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Technical Report

Relation of Agronomic and Multispectral Reflectance Characteristics of Spring Wheat Canopies

by J.S. Ahlrichs and M.E. Bauer

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16. Abstract

The relationships between crop canopy variables such as leaf area index which might be used in large scale applications of growth and yield models of wheat and other crops and their multispectral reflectance properties are not well defined. The objective of this investigation was to identify these relationships and assess the potential for estimating canopy variables from remotely sensed reflectance measurements. Reflectance spectra over the 0.4-2.5 µm wavelength range were acquired during each of the major development stages of spring wheat canopies at Williston, North Dakota, during three seasons. Treatments included planting date, N fertilization, cultivar, and soil moisture. Agronomic measurements included development stage, biomass, LAI, and percent soil cover.

High correlations were found between reflectance and percent cover, LAI, and biomass. A near infrared wavelength band, 0.76-0.90 µm, was most important in explaining variation in LAI and percent cover, while a middle infrared band, 2.08-2.35 µm, explained the most variation in biomass and plant water content. Transformations, including the near infrared/red reflectance ratio and greenness index, were also highly correlated to canopy variables. The relationship of canopy variables to reflectance decreased as the crop began to ripen. The canopy variables could be accurately predicted using measurements from three to five wavelength bands. The wavelength bands proposed for the thematic mapper sensor were more strongly related to the canopy variables than the Landsat MSS bands.

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INTRODUCTION

Crop identification and area estimation promises to be a major application of satellite remote sensing and the Large Area Crop Inventory Experiment (LACIE) advanced the technology to near operational use for wheat (MacDonald and Hall, 1980). Remote sensing also offers potential for obtaining accurate and timely information about the condition and yield of crops (Bauer, 1975). An important goal of agricultural remote sensing research is to spectrally estimate crop variables related to crop conditions which can subsequently be entered into crop growth and yield models. The synoptic, multidate views of cropland by the Landsat multispectral scanner (MSS) at a spatial resolution of 80 m (30 m for Landsat-4 thematic mapper launched in 1982) provide the opportunity for the first time to acquire the spectral-agronomic data required to implement development stage, evapotranspiration, and yield models over large geographic areas (Wiegand et al., 1979).

To achieve the full potential of remote sensing for crop assessment it is important to determine the relation of agronomic characteristics of crops to their multispectral reflectance properties. For instance, it is essential to know which regions of the spectrum contain maximum information related to variations in crop variables. This information is necessary for the optimum use of current Landsat MSS technology, as well as for the design and development of future remote sensing systems.

Many of the physiological and morphological factors affecting the reflectance properties of plant leaves have been investigated through laboratory measurements (Gates et al., 1970; Breece and Holmes, 1971; and Sinclair et al., 1971). Knowledge of the reflectance characteristics of single leaves is basic to understanding the reflectance properties of crop canopies, but cannot be applied directly. Due to many more interacting variables the reflectance characteristics of canopies are considerably more complex than those of single leaves. Some of the more important parameters determining the reflectance of crop canopies are: leaf area index (LAI), leaf angle distribution, optical characteristics of the leaves and soil, and soil cover percentage (Bunnick, 1978). Differences in these parameters are caused by variations in many cultural and environmental factors, including planting date, cultivar, seeding rate, fertilization, and soil moisture (Daughtry et al., 1980).

The objective of this research was to determine the relationships of LAI, percent soil cover, biomass and plant water content to the multispectral reflectance characteristics of spring wheat canopies.

EXPERIMENTAL APPROACH

Experiment Description

Data were collected at the North Dakota State Agricultural Experiment Station at Williston (43.32° N, 103.42° W) during the 1975, 1976 and 1977 growing seasons. The station, in the gently rolling uplands above the Missouri River Valley, is representative of dryland farms of the region. Because of limited precipitation (36 cm per year), the majority of the land is planted to crops every other year and is left fallow in intermediate years to accumulate subsoil moisture.

The spring wheat (*Triticum aestivum* L.) experiment was a split plot design. Within each available soil moisture condition (whole plot), there were two blocks (replications) of a factorial experiment with cultivar, N fertilization, and planting date treatments:

Soil Moisture: (1) low (wheat during previous year)
(2) high (fallow during previous year)

Cultivar: (1) Waldron (standard)
(2) Olaf (semi-dwarf)

N Fertilization: (1) none
(2) 44 kg/ha

Planting Date: (1) early (20 May 1975, 6 May 1976, 9 May 1977)
(2) late (30 May 1975, 17 May 1976, 23 May 1977).

The factors and levels were selected to represent regional agricultural practices that affect the growth, development, and yield of spring wheat. The treatments resulted in a relatively wide range of types of wheat canopies, differing in maturity, biomass, and percent soil cover at any one time and over the season.

The plots were 3.5 m wide and 15.3 m long with 18 cm wide, north-south rows. The soil was a Williams loam (fine-loamy, mixed Typic Argiboroll) which has a dark brown (10 YR 3/2) surface color when moist and very light (10 YR 4/3) color when dry. Although moisture in the top 20 cm was similar at planting for all plots, the profile of previously fallowed soil contained approximately 20% (3 cm) more water in the 20 to 60 cm zone than the profile of soil on which wheat was grown in the previous year.

Agronomic Data

On each date reflectance data were collected, the following agronomic variables were measured: development stage, plant height, percent soil cover, LAI, percent green leaves, fresh and dry biomass, and plant water content (difference between fresh and dry biomass). Vertical and oblique photographs were also taken of each plot on each measurement date. Development stage was recorded using a scale similar to that published by Large (1954). Percent soil cover was estimated from the vertical photographs. Biomass and LAI were determined by harvesting all plants in 1.0 m length of row and separating the plants into leaf blades (green, yellow, and brown), stems (including leaf sheaths), and heads. Each component was dried at 60°C and weighed. The area of a random subsample of green leaf blades was measured with an optically scanning leaf area meter (except in 1975 when leaf length and width were manually measured) and the ratio of leaf area to leaf dry weight was determined. LAI was calculated by multiplying this ratio times the dry weight of all green leaves in the sample and dividing by 0.18 m^2.

Meteorological Data

Daily meteorological data useful for describing the growing season were acquired at a National Weather Service cooperative station located on the experiment station. On each day that spectral data were collected, additional meteorological measurements including air temperature, barometric pressure, relative humidity, wind speed and direction, and total irradiance were recorded continuously on strip charts to document atmospheric conditions during data acquisition.

Spectral Data

Spectral reflectance measurements of the canopies over the wavelength range of 0.4-2.4 μm were made using an Exotech model 20C spectroradiometer (Leamer et al., 1973) mounted on the boom of a mobile aerial tower. Measurements were made at two locations over each plot, looking straight down from a 6.1 m altitude. With a 15° field of view the sensor viewed an area 1.6 m in diameter. All spectral measurements were made on cloudless or near cloudless days when the solar elevation was at least 45°. Duplicate observations were acquired over each plot and averaged for analysis.

The spectral measurements were expressed as reflectance factor which corrects for irradiance differences, facilitating comparisons within and between dates. A reflectance factor is defined as the ratio of incident radiant flux reflected by a sample surface (e.g. soil or crop canopy) to that reflected into the same beam geometry by a perfectly diffuse (Lambertian) standard reference surface identically irradiated and viewed (Nicodemus et al., 1977). A painted barium sulphate panel (1.2 x 1.2 m), with stable, known reflectance properties, was used as the reference surface. Robinson and Biehl (1979) have described the spectral measurements and calibration procedures.

Data Analysis Procedures

Correlation and regression analyses were used to relate the canopy variables to spectral response, with the primary analyses being for data collected between the seedling and milk stages of plant development. Since the application of remotely sensed spectral measurements will be with multispectral scanner systems (MSS) which measure the spectral response in selected wavelength bands, the data were averaged into the bandwidths of the Landsat MSS and thematic mapper (TM) sensors. The TM is a second generation multispectral scanner on planned for the Landsat-4 satellite launched in July 1982. The MSS bands are: 0.5-0.6 (green), 0.6-0.7 (red), and 0.7-0.8 and 0.8-1.1 µm (near infrared). The TM bands which are narrower and sample more parts of the spectrum are: 0.45-0.52 (blue), 0.52-0.60 (green), 0.63-0.69 (red), 0.76-0.90 (near infrared), 1.55-1.75 (middle infrared), and 2.08-2.35 µm (middle infrared). The TM also has a thermal infrared band, but thermal measurements were not acquired for this experiment.

In addition to the individual wavelength bands, several vegetation indices were evaluated. Greenness, a transformation of the Landsat MSS bands (Kauth and Thomas, 1976), was computed using coefficients derived for reflectance factor data (Rice et al., 1980). Greenness = $(-0.48935)(R_1) + (-0.61249)(R_2) + (0.17289)(R_3) + (0.59538)(R_4)$, where R_1 to R_4 are the reflectance factors of the four Landsat MSS spectral bands. The ratio of near infrared to red reflectance and the IR-red transformation were computed using the 0.76-0.90 and 0.63-0.69 µm bands. The normalized difference (ND) was calculated as follows: ND = (IR - red)/(IR + red), where red and IR are the reflectances in the 0.63-0.69 and 0.76-0.90 µm bands, respectively.

The Statistical Package for the Social Sciences (SPSS) was the primary source of statistical programs used in these analyses (Nie et al., 1975). Other statistical analyses were performed by a FORTRAN program written to calculate R^2 and C_p values (Mallows, 1973) for all possible regressions (Daniel and Wood, 1971) that can be formed from subsets of the independent variable (e.g. wavelength bands) entered. The output of this program listed subsets of independent variables for each subset size in order of the amount of variation explained in the dependent variable. The best subset was selected to be the smallest number and set of variables which explained most of the variability in the dependent variable and which was not significantly biased in the regression. The regression equations were developed using one-half the 1976 data; the remainder of the data were used in independent tests.

RESULTS AND DISCUSSION

Effects of Growth, Development and Cultural Practices on Reflectance Spectra

The amount of green vegetation is one of the principal factors influencing the reflectance of crop canopies. Fig. 1 illustrates the effect of amount of vegetation as measured by LAI, biomass and percent soil cover on the spectral response during the period between tillering and the beginning of heading when the maximum green leaf area was reached. As leaf area and biomass increase there is a progressive and characteristic decrease in the reflectance of the cholorophyll absorption region, increase in the near infrared reflectance, and decrease in the middle infrared reflectance.

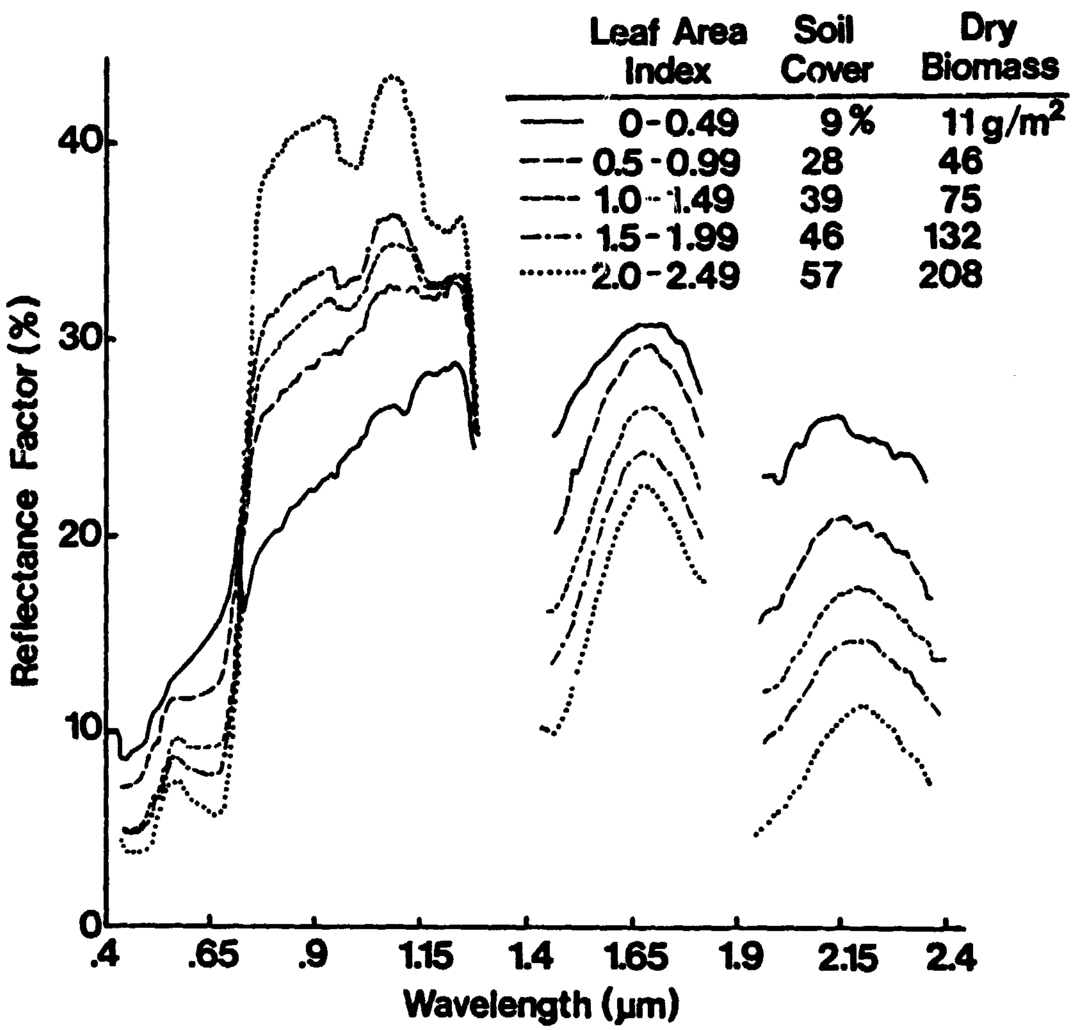

Fig. 1. Effect of leaf area index, percent soil cover, and dry biomass on the spectral reflectance of spring wheat during the period between tillering and beginning of heading when maximum green leaf area was reached.

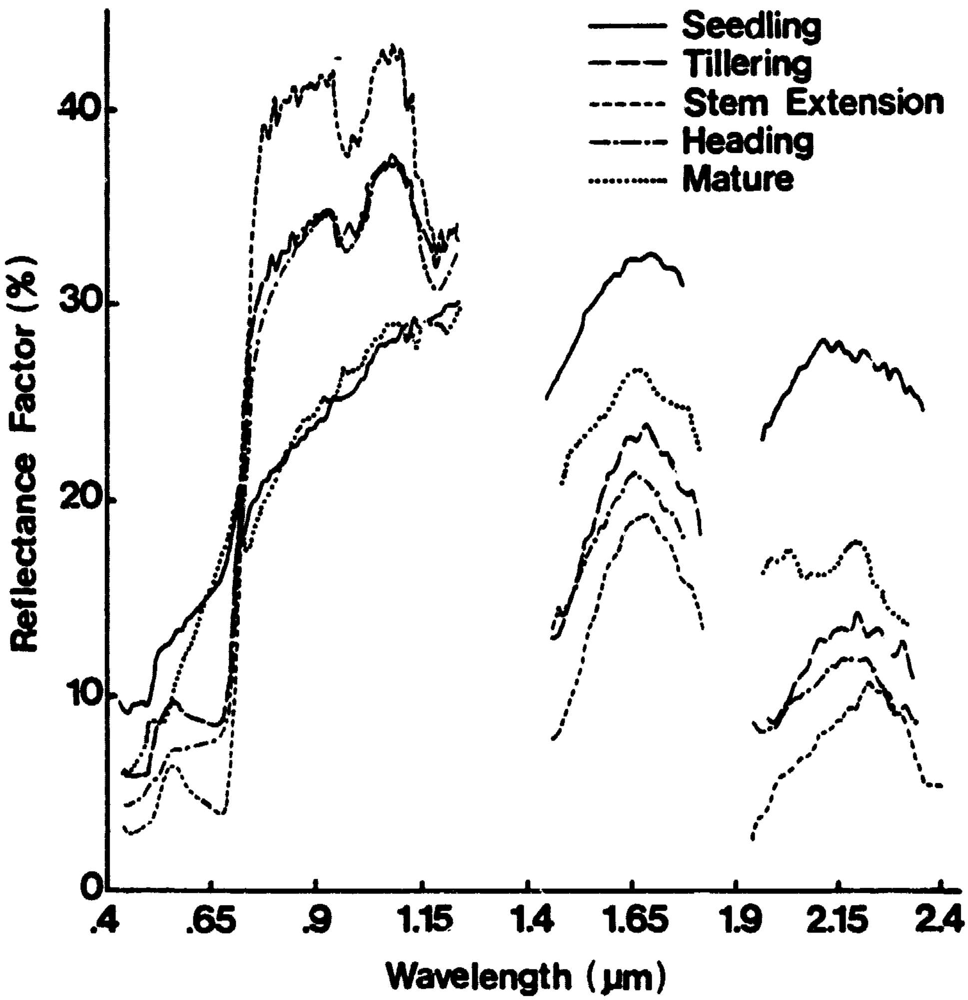

Fig. 2. Spectral reflectance of spring wheat canopies at several development stages.

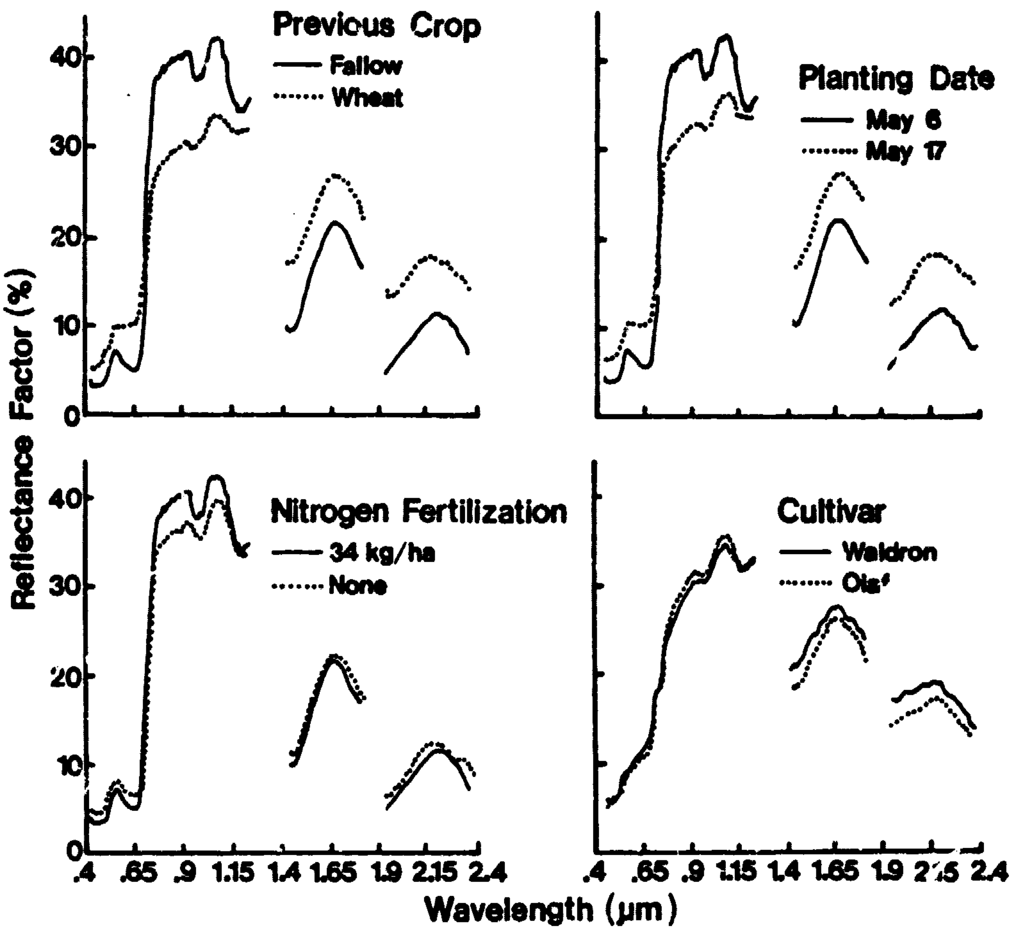

Fig. 3. Influence of cultural practices on reflectance spectra of spring wheat canopies. Spectra were measured on 18 June 1976 during stem extension stages of development, except for the spectra of cultivars that were measured on 16 July after heading.

Crop development (as opposed to growth or increase in size) also causes many changes in canopy geometry, moisture content, and leaf pigmentation which are manifested in the reflectance characteristics of canopies. Fig. 2 shows the reflectance spectra of a representative plot of spring wheat at several key development stages.

Typical effects of the cultural practices on reflectance spectra are illustrated in Fig. 3. Fallow soil (increased moisture), early planting and nitrogen fertilization caused increases in LAI, biomass and soil cover which were manifested in the spectra. The two cultivars had very similar spectral responses until after heading.

Relation of Canopy and Spectral Variables

The relationships of several canopy variables with spectral reflectance in selected wavelength bands are illustrated in Fig. 4. The linear correlations of five canopy variables with reflectances in the MSS and TM bands and transformations of the reflectance data are summarized in Table 1. Although some of the relationships appear curvilinear, inclusion of quadratic terms were generally not significant. The correlation analyses and graphs include data from all treatments, collected from the seedling through flowering stages of development when green leaves were present. As also found by Aase and Siddoway (1981) and Leamer et al. (1978), there was a substantial decrease in the correlation values when later development stages having large amounts of non-green vegetation were included.

Percent soil cover (Fig. 4a) consistently had the highest correlation with each spectral variable (Table 1). In this data, where

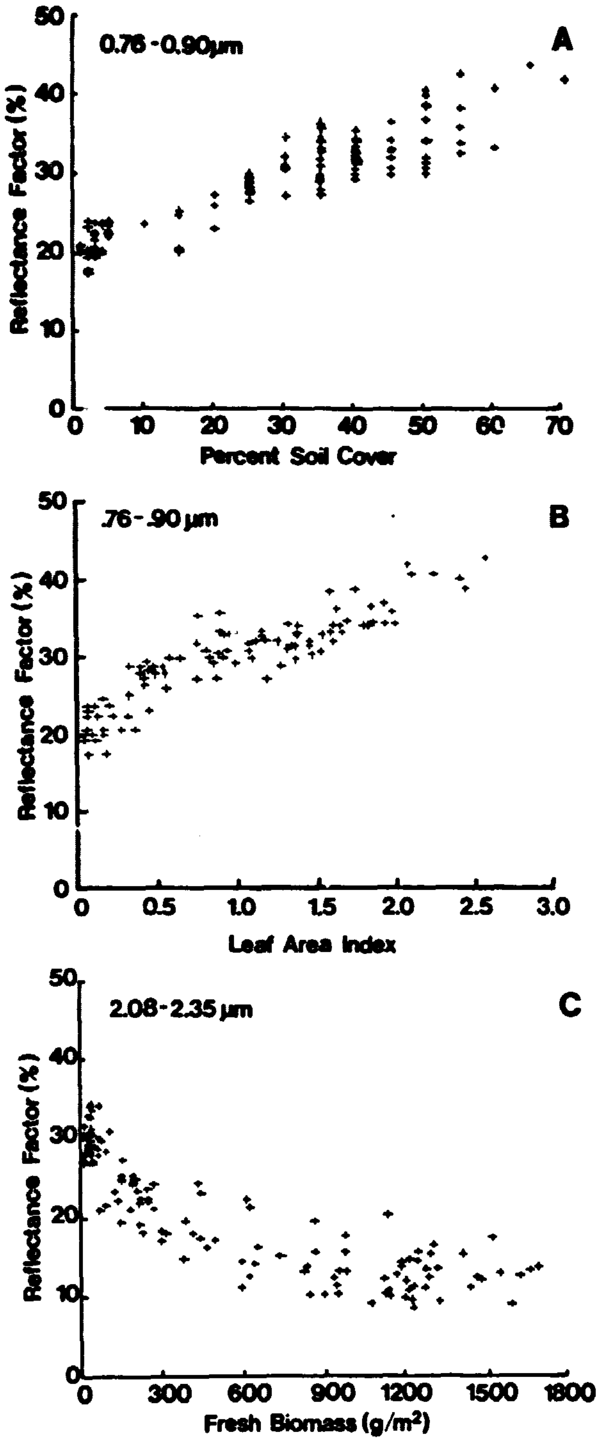

Fig. 4. Relationships of percent soil cover, leaf area index, and fresh biomass to reflectances of spring wheat canopies. Measurements for seedling through flowering stages of maturity are included for 16 treatments representing different levels of soil moisture availability, planting dates, nitrogen fertilization rates, and cultivars.

Table 1. Linear correlations of reflectances in the Landsat MSS and TM wavelength bands and transformations with agronomic characteristics of spring wheat canopies (1976).

Spectral Variable	Percent Soil Cover	Leaf Area Index	Fresh Biomass	Dry Biomass	Plant Water Content
Landsat MSS					
0.5-0.6	-0.82	-0.79	-0.81	-0.76	-0.81
0.6-0.7	-0.90	-0.85	-0.81	-0.74	-0.82
0.7-0.8	0.84	0.84	0.57	0.46	0.60
0.8-1.1	0.91	0.90	0.77	0.68	0.79
Thematic Mapper					
0.45-0.52	-0.82	-0.79	-0.75	-0.69	-0.76
0.52-0.60	-0.82	-0.78	-0.81	-0.77	-0.82
0.63-0.69	-0.91	-0.86	-0.80	-0.73	-0.81
0.76-0.90	0.93	0.92	0.76	0.67	0.79
1.55-1.75	-0.85	-0.80	-0.83	-0.79	-0.84
2.08-2.35	-0.91	-0.85	-0.86	-0.81	-0.86
Transformations					
IR/Red*	.89	.90	.76	.67	.78
IR - Red	.95	.93	.81	.72	.83
Normalized Difference	.95	.90	.82	.74	.83
Greenness	.90	.89	.68	.58	.70

* Red = 0.63-0.69 μm, IR - 0.76-0.90 μm

the maximum soil cover was 70%, the relationship of soil cover to near infrared reflectance and several of the transformations (e.g. IR/red ratio, ND, and greenness) was linear.

The 0.76-0.90 μm wavelength band (Fig. 4b) and several of the transformations (Table 1) were also strongly related to green LAI. The near infrared reflectance was sensitive to increases in green LAI up to an LAI of 3 throughout the spring wheat growing season (Fig. 6). The 0.63-0.69 μm and 0.45-0.52 μm wavelength bands (not shown) were only sensitive to increases up to an LAI of 2, and the 0.52-0.60, 1.55-1.75 and 2.08-2.35 μm wavelength bands (also not shown) were sensitive to changes in LAI only through the range of 0-1. Lower sensitivity of the chlorophyll and water absorption regions to leaf area and biomass compared to the near infrared region has also been reported by Tucker (1977).

Biomass was more strongly related to reflectances of spectral bands in the green, red, and middle infrared regions of the spectrum than reflectance in the near infrared (Table 1). However, the reflectance in each of these bands was sensitive to changes in fresh and dry biomass only through the first 500 and 200 g/m^2, respectively, after which reflectance was unrelated to further increases in biomass (Fig. 4c).

From these relationships, along with the relationships of near infrared reflectance to percent soil cover and LAI, we conclude that the spectral measurements appear not to be related to the amount of total biomass present, but rather to the amount of green vegetation, particularly leaves. In the first part of the growing season, fresh and dry biomass were highly correlated with reflectance because the amount of green leaf area increased proportionally to the increase in biomass. However, after the plants reached their maximum leaf area (flowering stage), the amount of green vegetation decreased while total dry biomass increased.

Plant water content was most strongly related to middle infrared reflectance. Plant water content, which was highly correlated with fresh biomass ($r = 0.98$), had slightly higher correlaticns with reflectance than fresh biomass (Table 1). Percent water content was not highly correlated with any spectral variable.

The correlations of canopy variables with reflectanes in the MSS bands were usually less than for the corresponding TM bands. The higher correlations for the TM bands is attributed to the more optimum width and location of the bands with respect to the spectral characteristics of vegetation. For example, inclusion in the 0.7-0.8 µm band of the wavelengths in the transition from the chlorophyll absorption region of the spectrum to the highly reflecting near infrared region weakens the relationship to canopy variables compared to that found with 0.8-1.1 and the 0.76-0.90 µm bands. Similar effects have been reported by Tucker and Maxwell (1976).

Several investigators have examined the use of ratios, particularly the infrared/red ratio, and other transformations of two or more spectral bands to enhance the relationship between spectral and agronomic properties of vegetative canopies. Compared to single wavelength bands, these investigators have generally found stronger relationships using infrared/red ratios, radiance differences, various vegetation indices, and the greenness transformation (Jackson et al., 1983; Tucker, 1979). The transformations also have the effect of normalizing measurements acquired under varying conditions. However, since our data were acquired over one soil on clear days at relatively uniform (high) sun angles that advantage of the transforms was probably minimal and correlations of the canopy variables with the transforms were not significantly larger than the highest individual bands. The various transforms were all found to be highly correlated with each other and it was difficult to determine that any specific one is superior.

Prediction of Canopy Variables

Estimation of canopy variables from multispectral data for use in crop growth and yield models is an important potential application of multispectral remote sensing (Wiegand et al., 1979). Understanding the relation of agronomic properties of crop canopies to reflectance in various regions of the spectrum, as discussed above, leads to the development of models for estimating canopy variables from reflectance measurements in several wavelength bands. Table 2 shows results using selections of the best one to six wavelength bands for predicting several canopy variables. The ability to predict each canopy variable generally increased as additional bands were added. By computing all possible regressions, the best subset of spectral bands of each size was selected considering the amount of variability explained and the bias of the resulting regression equation.

The near and middle infrared bands were found to be most important in explaining the variation in canopy variables. For LAI and percent

Table 2. Selection of combinations of the best 1, 2, . . .6 wavelength bands for estimating percent soil cover, leaf area index, and fresh biomass during the seedling through flowering stages of development.

Canopy Variable	No. Bands Entered	R^2	C_p*	Bands Entered (µm) 0.45-0.52	0.52-0.60	0.63-0.69	0.76-0.90	1.55-1.75	2.08-2.35
Percent	1	.86	132				X		
Soil	2	.92	16				X		X
Cover	3	.92	15	X			X		X
	4	.93	4	X	X		X		X
	5	.93	5	X	X	X	X		X
	6	.93	7	X	X	X	X	X	X
Leaf	1	.84	37				X		
Area	2	.87	7				X	X	
Index	3	.88	2				X	X	X
	4	.88	4	X			X	X	X
	5	.88	5	X	X		X	X	X
	6	.88	7	X	X	X	X	X	X
Fresh	1	.73	239						X
Biomass	2	.76	211		X				X
	3	.83	109		X	X			X
	4	.88	41		X	X	X		X
	5	.90	12	X	X	X	X		X
	6	.93	7	X	X	X	X	X	X

* The regression equation is unbiased when the 'C_p' value is equal to or less than the number of terms in the equation.

soil cover, the 0.76-0.90 µm wavelength band accounted for more of the variation than any other single band. The 2.08-2.35 µm wavelength band was one of the two most important in explaining the variation in percent soil cover and one of the three most important bands explaining the variation in LAI.

Of the three best bands for predicting a variable, each one was almost always from a different region of the spectrum, illustrating the importance of collecting spectral information in several different regions of the spectrum. Similar results were reported by MacDonald et al. (1972) who found that the four most important wavelength bands for discriminating levels of southern corn leaf blight severity were, one each, from the visible, near infrared, middle infrared and thermal infrared regions of the spectrum.

In Table 2 the difference between the number of bands entered that produce a near maximum R^2 the number of bands entered where the resulting prediction equation is unbiased can also be examined. An unbiased equation (based on the data entered) results when the C_p value is equal to or less than the number of terms in the resulting regression equation (Mallows, 1973). For LAI and percent soil cover, the near maximum R^2 value was reached after the entry of three of the six possible TM bands. However, the C_p values indicate that three bands would need to be used to produce an unbiased prediction of LAI and four bands would be necessary for percent soil cover. Percent soil cover and LAI are potentially much easier to estimate than the other variables because they have a higher correlation with reflectance in the single wavelength bands and their prediction equations became unbiased before all of the possible terms (bands) were entered.

The agreement between the measured and predicted values for LAI and percent soil cover for the 1976 data is shown in Fig. 5. The deviation from the 1:1 line is relatively small considering all the potential sources of variation; these include: (1) measurement errors in the agronomic variables, (2) plant development stage has an effect on reflectance (for example, a canopy with an LAI of 1.0 early in the season has a different spectral response than a canopy with an LAI of 1.0 later in the season), (3) variation caused by the different agronomic treatments, and (4) varying solar zenith and azimuth angles at the time of day data were collected has some effect due to shadowing within the canopy on canopy reflectance (Jackson et al., 1979). Despite the variation induced by each of these factors, measurements in a small number of wavelength bands in important regions of the spectrum did explain much of the variation in and result in satisfactory predictions of canopy variables.

The only true test for a prediction equation is whether it can accurately predict the same variable measured in an independent data set. Prediction equations that used the reflectances in three to five bands (see Table 2) to explain the variation in 1976 were applied to similar data collected in 1975 and 1977. The relatively high agreement found between the measured and predicted canopy variables (Table 3) indicates the potential for developing prediction equations that can be applied to data collection any year.

Table 4 shows the maximum R^2 value obtainable using the MSS bands, the best four of the six possible TM bands, and then all six TM bands to predict each canopy variable. In every case the best four of six TM

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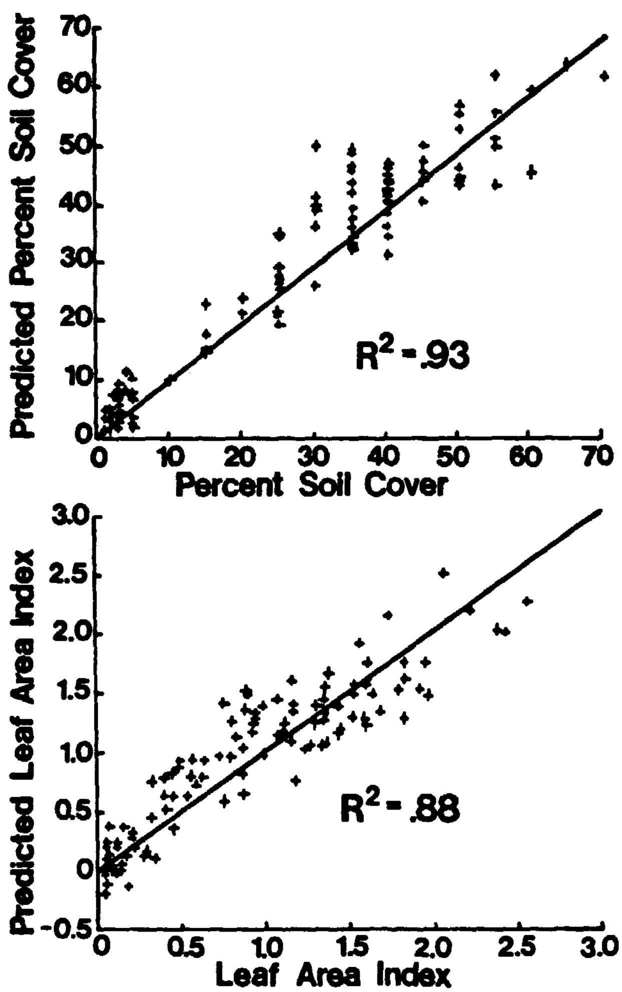

Fig. 5. Comparison of measured and predicted percent soil cover and leaf area index of spring wheat canopies (1976 data).

Table 3. Comparisons (R^2) of measured and predicted canopy variables for 1975, 1976 and 1977 measurements using prediction equation developed from 1976 data acquired in the thematic mapper bands.

Canopy Variable	Year 1975	Year 1976	Year 1977
Percent soil cover	.70	.93	.86
Leaf area index	-	.88	.74
Fresh biomass	-	.88	.81
Dry biomass	-	.84	.73
Plant water content	-	.88	.84

Table 4. The R^2 values for predictions of percent soil cover, leaf area index, fresh and dry biomass, and plant water content with four Landsat MSS bands, the best four thematic mapper bands, and the six thematic mapper bands (1976 data).

Wavelength Bands	Percent Soil Cover	Leaf Area Index	Fresh Biomass	Dry Biomass	Plant Water Content
MSS Bands	0.91	0.86	0.86	0.84	0.85
Best Four TM Bands*	0.93	0.88	0.88	0.84	0.88
Six TM Bands	0.93	0.88	0.91	0.88	0.90

* See Table 2.

bands explained more of the variation in a canopy variable than the four MSS bands. Addition of the other two TM bands usually resulted in only small increases in the R^2 values. This indicates that four optimally selected wavelength bands have potential to explain most of the variation in many crop canopy variables. However, it should be emphasized that the best wavelength bands for explaining the variation in each canopy variable are not always the same, necessitating bands in all important regions of the spectrum to select from.

SUMMARY AND CONCLUSIONS

Strong relationships between spectral response and percent soil cover, LAI, biomass and plant water content were found. Because the relationships are adversely influenced by crop senescence, the best time period for assessing these canopy variables is from the tillering to heading stages of development. Prior to tillering, the spectral response is strongly dominated by the soil background. As the crop begins to ripen after heading, the spectral sensitivity to measures such as LAI, biomass, and plant water content decrease.

The correlations of the TM spectral bands with crop canopy variables were greater than for the corresponding MSS bands. The difference is attributed to the narrower and more optimal placement of the thematic mapper bands in relation to the spectral characteristics of vegetation. Prediction equations developed to explain the variation in crop canopy variables showed that the near infrared band (0.76-0.90 µm) explained the most variation in LAI and percent soil cover and that the

2.08-2.35 μm wavelength band was the single most important band in explaining the variation in fresh biomass, dry biomass, and plant water content. The results demonstrate the importance of spectral measurements in the middle infrared wavelength region, as well as the visible and near infrared, for monitoring crop condition.

The strong relationship between spectral reflectance and several crop canopy variables demonstrates the potential of multispectral remote sensing to monitor crop growth and condition. Future research needs to investigate the sensitivity of the relationships to different agronomic treatments and determine whether important cultural practices are spectrally separable. The relatively simple regression equations developed in this study need to be converted to more physically based models of the relationships between spectral and agronomic variables.

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