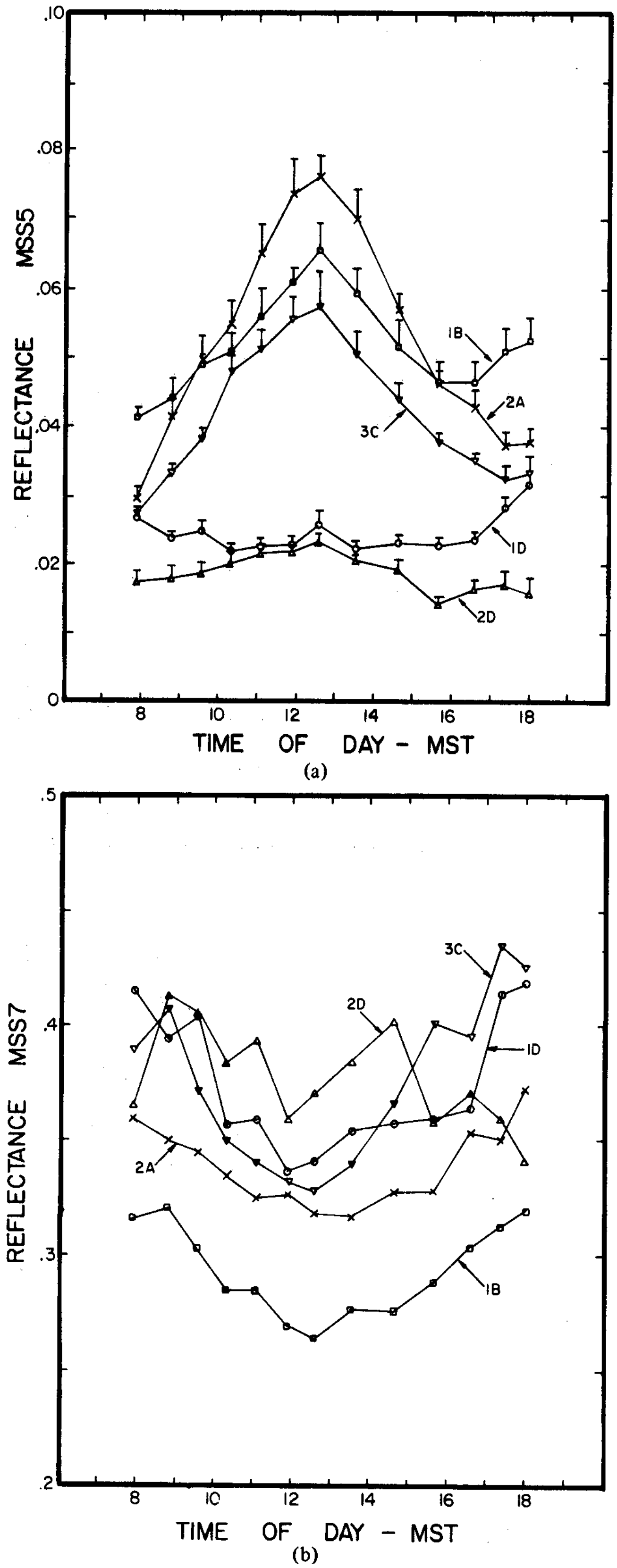


Fig. 3. Reflectance in MSS5 and MSS7 for selected Produra wheat fields as a function of time of day. (a) Vertical bars represent +1 SE. (b) They have been omitted to reduce clutter.

recent irrigation. On the other hand, the vertical reflectance of visible light from more sparse canopies was very dependent upon the direction of insolation and varied by a factor of 2 with a pronounced maximum at solar noon. At low sun altitudes, with the sun azimuth at right angles to row orientation, only the upper canopy elements were illuminated by direct beam insolation. In most of our fields these elements were predominately green plant tissue (heads, awns, and/or upper canopy leaves). Consequently, early and late in the day all fields should and did look similar from a reflectance standpoint in visible wavelengths. However, as the sun's altitude increased, the azimuth angle became more parallel with the rows, progressively more and more sunlight penetrated deeper into the canopy, striking both soil and brown leaf targets which have a much higher reflectance for visible light than do green plant leaves. As a result, scene reflectance was higher at noon in plot 1B because of the illumination of brown canopy elements beneath the partly green flag leaves. The reflectance was higher in 2A and 3C because varying amounts of soil and brown leaves were being illuminated. In the dense canopies, the proportion of illuminated green plant tissue remained essentially constant throughout the day, with the consequence that reflectance remained rather uniform despite changing solar angles.

We found reflectance of near-IR light (MSS7) to behave quite differently, reaching a minimum during midday. The near-IR reflectance from the senescent vegetation in field 1B was distinctly lower, but differences between the other canopies were not as clear-cut as were those we observed in the visible wavebands. There are several explanations for less diurnal change in the near-IR. The first, and most obvious, is that there was less difference in reflectance between bare, dry sunlit soil and dense green canopy in MSS7 (32 versus 37 percent, respectively, at solar noon) than in MSS5 (25 versus 2 percent). Thus even though more soil was illuminated at high sun angles, the net effect on reflectance in MSS7 was not as great. A second explanation involves the transmittance properties of green leaves. Although they are relatively opaque to visible light, they are considerably less so in the longer wavelengths, with near-IR light being transmitted through as many as eight leaf layers before complete attenuation (and hence maximum reflectance) occurs. Thus at low sun angles, incident light in MSS7 is intercepted by the same number of leaves in low as well as high GLAI situations; and since reflectance is always near maximum, the near-IR does not permit discrimination between the two canopy conditions. However, during midday, maximum near-IR reflectance occurs in fields wherein the intercepted density of leaves in the path of incoming light approaches eight layers, a situation which occurs only under very high green biomass conditions.

c) Other vegetation indices: Other types of spectral vegetation indices, such as the Green Vegetation Index (GVI), Soil Brightness Index (SBI), and Perpendicular Vegetation Index (PVI) are linear combinations of two or more wavebands. In order to make these indices more comparable between days, seasons, or latitudes, the radiometric data must be expressed as reflectances or converted by some other normalization procedure so that their absolute values are not proportional to the levels of illumination. If irradiances are not measured directly, as is often the case with satellite and aircraft measurements, they must be estimated by invoking a regular season/time/latitude dependent cosine response function, or by measuring the spectral response of a known relatively unchanging target and then normalizing all unknown targets to that observation. It is important to recognize that these "sun angle corrections" will not remove the diurnal changes we report here, since they do not correct for the nonLambertian reflectance of light from a canopy. Indeed, when we converted target radiances to reflectances and calculated GVI and SBI using published empirical coefficients and PVI using a soil background line derived for our soil, we found these three indices also changed significantly with time-of-day.

D. Correlations with GLAI

Numerous studies have documented correlations between spectral indices and various agronomic characteristics, particularly those related to the canopy's photosynthetically active biomass. Little attention has been given to the influence that sun angles have on these relationships. Our data provided a means to test whether certain times of the day were better than others for monitoring canopy conditions. Using simple linear regressions, we tested whether spectral radiances could be used to predict green leaf area index of all 12 wheat plots at thirteen different times of the day. An examination of the residuals associated with each regression indicated that linear models provided an acceptable characterization of the relation.

a) Individual wavebands: The coefficients of determination, which indicate the amount of variation in GLAI accounted for by a particular waveband are shown as a function of time of day in Fig. 4(a). We found that radiances in both MSS4 and MSS5 accounted for more than 60 percent of the total variability in GLAI regardless of time of day (Fig. 4(a)). Furthermore, our data show that MSS6 has relatively little information about the photosynthetically active biomass in a canopy, since its coefficient of determination remained lower than 0.20 for all but one time period. Although the 0933-h radiances in the MSS-7 near-IR waveband explained more of the variability in GLAI than the visible radiances, its overall performance was lower. It was particularly degraded before that time and after 1400 h, implying that radiance in this waveband cannot discriminate different GLAI at low sun angles.

b) Vegetation indices: Transforming the spectral data into commonly used vegetation indices improved their ability to predict GLAI (Fig. 4(b)). Both the ratio of MSS7/MSS5 and ND consistently accounted for more variability in GLAI than did any of the wavebands taken separately. In addition, there does not appear to be any one time-of-day which is best for inferring GLAI. The ratio and ND also remained superior to PVI calculated from either radiances or reflectances. In fact, prior to 0930 or after 1400, PVI did not appear to be very responsive to GLAI at all. We suspect that this was due to the relative importance of MSS7 in determining the value of PVI and the fact that there is a serious reduction in green canopy information content of that band at low sun angles.

c) Temporal changes in correlations: Although a relatively good correlation exists between the MSS7/MSS5 ratio and ND, and GLAI throughout the day, the nature of the relation changes significantly with time. To illustrate this point, we show these indices versus GLAI for the solar noon and 1800-h observations in Fig. 5. These two sets of data bound the ex-

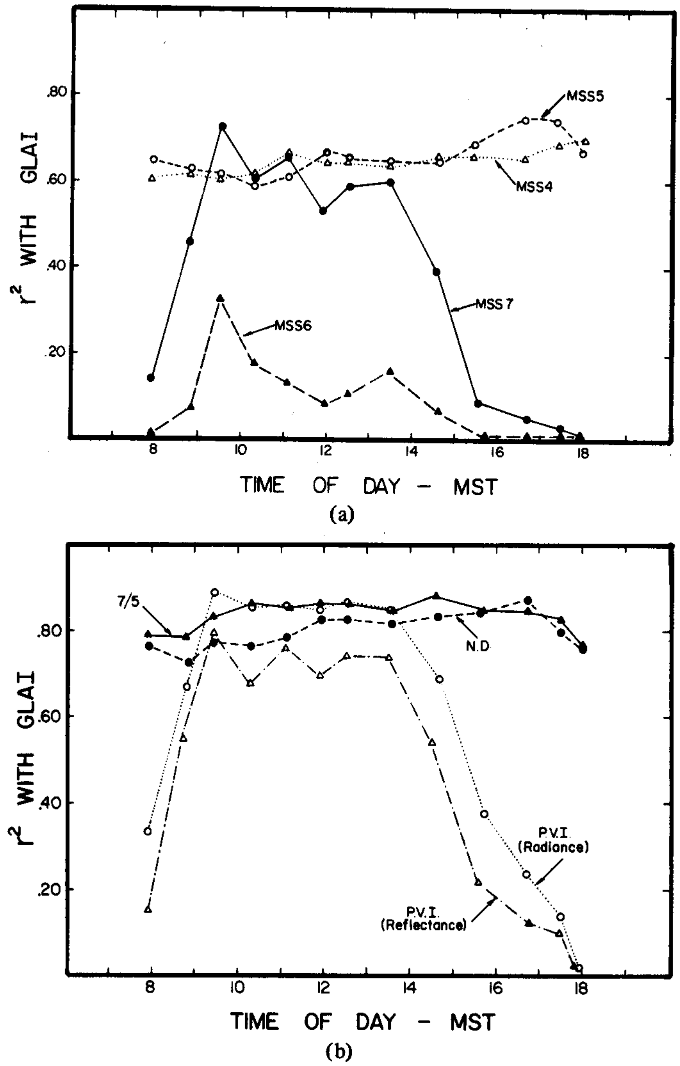


Fig. 4. Coefficients of determination calculated for the relationship between GLAI of 12 experimental fields and the radiances measured in each waveband (a), and four indices calculated from them (b).

tremes in sun altitude and azimuth which we observed during our study. Data collected at other time periods were intermediate in nature. Our data set is unique in that it encompasses plants in different stages of growth and senescence conditions as well as different levels of plant water status, yet the standard error of the estimate of GLAI remained at approximately 0.5 units regardless of the time of day. This is an acceptable error level since the field measurement of GLAI itself, using an optical planimeter, has approximately the same degree of precision associated with it. The slope of the ratio versus GLAI remained constant throughout the day while the intercept approached a maximum at solar noon. As a consequence, a predictive equation based on empirical data collected for one set of sun angles will not be able to predict GLAI well unless the spectral data are taken under similar sun angle conditions and unless row configuration remains approximately the same.

Both the slope and intercept of ND versus GLAI changed with time but the relationships appeared to pivot about the higher GLAI values. This implies that under relatively high GLAI conditions the value of ND will be similar regardless of time of day.

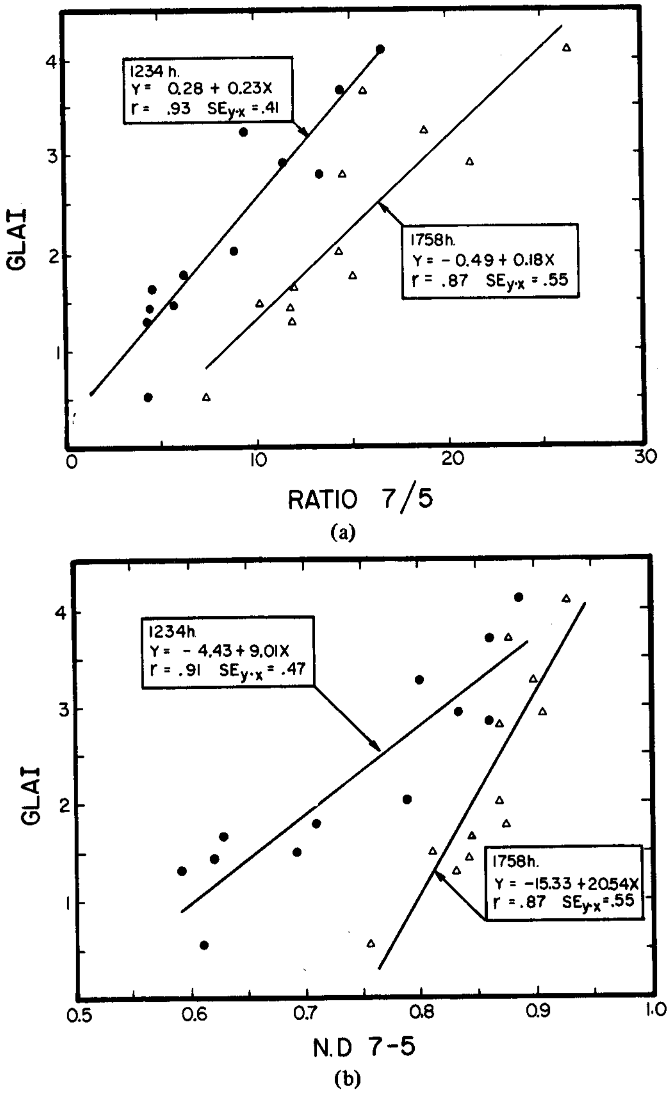


Fig. 5. The relationship between GLAI and two vegetation indices calculated from spectral data in MSS5 and MSS7 for two times of the day when sun angles were at extremes.

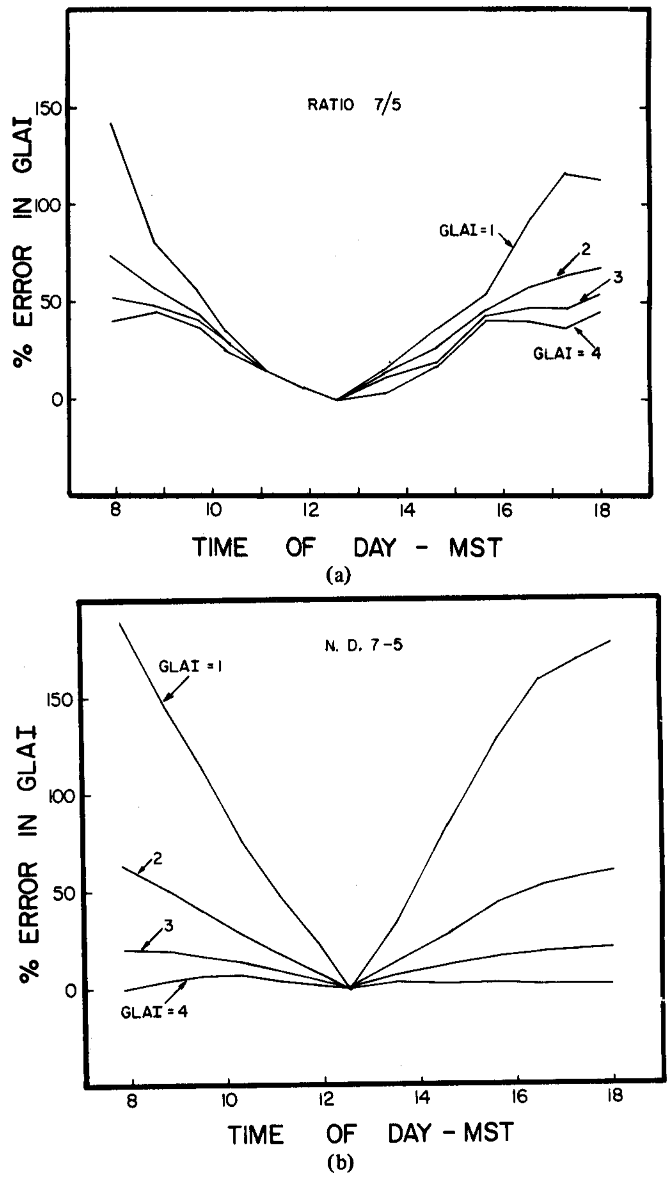


Fig. 6. Percent error in GLAI when the relation between spectral indices and GLAI at solar noon was used with spectral indices observed at other times of the day.

E. Potential Errors in GLAI Prediction

The final step in our analysis concerned the determination of how much error could be introduced in the estimation of GLAI from use of these spectral indices if an empirical relationship were derived from measurements at solar noon and then applied to spectral data collected at other times. To perform this error analysis, we first calculated an expected spectral vegetation index for GLAI = 1-4 using the specific relationship between GLAI and the observed ratio 7/5 and ND at each time. Then we used that expected index value to calculate GLAI using the solar noon relationship. Fig. 6 shows the percent error from the true GLAI which occurred when we used spectral data collected at different times of the day. Note that substantial errors are introduced for time periods extending several hours on either side of solar noon, a time period generally considered "safe" for data collection. Errors introduced at the time of LANDSAT overpass are also significant. Our results show that if the ratio 7/5 data collected at solar noon are used to generate a model for the prediction of GLAI from LANDSAT data (atmospheric attenuation problems aside), it will overpredict GLAI by 25 to 35 percent (Fig. 6(a)). Earlier in the day the problem becomes even more acute. For example, if the 0900 ratio data were used, we would predict a GLAI of almost 6 for a field where it actually was 4.

In general, the percent errors are greater for low GLAI situations and become more tolerable as GLAI approaches higher values. This was particulary evident when we performed the same type of analysis with ND and found that errors remained less than 10 percent for a GLAI ≥ 4 regardless of the time of day. This was evident in Fig. 2(b) where values of the normalized difference in plots 1D and 2D remained fairly constant at 0.9 throughout the day. The exact reason for the difference in information content of the ratio of MSS7 to MSS5 and the Normalized Difference is unclear at this point.

IV. Conclusions and Recommendations

Although our conclusions may be specific to the bright soil and north-south row orientation used in this experiment, we have shown that the diurnal changes in sun altitude and azimuth angles affect visible and near-IR reflectance measurements of a wheat canopy in a complex manner. This is due to the interaction of the specular component of irradiance with crop geometry, soil, and both green and brown plant tissues. At solar noon, more direct beam sunlight penetrates to the ground in a wheat canopy with N-S oriented rows than at other times of the day, causing maximum reflectance in visible wavebands and minimum near-IR reflectance. As a consequence, several vegetation indices calculated from radiances in these wavebands attained minimum values at that time. Earlier and later in the day values of these indices were significantly higher which could lead to a serious misinterpretation of canopy conditions if illumination angles and crop geometry are not properly accounted for.

Our findings suggest that the remote detection of low green biomass levels will be enhanced if spectral measurements are made under low sun angle conditions. Also, the ability to differentiate between very high green biomass situations will be facilitated by a high sun altitude and a sun azimuth parallel with row orientation. Finally, seasonal and latitudinal ranges of sun position might impose limitations on the use of remotely sensed spectral data for assessment of dense vegetation conditions in some locations.

Researchers must employ caution when extrapolating empirical relations derived under specific sun angle and row orientation conditions to other latitudes, seasons and times-of-day. Poor correlations between instantaneously acquired satellite spectra and "ground truth" collected over a span of several hours may be a result of rapid diurnal changes we observed in spectral reflections. Likewise, we believe that some apparent differences or similarities between crops could conceivably result from a systematic bias in spectral data caused by a regular measurement sequence in which one target was consistently viewed under a different set of sun angles.

Much information is contained in the diurnal course of canopy spectral reflectance and it should be more thoroughly investigated to exploit its potential. The remote sensing community has extracted a great deal of information from our present sunsynchronous LANDSAT's. However, we may find that seasonal and latitudinal variation in the sun's relative position could place an upper limit on the amount of useful agricultural information which can be extracted from those vehicles. It is likely that the agricultural community would derive more benefit from geostationary satellite platforms capable of monitoring MSS or Thematic Mapper wavebands on a more continuous basis.

The irradiance levels and target radiance data for each time period are available in tabular form as an appendix in the AgRISTAR'S version of this report (EW-U2-04349 JSC-18561).

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