070378

Submitted to Proc. Int'l. Symp. on Remote Sensing for Observation and Inventory of Earth Resources and Environment. July 2-8, 1978. Freiburg, West Germany.

RELATION OF CROP CANOPY VARIABLES TO THE MULTISPECTRAL REFLECTANCE OF SMALL GRAINS

J. S. Ahlrichs, M. E. Bauer, M. M. Hixson,
C. S. T. Daughtry, and D. W. Crecelius

Purdue University
Laboratory for Applications of Remote Sensing
West Lafayette, Indiana U.S.A.

Abstract

Reflectance spectra over the wavelength range 0.4-2.5 μm were acquired during each of the major development stages of spring wheat canopies. Treatments in the experiment included planting date, nitrogen fertilization, cultivar, and soil moisture. Agronomic characterization of the wheat canopies included measurements of maturity stage, plant height, fresh and dry biomass, leaf area index, and percent soil cover. Analysis of variance, correlation, and regression analyses were used to relate the agronomic variables to reflectance.

Strong relationships were found between reflectance and percent soil cover, leaf area index, biomass, and plant water content. A middle infrared wavelength band, 2.08-2.35 μm, was most important in explaining variation in fresh and dry biomass and plant water content, while a near infrared band, 0.76-0.90 μm, explained the most variation in percent soil cover and leaf area index. The relationship of canopy variables to reflectance, however, is influenced by the maturity stage of the crop and decreases as the crop begins to ripen. The canopy variables could be accurately predicted using measurements from three to five wavelength bands. The reflective wavelength bands proposed for the thematic mapper sensor were more strongly related to and better predictors of the canopy variables than the Landsat MSS bands.

Introduction

Crop identification and area estimation promises to be one of the major applications of remote sensing and the Large Area Crop Inventory Experiment (LACIE) has pushed the technology to near operational use for wheat (MacDonald et al., 1978). Remote sensing also offers great potential for obtaining accurate and timely information about the condition and yield of crops (Bauer, 1975).

To fully realize the potential of remote sensing for crop identification, condition assessment, and yield prediction it is important to understand and quantify the relation of agronomic characteristics of crops to their multispectral reflectance properties. For example, it is essential to know in which regions of the spectrum information relating to variations in crop parameters is contained. This information is necessary for the optimum use of current Landsat technology, as well as for the design and development of future remote sensing systems.

Differences among crop species and dynamic changes due to growth, development, stress, and varying cultural practices cause differences in the reflectance spectra of crops.

Many of the factors affecting the reflectance properties of plant leaves have been identified and investigated utilizing laboratory measurements. The relationships of physical-biological parameters such as chlorophyll concentration, water content and leaf morphology to reflectance, transmittance and absorption have been well-established for leaves. Some of the papers and reviews describing these relationships include: Gates et al. (1965), Breece and Holmes (1971), Gausman et al. (1970), and Sinclair et al. (1971).

Knowledge of the reflectance characteristics of single leaves is basic to understanding the reflectance properties of crop canopies in the field, but cannot be applied directly since there are significant differences in the spectra of single leaves and canopies. The reflectance characteristics of canopies are considerably more complex than those of single leaves because there are many more interacting variables in canopies. Some of the more important agronomic parameters influencing the reflectance of field-grown canopies are: leaf area index, biomass, leaf angle, soil cover percentage, soil color, and leaf color. Differences in these parameters are caused by variations in many cultural and environmental factors, including planting date, cultivar, seeding rate, fertilization, soil moisture, and temperature. Solar elevation and azimuth angle and the view angle and direction of the sensor also affect the measured reflectance of crops and soils.

The spectral and agronomic measurements which have been acquired during the three years of the LACIE field research program are being analyzed to provide an understanding of the relationship of reflectance to the biological and physical characteristics of crops and soils. The primary data analyzed to date are the spectrometer data acquired by the truck- and helicopter-borne systems. These data are particularly useful because the spectral data were acquired in 0.01 μm wavelength intervals and are calibrated in terms of bidirectional reflectance. Having the entire spectrum from 0.4 to 2.4 μm permits simulation of the response in any specified waveband. In other words, the analysis is not restricted to a fixed set of bands such as Landsat MSS or one of the aircraft scanner systems. Calibration of the data permits valid comparisons to be made among different dates, locations, and sensors.

The overall objective of the analyses being conducted is to quantitatively determine the spectral-temporal characteristics of wheat, small grains, and other agricultural crops. The specific objectives of the analyses reported here are:

1. To examine the effects of cultural and environmental factors on the spectral response of spring wheat.

2. To determine the relationship of agronomic variables such as biomass and leaf area index to multispectral reflectance of spring wheat.

Experimental Approach

The data used for these analyses were collected using a truck-mounted spectrometer during the first two years of the LACIE field research program at the agriculture experiment station at Williston, North Dakota. Measurements were made at approximately weekly intervals of the bidirectional reflectance factor and agronomic characteristics of 32 plots of spring wheat (Robinson *et al.*, 1978). The design of the experiment was a 2^4 factorial with two replications. The factors and levels were:

Soil Moisture: (1) wheat during previous year, (2) fallow during previous year.

Planting Date: (1) early, (2) late.

Cultivar: (1) standard height, (2) semi-dwarf.

Nitrogen Fertilization: (1) None, (2) 34 kg/ha.

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.

In addition to reflectance, the following agronomic variables were measured: maturity stage, height, percent soil cover, leaf area index, percent green leaves, fresh and dry biomass, and plant water content (difference between fresh and dry biomass). Vertical and oblique photographs were taken of each plot on each measurement date.

After processing, graphs of the spectral data were examined to verify data quality and qualitatively assess the information contained in the spectra. Correlation and regression analyses were used to relate biological and physical variables describing the canopies to spectral response.

Since the application of remotely sensed spectral measurements will be with multispectral scanner systems which measure the spectral response in selected wavelength bands, the statistical analyses were performed using wavelength bands. Two different sets of bands were considered, Landsat MSS and Landsat thematic mapper. The thematic mapper is a second generation satellite multispectral scanner system planned for Landsat-D which is to be launched in 1981. The Landsat MSS bands are: 0.5-0.6 (green), 0.6-0.7, (red), 0.7-0.8 (near infrared), and 0.8-1.1 μm (near infrared). The thematic mapper 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 thematic mapper will also have a thermal infrared band, but thermal measurements were not acquired for this experiment.

Results and Discussion

One of the major long term goals of agricultural remote sensing research is to estimate or predict crop variables that can subsequently be used to assess crop vigor or be entered into a yield prediction model. To achieve this goal the complex relationship between the spectral reflectance of crop canopies and their biological and physical characteristics must be understood.

The effects of agronomic treatments on the spectra of spring wheat and the relation of canopy variables to multispectral reflectance were investigated. This information was used to develop equations for predicting canopy variables from reflectance data. The analyses were performed using wavelength bands of the current and future satellite multispectral scanner systems.

Effect of Agronomic Factors on Spectral Reflectance

The crop canopy is a dynamic entity influenced by many cultural and environmental factors. The factors investigated in this experiment were available soil moisture, planting date, nitrogen fertilization, and cultivar. Several examples of spectra are shown in Figure 1 to illustrate the effect of the individual treatments on selected measurement dates.

Each of the different treatment levels was compared to the Waldron (standard height) cultivar, early planting date, with nitrogen fertilization. The spectra were measured on June 18, 1976 during the stem extension phase of development, except for the comparison of cultivars which was on July 16, after heading.

In 1976 the effect of available soil moisture on plant growth and spectral response was quite significant. Wheat planted on fallow land had more tillers and, therefore, greater biomass, leaf area, and percent soil cover than the wheat crop grown on land which had been cropped the previous year. These differences account for the decreased visible, increased near infrared, and decreased middle infrared reflectances for fallow treatment.

The effect of planting date on spectral response is also illustrated in Figure 1. The differences are attributed primarily to differences in the amount of vegetation present, as well as differences in maturity stage.

Adding nitrogen fertilizer increased the amount of green vegetation early in the growing season. The fertilized treatment had the spectral characteristics of a greener, denser vegetative canopy: decreased red reflectance, slightly greater near infrared reflectance, and reduced middle infrared reflectance.

The two wheat cultivars, Olaf (semi-dwarf, awned) and Waldron (standard height, awnless), were similar in appearance before heading. After heading, some differences between the two cultivars were visually apparent, but are probably not significant. The greatest differences were in the middle infrared, indicating a difference in the moisture and biomass between the two cultivars at this growth stage.

These spectra emphasize that the wheat canopy is very dynamic and that the spectral reflectance of a canopy is influenced by many cultural factors. More quantitative analyses of the effect of agronomic treatments and environmental variables on reflectance of wheat are currently being conducted.

Relation of Canopy Variables to Multispectral Reflectance

The primary objectives of this study were to determine the relationship of canopy variables to reflectance and to assess the potential for estimating them from remotely sensed measurements of reflectance. The canopy variables selected for analysis are indicators of crop vigor and growth which could be inputs to a yield model and which preliminary analyses showed were most strongly related to spectral response. In the remainder of the paper the effect of varying amounts of vegetation and maturity stage on the spectra of wheat canopies, the relationship of canopy variables to reflectance in different regions of the spectrum, and the potential capability to predict canopy variables from reflectance measurements are examined. As part of the analysis the wavelength bands of current and proposed future satellite multispectral scanner systems were compared.

The amount of vegetation present is one of the principal factors influencing the reflectance of crop canopies. Figure 2 illustrates the effect of amount of vegetation as measured by leaf area index, 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 chlorophyll absorption region, increase in the near infrared reflectance, and decrease in the middle infrared reflectance.

Plant development and maturity (as opposed to growth or increase in size) cause many changes in canopy geometry, moisture content, and pigmentation of leaves which are also manifested in the reflectance characteristics of canopies. Figure 3 shows the spectra of spring wheat at several different maturity stages. A plot of spectral responses through the season in selected wavelength bands is shown in Figure 4. The temporal pattern of changes in spectral response has been demonstrated by the LACIE project to be an important feature for identifying wheat from Landsat MSS data.

Plant maturity affects canopy reflectance throughout the growing season; however, the variation early in the growing season caused by different planting dates was considerably reduced by the time of plant heading. Percent soil cover, leaf area index, and plant water content had high linear correlations with reflectance in most wavelength bands and reflectance was sensitive to changes in these variables throughout the growing season. On the other hand, reflectance was only sensitive to changes in fresh and dry biomass early in the season. The 0.76-0.90 μm wavelength band has a high correlation with each crop canopy variable early in the growing season indicating a sensitivity to small amounts of biomass. As the canopy begins to ripen there was a significant decrease in the capability to estimate the amount of vegetation present. Leamer _et al._ (1978) reported a similar decrease in the correlation of spectral response with canopy variables after heading for winter wheat.

Correlation of Canopy Variables with Reflectance

The linear correlation of the five different crop canopy variables with the thematic mapper and Landsat MSS bands are summarized in Table 1. The relationships of four of these with spectral reflectance are illustrated in Figures 5 and 6. Percent soil cover, leaf area index, and plant water have a high correlation with spectral reflectance in each of the six thematic mapper bands (Figures 5 and 6). The relationship of reflectance to fresh and dry biomass is non-linear, resulting in lower correlation values (Figure 6).

The middle infrared band, 2.08-2.35 μm, has the highest correlation of the six individual thematic mapper bands with fresh biomass, dry biomass, and plant water, and is highly correlated with leaf area index and percent soil cover. These results illustrate the importance of making measurements in several regions of the spectrum, especially in the middle infrared wavelength region which is not measured by the present Landsat multispectral scanners.

Correlations of the four Landsat MSS bands with the same five crop canopy variables are also shown in Table 1. The correlation of canopy variables with each Landsat MSS band is less than with the corresponding thematic mapper band. The lower correlation is attributed to the width and location of the bands with respect to the spectral characteristics of vegetation.

For example, the data in Table 1 demonstrate a disadvantage of collecting data in the 0.7-0.8 μm wavelength region. The inclusion of the region of rapid transition from the chlorophyll absorption region of the spectrum to the highly reflecting near infrared region (0.70-0.74 μm) results in a weaker relation between reflectance and the crop canopy variables. Similar results were reported by Tucker and Maxwell (1975). This region of low correlation reduces the ability of the 0.7-0.8 μm wavelength region to estimate crop canopy variables. The 0.8-1.1 μm wavelength band has a greater correlation with each of the agronomic factors than the 0.7-0.8 μm wavelength band, and the 0.76-0.90 μm wavelength band has a correlation with each agronomic factor that is greater than either the 0.7-0.8 or the 0.8-1.1 μm wavelength bands.

In Figures 5 and 6 the relationship of several canopy variables to reflectance in selected wavebands is plotted. These plots include data from all treatments when green leaves were present (seedling to approximately the milk stages of maturity). Plotting the spectral reflectance versus canopy variables allows visual assessment of the relation of canopy variables and reflectance, and permits better interpretation of the correlation analyses (Table 1).

Percent Soil Cover: Percent soil cover (Figure 6) consistently had the highest correlation with reflectance in each wavelength band (Table 1). Since the reflectance in each band was sensitive to changes in percent soil cover throughout the growing season and the relationship between percent soil cover and reflectance was almost linear in the range of 0-70 percent, this crop canopy variable has great potential to be accurately estimated by spectral measurements.

Leaf Area Index: The 0.76-0.90 μm wavelength band was the best single band for explaining the variation in green leaf area index (LAI) because the reflectance is sensitive to changes in LAI throughout the entire spring wheat growing season (Figure 5). The reflectance in other wavelength bands is not as sensitive to changes in leaf area (Table 1). The lower sensitivity of the chlorophyll absorption band to leaf area and biomass has also been reported by Colwell (1974) and Tucker (1977).

Fresh and Dry Biomass: The reflectance in each of the bands is sensitive to changes in dry biomass only through the first 200 g/m^2, after which the data were basically uncorrelated with reflectance. The trends shown in Figure 6 and other graphs result because the collected spectral measurements appear not to be related to the amount of total biomass present, but rather to the amount of photosynthetically active (green) vegetation present. Dry biomass was initially highly correlated with reflectance because the amount of green leaves increased proportional to the increase in biomass. However, after the plants reached their maximum biomass (which, in these data, was the boot stage), the amount of green vegetation decreased at a rate that was not correlated with further increase in total dry biomass. The relationship between fresh biomass and reflectance in each of the bands was very similar to that for dry biomass.

Plant Water: Plant water content (Figure 6), which is one indicator of the amount of photosynthetically active vegetation, was highly correlated with reflectance in each wavelength band. Reflectance was sensitive to changes in plant water throughout the growing season, resulting in a much higher correlation than fresh or dry biomass. Another measure of plant moisture analyzed was percent moisture. Early in the growing season the percent plant moisture was high, and due to the sparse ground cover, the near infrared reflectance was low. As the plants grew, the plant moisture remained around 80 percent while the amount of green vegetation and the near infrared reflectance increased to a maximum. Therefore, there was no correlation between the spectral data and percent plant moisture early in the growing season. When heading occurs and the leaves begin to senesce, the percent plant moisture begins to decrease along with the near infrared reflectance.

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. Understanding the relation of agronomic properties of crop canopies to reflectance in various regions of the spectrum leads to the development of regression models for estimating canopy variables from measurements in several wavelength bands.

Table 2 shows results using selections of one to six wavelength bands for prediction of canopy variables. By computing all possible regressions, the best subset 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 leaf area index and percent soil cover, the 0.76-0.90 μm wavelength band accounts for more of the variation than any other single band. The 2.08-2.35 μm wavelength band is the single most important band in explaining the variation in fresh biomass, dry biomass, and plant water. The 2.08-2.35 μm wavelength band is one of the two most important bands in explaining the variation in percent soil cover and one of the three most important bands explaining the variation in leaf area index.

From Table 2 the difference between the number of bands entered that produce a near maximum R^2 and the number of bands entered where the resulting prediction equation is unbiased can also be examined. An unbiased equation results when the 'C_p' value is equal to or less than the number of terms in the resulting regression equation (Mallows, 1973). For leaf area index and percent soil cover, the near maximum

R^2 value is reached after the entry of three out of the six possible thematic mapper bands. However, the 'C_p' values indicate that five bands would have to be used to have an unbiased prediction of leaf area index and four bands would be necessary for percent soil cover.

The agreement between the measured and predicted leaf area index is shown in Figure 7. Similar results were obtained for the other canopy variables. There are several factors that make a perfect prediction impossible for these data, including: (1) the agronomic measurements of the crop canopy were subject to measurement error, (2) plant maturity 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) the data that the prediction equations are derived from contains variation induced by the different agronomic treatment levels, and (4) the time of day that the data were collected may have some effect on canopy reflectance. Despite the variation induced by each of these factors, measurements in a small number of wavelength bands in important regions of the spectrum can explain much of the variation in canopy variables and thus, result in satisfactory predictions of canopy variables.

Table 3 shows the maximum R^2 value obtainable using the Landsat bands, the best four out of the six possible thematic mapper bands, and then all six thematic mapper bands to predict each canopy variable. In every case the best four out of six thematic mapper bands explained more of the variation in a canopy variable than the four Landsat bands. Addition of the other two thematic mapper bands resulted in only small increases in the R^2 values.

Summary and Conclusions

Spectral and agronomic measurements of spring wheat canopies were analyzed to determine the relation of agronomic properties of crop canopies to their spectral reflectance. Initial analyses showed that several agronomic treatments such as soil moisture and nitrogen fertilization affect the spectra of wheat. A strong relationship between spectral response and percent soil cover, leaf area index, biomass and plant water content was found. The relationship, however, is influenced by crop maturity. 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 and, as the crop begins to ripen, the spectral sensitivity to measures such as leaf area index, biomass, and plant water content decreases.

In each wavelength region, the correlation of the thematic mapper band with crop canopy variables was greater than that of the corresponding Landsat MSS band. Prediction equations developed to explain the variation in crop canopy variables showed 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; whereas, the near infrared band (0.76-0.90 μm) explained the most variation in leaf area index and percent soil cover. The results demonstrate the importance of collecting spectral information in the middle infrared wavelength region, as well as the visible and near infrared, for crop studies.

The R^2 values for comparisons of measured and predicted canopy variables ranged from 0.80 to 0.91 when three or more spectral bands were included, indicating the potential for using remotely sensed spectral measurements to characterize the status of crops. Analyses showed that the best four thematic mapper bands could estimate crop canopy variables as well or better than the four Landsat bands. The difference is attributed to the narrower and more optimum placement of the thematic mapper bands in relation to the spectral characteristics of vegetation.

The strong relationship between spectral reflectance and different crop canopy variables illustrates the potential to monitor crop development and predict yield. Future research needs to investigate the amount of variation induced by different agronomic treatment factors on spectral reflectance and whether important treatment factors are spectrally separable. The type of prediction equations developed in this thesis need to be extended to several years of data, then used to estimate independent data sets.

References

Bauer, M. E. 1975. The Role of Remote Sensing in Determining the Distribution and Yield of Crops. Advances in Agronomy 27:271-304.

Breece, H. T., and R. A. Holmes. 1971 Bidirectional scattering characteristics of healthy green soybean and corn leaves _in vivo_. Applied Optics 10:119-127.

Colwell, J. E. 1974a. Vegetation Canopy Reflectance. Remote Sensing of Environment 3:175-183.

Gates, D. M., H. J. Keegan, J. C. Schleter, and V. R. Weidner. 1965. Spectral Properties of Plants. Applied Optics 4:11-20.

Gausman, H. W., W. A. Allen, and C. L. Wiegand. 1972. Plant Factors Affecting Electromagnetic Radiation. Soil and Water Conserv. Res. Rep. 342. Agr. Res. Service, U.S. Dept. of Agr., Weslaco, Texas.

Leamer, R. W., J. R. Noriega, and C. L. Wiegand. 1978. Seasonal Changes in Reflectance of Two Wheat Cultivars. Agronomy Journal 70:113-118.

Mallows, C. L. 1973. Some Comments on Cp. Technometrics 15:661-675.

MacDonald, R. B., F. G. Hall, and R. B. Erb. 1978. The LACIE Experience - - A Summary. Proc. Int'l. Symp. on Remote Sensing for Observation and Inventory of Earth Resources and Environment. July 2-8, 1978. Freiburg, Federal Republic of Germany.

Robinson, B. F., M. E. Bauer, L. L. Biehl, and L. F. Silva. 1978 The Design and Implementation of a Multiple Instrument Field Experiment to Relate the Physical Properties of Crops and Soils to their Multispectral Reflectance. Proc. Int'l. Symp. on Remote Sensing for Observation and Inventory of Earth Resources and Environment. July 2-8, 1978. Freiburg, Federal Republic of Germany.

Sinclair, T. R., R. M. Hoffer, and M. M. Schreiber. 1971. Reflectance and Internal Structure of Leaves from Several Crops During a Growing Season. Agronomy Journal 63:864-868.

Tucker, C. J. 1977. Spectral Estimation of Grass Canopy Variables. Remote Sensing of Environment. 6:11-26.

Tucker, C. J., and E. L. Maxwell. 1976. Sensor Design for Monitoring Vegetation Canopies. Photogrammetric Engineering and Remote Sensing 42:1399-1410.

Acknowledgements

The research reported in this paper was sponsored by the National Aeronautics and Space Administration, contracts NAS9-14970 and NAS9-15466.

Date of paper preparation: July, 1978.

Table 1. The linear correlations (r) of the proposed thematic mapper and Landsat MSS wavelength bands with percent soil cover, leaf area index, fresh and dry biomass, and plant water content.

Wavelength Band (μm)	Percent Soil Cover	Leaf Area Index	Fresh Biomass	Dry Biomass	Plant Water Content
Thematic Mapper					
0.45-0.52	-0.79	-0.75	-0.69	-0.54	-0.74
0.52-0.60	-0.78	-0.74	-0.74	-0.59	-0.78
0.63-0.69	-0.84	-0.83	-0.67	-0.48	-0.75
0.76-0.90	0.91	0.89	0.68	0.48	0.76
1.55-1.75	-0.81	-0.76	-0.76	-0.61	-0.80
2.08-2.35	-0.89	-0.81	-0.81	-0.66	-0.85
Landsat MSS					
0.5-0.6	-0.79	-0.75	-0.74	-0.59	-0.78
0.6-0.7	-0.84	-0.82	-0.68	-0.49	-0.76
0.7-0.8	0.79	0.80	0.47	0.27	0.55
0.8-1.1	0.90	0.87	0.70	0.52	0.77

Table 2. Selection of combinations of the best 1, 2,...6 wavelength bands for estimating percent soil cover, leaf area index, fresh biomass, dry biomass, and plant water content.

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 Soil Cover	1	.82	148				X		
	2	.90	17				X		X
	3	.90	13				X	X	X
	4	.91	3	X	X		X		X
	5	.91	5	X	X	X	X		X
	6	.91	7	X	X	X	X	X	X
Leaf Area Index	1	.80	62				X		
	2	.84	22			X	X		
	3	.86	6				X	X	X
	4	.86	7			X	X	X	X
	5	.86	5		X	X	X	X	X
	6	.86	7	X	X	X	X	X	X
Fresh Biomass	1	.65	279						X
	2	.68	257			X			X
	3	.81	83		X	X			X
	4	.85	31		X	X	X		X
	5	.87	14	X	X	X	X		X
	6	.87	7	X	X	X	X	X	X
Dry Biomass	1	.43	364						X
	2	.51	291			X			X
	3	.79	40		X	X			X
	4	.81	18		X	X		X	X
	5	.82	9	X	X	X		X	X
	6	.83	7	X	X	X	X	X	X
Plant Water Content	1	.72	200						X
	2	.74	177				X		X
	3	.80	104		X	X			X
	4	.85	36		X	X	X		X
	5	.87	9	X	X	X	X		X
	6	.88	7	X	X	X	X	X	X

Table 3. 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.

Wavelength Bands	Percent Soil Cover	Leaf Area Index	Fresh Biomass	Dry Biomass	Plant Water Content
Landsat MSS Bands	0.86	0.84	0.82	0.75	0.84
Best Four Thematic Mapper Bands	0.91	0.86	0.85	0.81	0.85
Six Thematic Mapper Bands	0.91	0.86	0.87	0.83	0.88

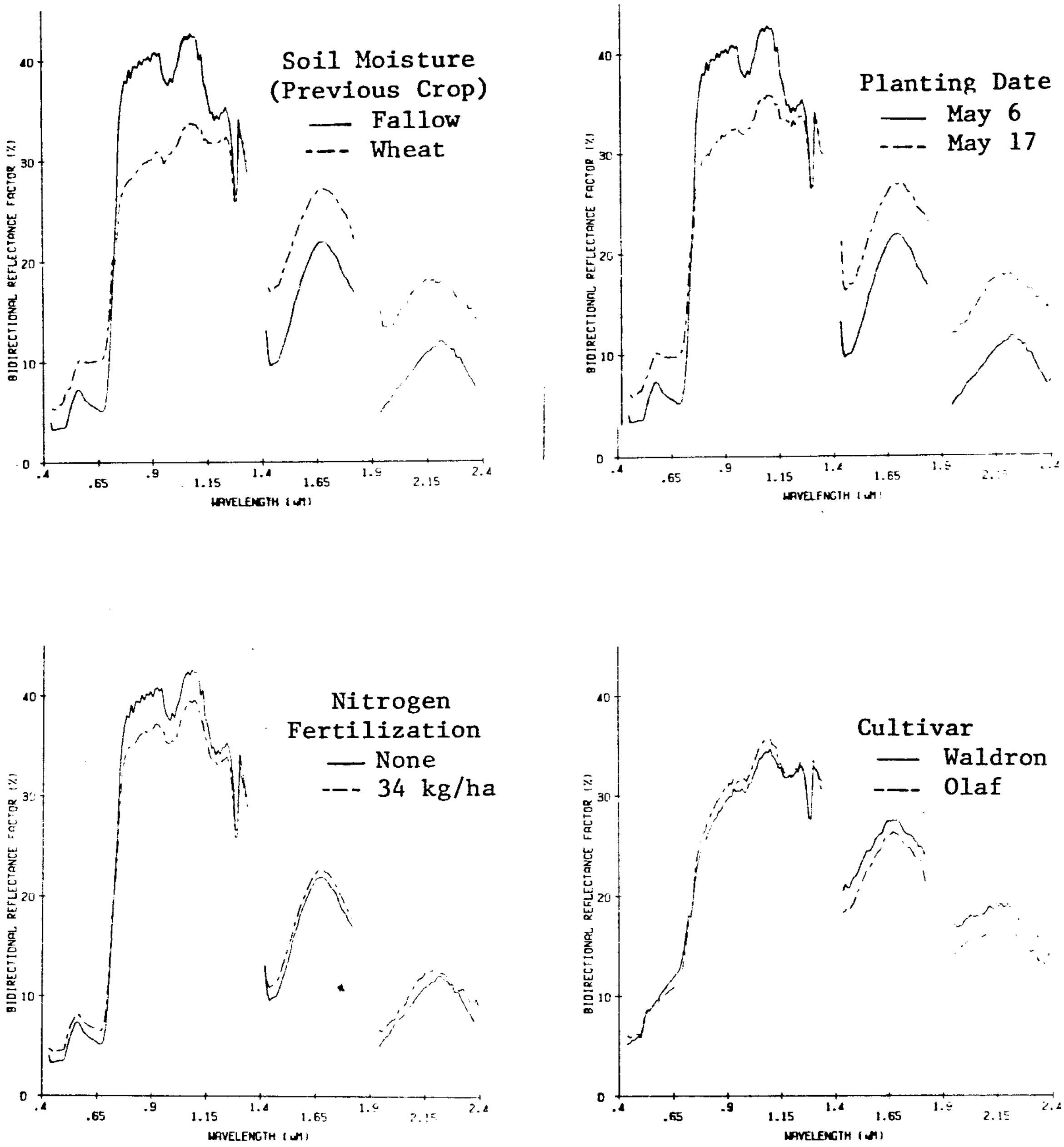
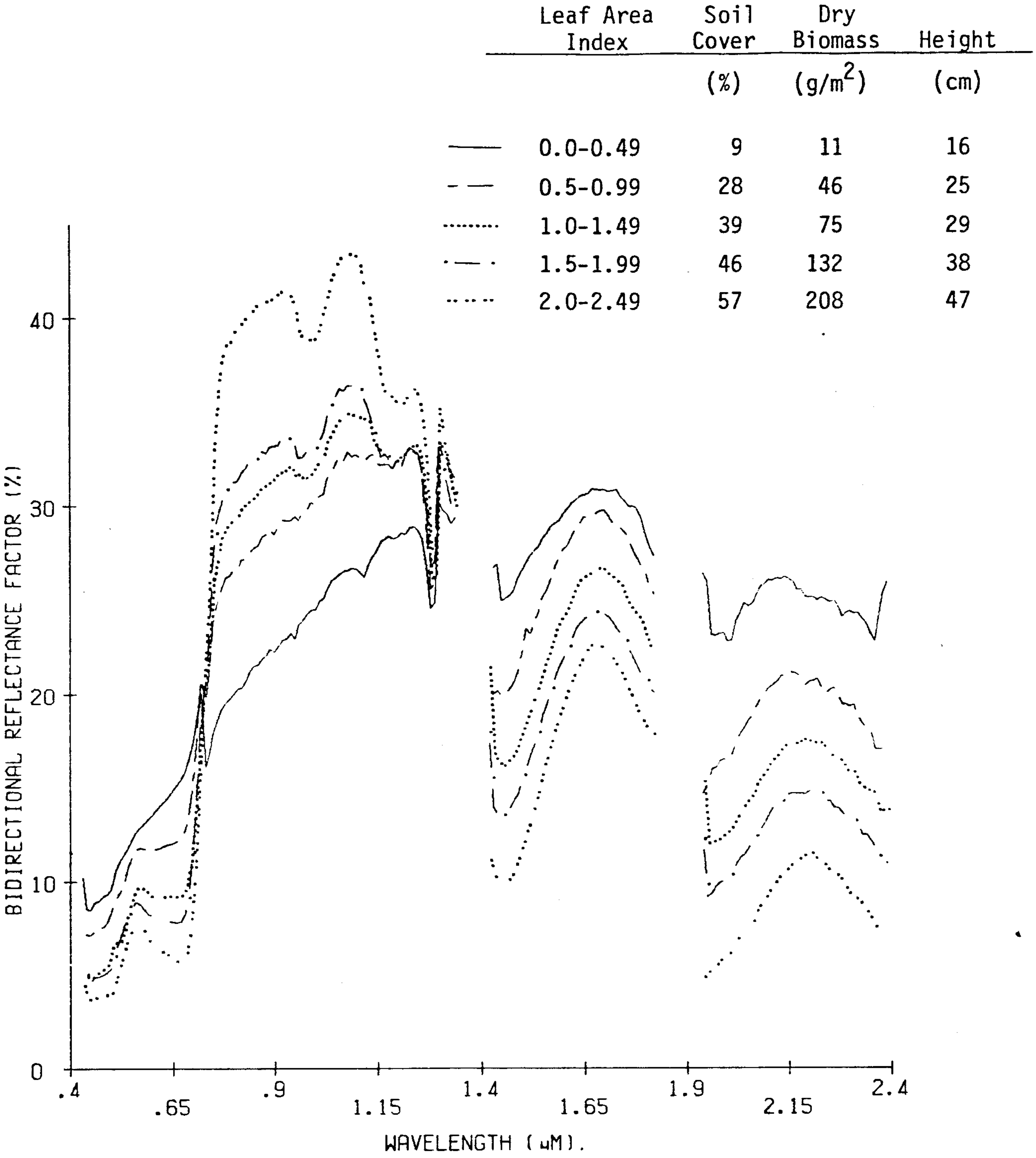


Figure 1. Effects of agronomic treatments on the spectral reflectance of spring wheat. Spectra were measured on June 18 during the stem extension stage of development, except for the spectra of cultivars which were measured on July 16 after heading.



	Leaf Area Index	Soil Cover (%)	Dry Biomass (g/m^2)	Height (cm)
——	0.0-0.49	9	11	16
– —	0.5-0.99	28	46	25
········	1.0-1.49	39	75	29
·— ·	1.5-1.99	46	132	38
·· ·· ·	2.0-2.49	57	208	47

Figure 2. Effect of leaf area index, percent soil cover, dry biomass, and plant height on the spectral reflectance of spring wheat during the period between tillering and the beginning of heading when the maximum green leaf area was reached.

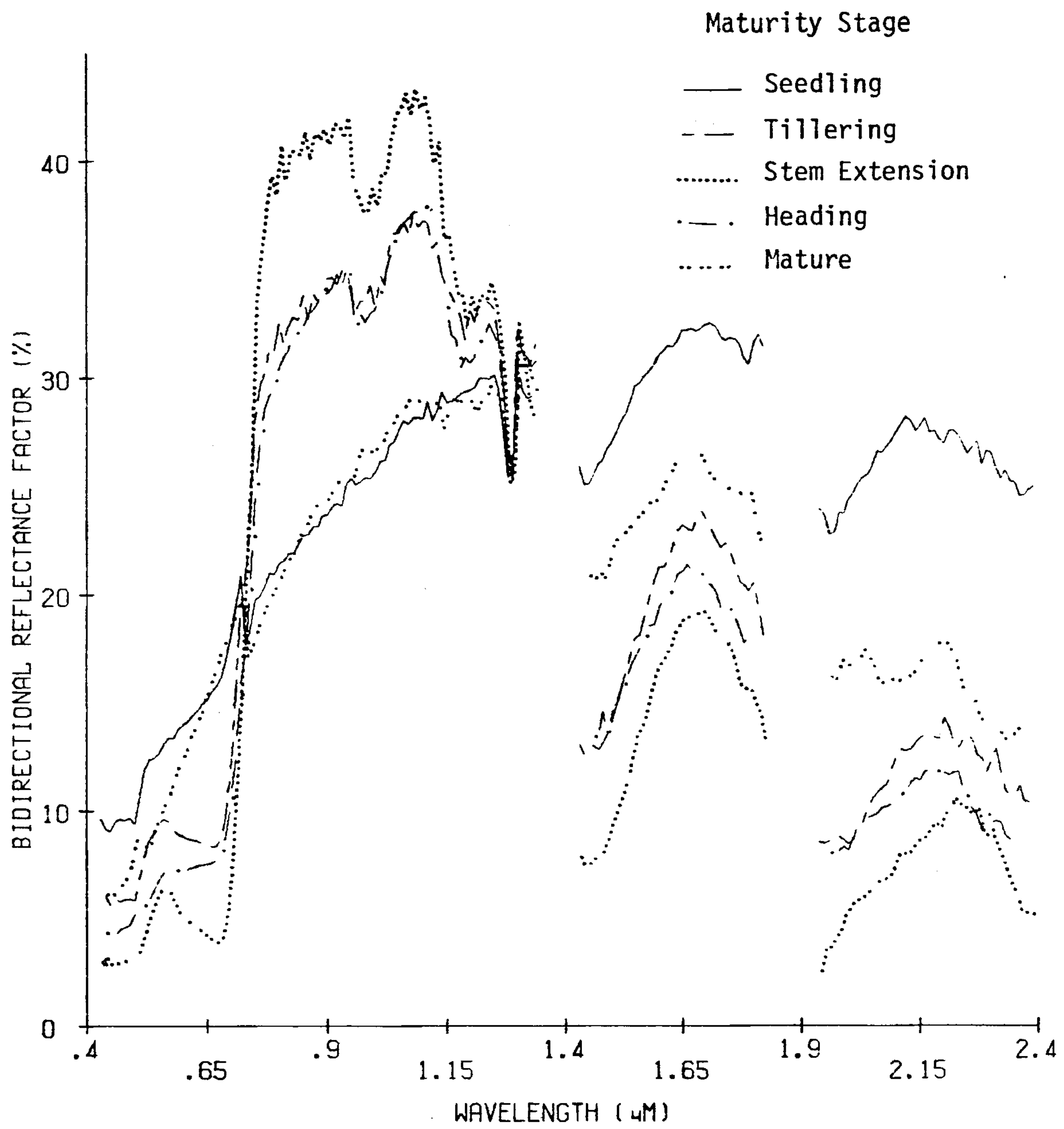


Figure 3. Effect of maturity stage on the spectral reflectance of spring wheat canopies.

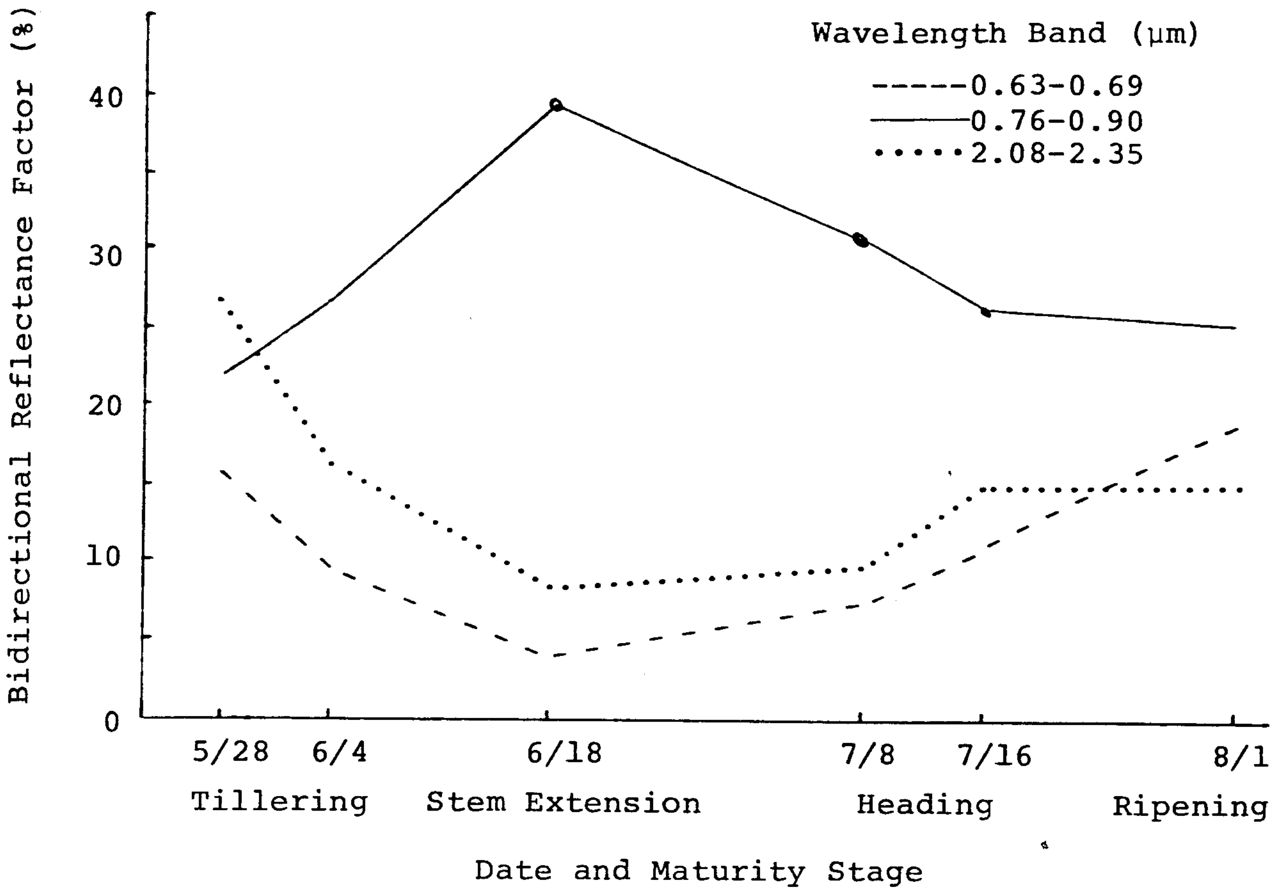


Figure 4. Reflectance of spring wheat in visible, near infrared, and middle infrared wavelength bands as a function of maturity stage.

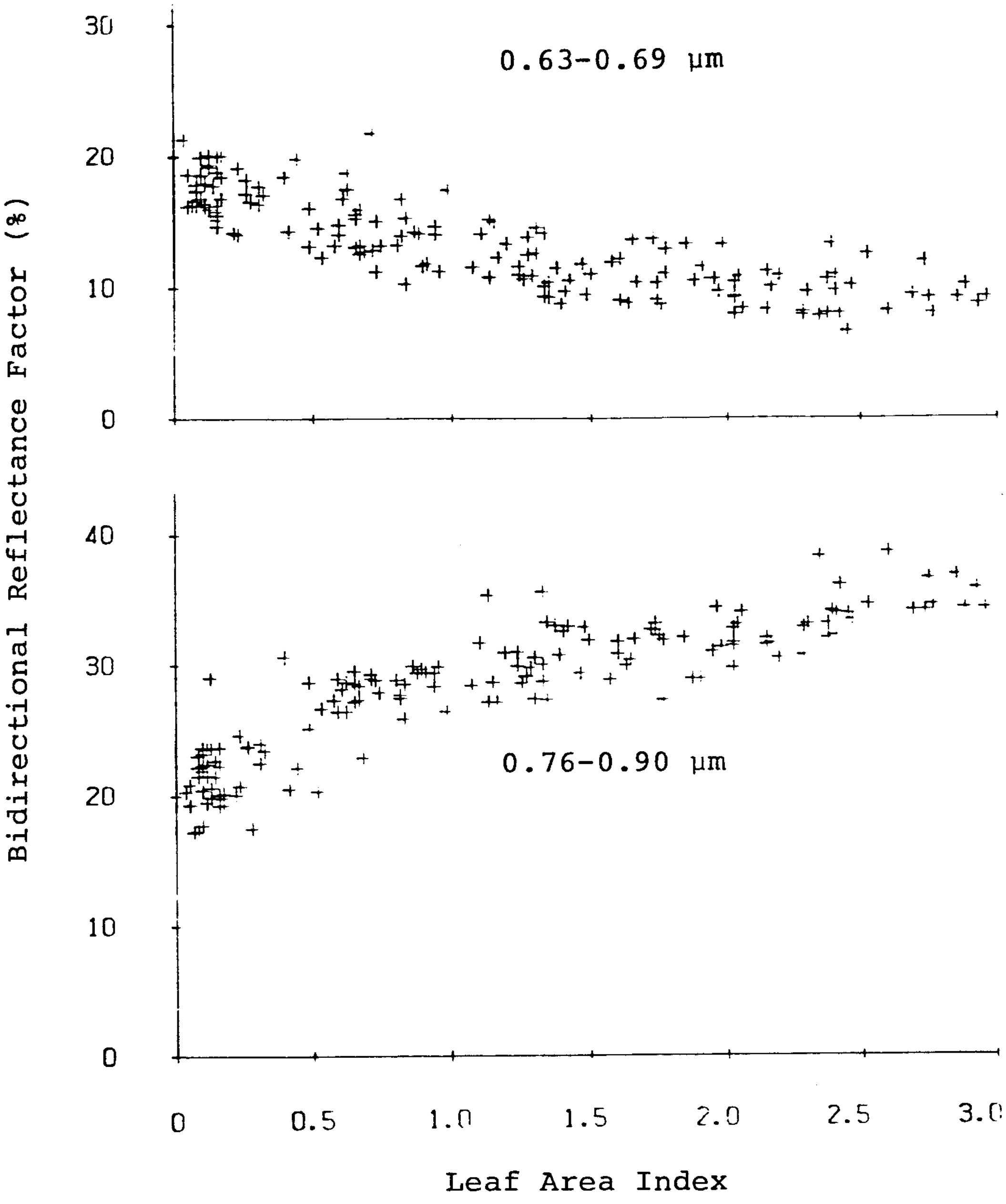


Figure 5. The relation of leaf area index to reflectance in the chlorophyll absorption (0.63-0.69 µm) and near infrared (0.76-0.90 µm) regions of the spectrum.

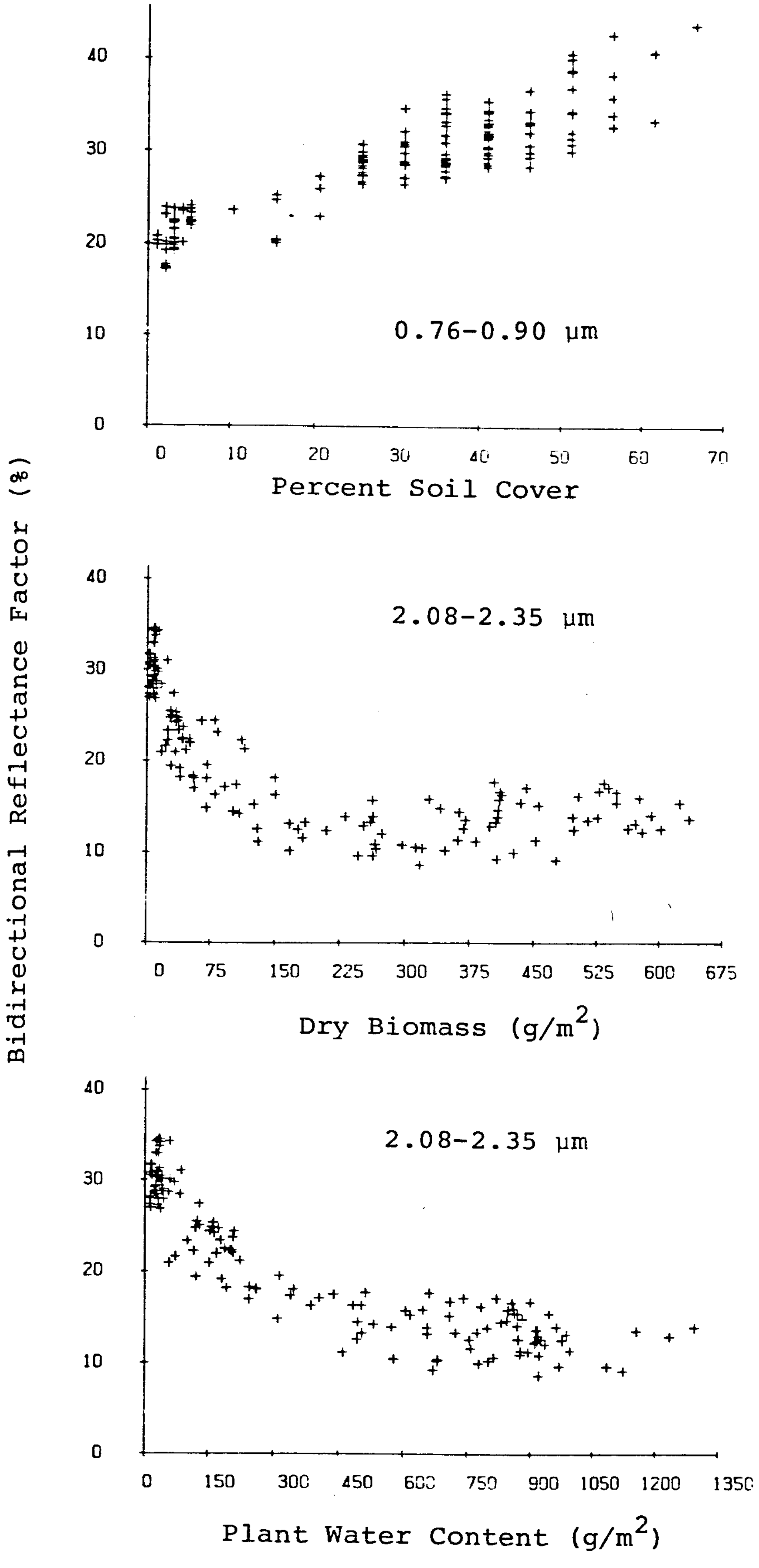


Figure 6. Relationship of percent soil cover, dry biomass, and plant water content to reflectance in selected wavelength bands.

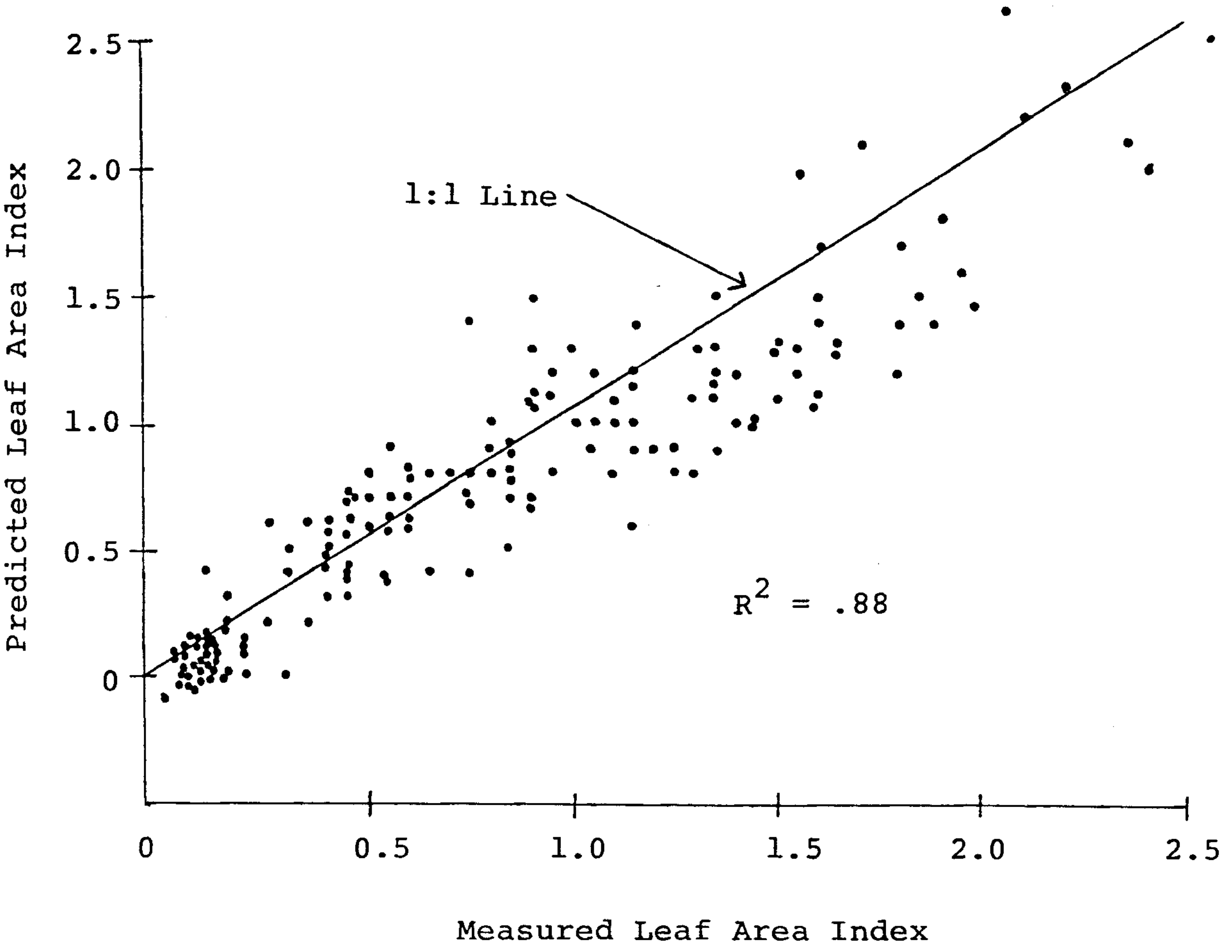


Figure 7. Comparison of measured and predicted leaf area index of spring wheat. Predicted LAI = $-0.65 + 0.11X_1 - 0.13X_2 + 0.90X_3$, where X_1, X_2, and X_3 are the reflectances of the following wavelength bands: .76-.90, 1.55-1.75, and 2.08-2.35 μm.