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Supporting Research

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Technical Report

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by M.E. Bauer, C.S.T. Daughtry, and V.C. Vanderbilt

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16. Abstract

To fully achieve 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. During the past six years several thousand reflectance spectra of corn, soybean, and wheat canopies have been acquired and analyzed. The relationships of biophysical variables, including leaf area index, percent soil cover, chlorophyll and water content, to the visible and infrared reflectance of canopies are described. The effects on reflectance of cultural, environmental, and stress factors such as planting date, seeding rate, row spacing, cultivar, soil type and nitrogen fertilization are also described. The conclusions are that several key agronomic variables including leaf area index, development stage and degree of stress are strongly related to spectral reflectance and that it should be possible to estimate these descriptors of crop condition from satellite-acquired multispectral data.

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SPECTRAL-AGRONOMIC RELATIONSHIPS OF CORN, SOYBEAN AND WHEAT CANOPIES*

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1. INTRODUCTION

Identification and area estimation of agricultural crops promise to be major applications of satellite remote sensing. Multispectral remote sensing can also provide significant amounts of information about the condition and yield of crops. To fully achieve 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 (2).

The relationships of biological parameters such as chlorophyll concentration, cell structure and water content to the optical properties of leaves have been well established. However, canopies are more than simple collections of leaves. Complex interactions which are not factors when spectra of single leaves are measured must be considered in remote sensing of canopies grown under field conditions. Some of the important variables influencing the reflectance of canopies are: leaf area index (LAI), leaf angle distribution, soil cover

* Reprint of presentation at and paper in proceedings of International Colloquium on Signatures of Remotely Sensed Objects, Avignon, France, September 8-11, 1981.

percentage, soil reflectance, and the optical properties of leaves and other canopy components (4). Differences in these parameters are caused by variations in many cultural and environmental factors including: planting date, cultivar, inter- and intra-row spacing, fertilization, and soil moisture. Solar elevation and azimuth angles and the view angle and direction of the sensor also affect the measured reflectance of crops and soils.

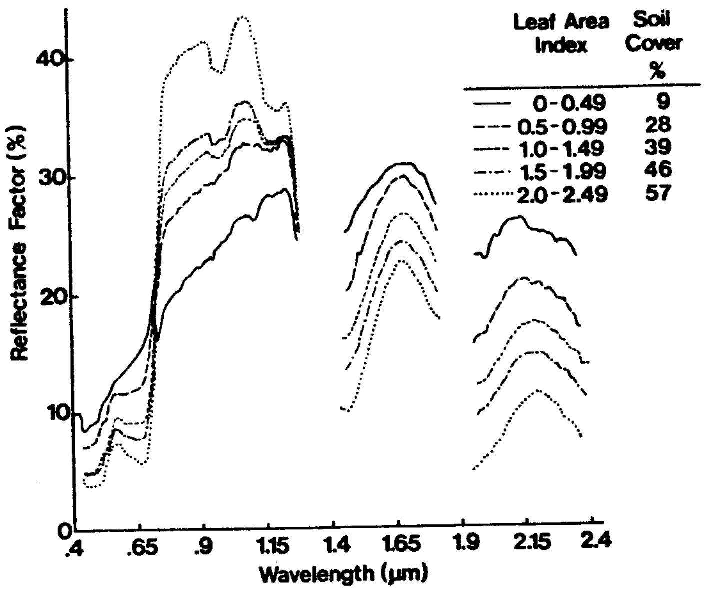
During the past six years several thousand reflectance spectra of corn, soybean and wheat canopies have been acquired and analyzed by agronomists and engineers at LARS/Purdue University (3, 9). The replicated, factorial experiments have involved different planting dates, row spacings, plant populations, cultivars, levels of nitrogen fertilization, and soil types. Reflectance spectra over the 0.4 to 2.4 μm wavelength have been acquired; these data permit simulation and comparison of various spectral bands such as MSS and thematic mapper. Data have also been acquired by multiband radiometers over the 0.5-1.1 μm range and in 1981 over the 0.45-12.4 μm range. Measurements from the various sensors are calibrated in terms of reflectance factor to facilitate comparisons among sensors, measurement dates-times, and experiments-locations. At the same time spectral data are acquired, agronomic measurements characterizing the canopy have been acquired. These data include development stage, LAI, biomass (fresh and dry leaves, stems, grain), percent soil cover, soil moisture, and leaf chlorophyll concentration.

The results of two types of analyses will be described: (1) determination of the effects of various cultural, environmental, and stress factors on canopy spectral response as a function of crop development stage, and (2) determination of the relationships of development stage, LAI, percent soil cover, plant water content, and chlorophyll concentrations to canopy reflectance in the visible, near infrared and middle infrared wavelengths and to transformations of the reflectance data. More specific, detailed descriptions of the various experiments and results may be found in several other reports (1, 5-8, 10).

2. REFLECTANCE SPECTRA OF CROP CANOPIES

Figure 1A illustrates the effect of amount of vegetation (as measured by leaf area index and percent soil cover) on the multispectral reflectance of spring wheat canopies during the period between tillering and the beginning of heading, when the maximum green leaf area is reached. As the LAI increases there is a progressive and characteristic decrease in reflectance in the chlorophyll absorption region, increase in the near infrared (0.7-1.1 μm) reflectance, and decrease in middle infrared (1.4-2.4 μm) reflectance. Similar spectral responses have been observed for corn and soybean canopies.

Plant development (as opposed to growth or increase in size) causes many changes in canopy geometry, moisture content and leaf pigmentation. These changes are manifested in the reflectance of canopies. Figure 1B shows the spectra of spring wheat canopies at several development



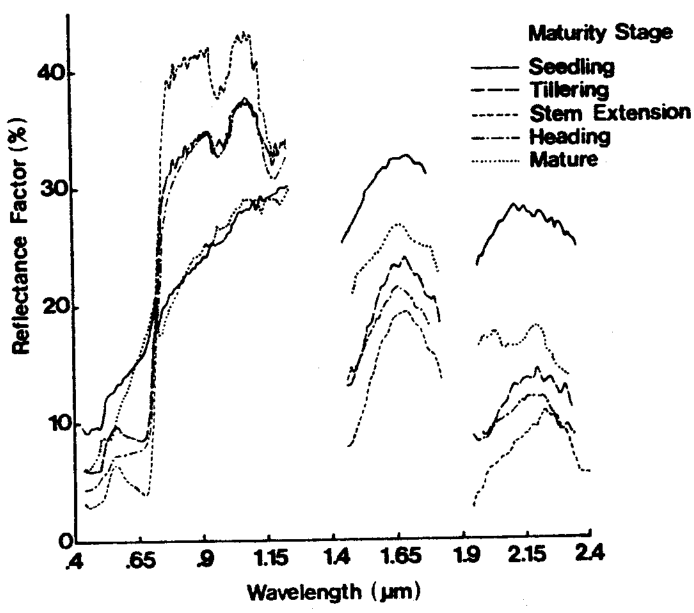


Figure 1. Effect of amount of vegetation and development stage on the reflectance spectra of spring wheat canopies.

stages. Visible reflectance decreases and near infrared reflectance increases until the time of heading when these patterns are reversed.

3. VISIBLE REFLECTANCE AND LEAF CHLOROPHYLL

In the visible portion of the spectrum, 0.4 to 0.7 µm, the reflectance properties of canopies are dominated by the optical properties of leaf pigments, particularly chlorophyll. Because chlorophyll absorbs a large percentage of visible radiation, reflectance decreases as the amount of green leaf area increases. We have found, in contrast to individual leaves, that chlorophyll concentration is not strongly related to canopy reflectance. However, when the leaf chlorophyll concentration of the flag leaf is multiplied by the LAI (giving a variable we have called chlorophyll density), a reasonably strong relationship to reflectance in the 0.63 to 0.69 µm wavelength band is observed (Figure 2). The form of the relationship is logarithmic with minimum reflectance of 2 to 3 percent at a chlorophyll density of about 100 ug cm^{-2}. For all three canopy types the minimum red reflectance has been reached at LAI of 2 to 3.

4. NEAR INFRARED REFLECTANCE AND AMOUNT OF VEGETATION

After 0.7 µm the absorbing properties of pigments disappear suddenly and there is a sharp increase in reflectance (Figure 1). The high reflectance, as well as transmittance, in the near infrared plateau between 0.7 and 1.3 µm is explained by multiple scattering in the leaf mesophyll, caused by the discontinuities in the refractive index between cell walls and intercellular air spaces. As has been found for stacked

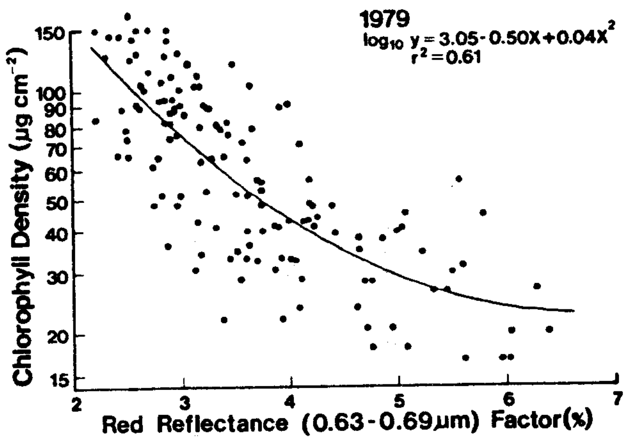


Figure 2. Relationship of amount of canopy chlorophyll and red reflectance of winter wheat canopies.

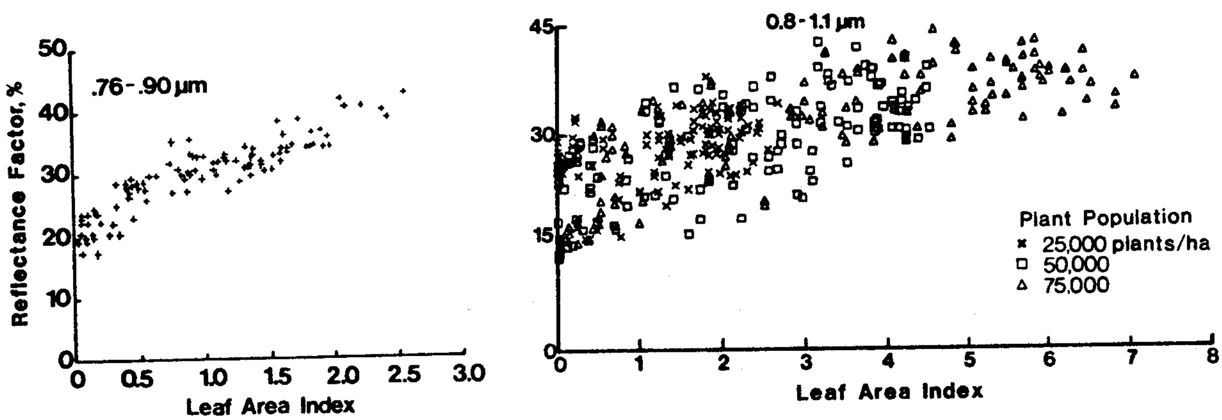


Figure 3. Relationship of leaf area index and near infrared reflectance for corn (right) and winter wheat (left) canopies.

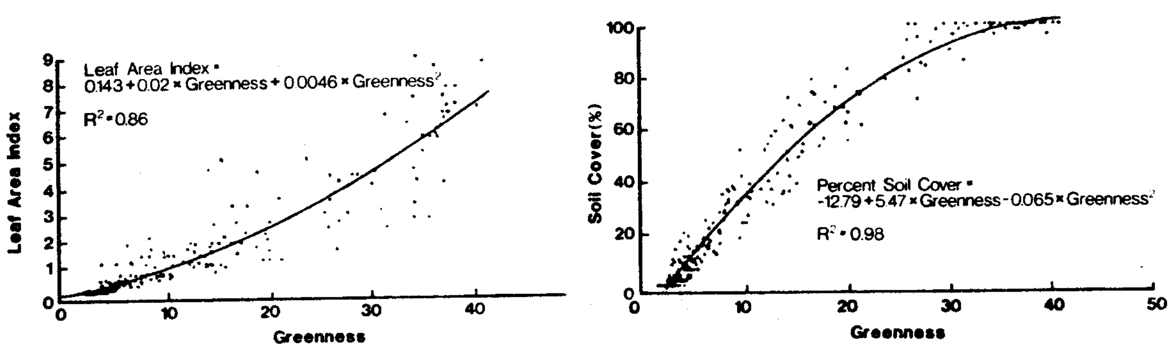


Figure 4. Regression models of the relationship of the greenness transformation to percent soil cover and leaf area index of soybean canopies.

layers of leaves, the near infrared reflectance of canopies increases as the amount of leaf area increases. We have found the relationship of near infrared reflectance and LAI is nearly linear up to LAI of about four, at which point reflectance begins to level off (Figure 3). No further increases in reflectance are observed after a LAI of about six is reached.

Similar and equally strong relationships of percent soil cover to near infrared reflectance have been found. Total biomass (stems and reproductive canopy components together with leaves) is not strongly related to reflectance. While for a time biomass and leaf area increase along with near infrared reflectance, when reproductive growth begins there are continued increases in biomass but not leaf area or reflectance. We have therefore concluded that canopy reflectance in the near infrared is influenced most by amount of leaf area and percent soil cover (and probably leaf angle distribution, although we have not measured that variable in our experiments) and not by total biomass. The linearity of the near infrared reflectance in relation to LAI and soil cover over the range of agronomically important leaf area indices indicates that these variables, important variables influencing crop growth and yield, can be estimated from remotely sensed spectral observations and used as input variables to growth, evapotranspiration and yield models (Figure 4).

5. MIDDLE INFRARED REFLECTANCE AND PLANT WATER CONTENT

From 1.3 to 2.5 µm absorption by water has a dominant role in the spectral responses of vegetative canopies. Reflectance maxima occur at 1.7 and 2.2 µm. As water content of the canopy increases, absorption increases and reflectance decreases. Spectral bands in the middle infrared may be useful as indicators of crop vigor; however, the response saturates at relatively low levels of canopy water content (Figure 5). The response is related not to relative water content, which is more indicative of canopy condition, but to total plant water content. Still, bands in this region have been found to be important for spectral crop identification and estimation of varibles such as LAI. As canopies are senescing with rapid loss in moisture content, sharp increases in middle infrared reflectance have been observed, indicating potential utility for identifying crop maturity.

6. EFFECTS OF SOIL BACKGROUND

At low levels of vegetation the soil background can have substantial effects on the reflectance of crop canopies. A comparison of the effects of red and near infrared reflectance of canopies grown on dark- and light-colored soils is shown in Figure 6. It is noted that relative differences in canopy reflectance of 100 percent may exist early in the season due to differences in the reflectivity of the soil. The sources of variation are primarily due to differences in soil type, moisture content, and surface roughness. Increases in surface moisture and roughness cause decreases in soil reflectance (and therefore canopy

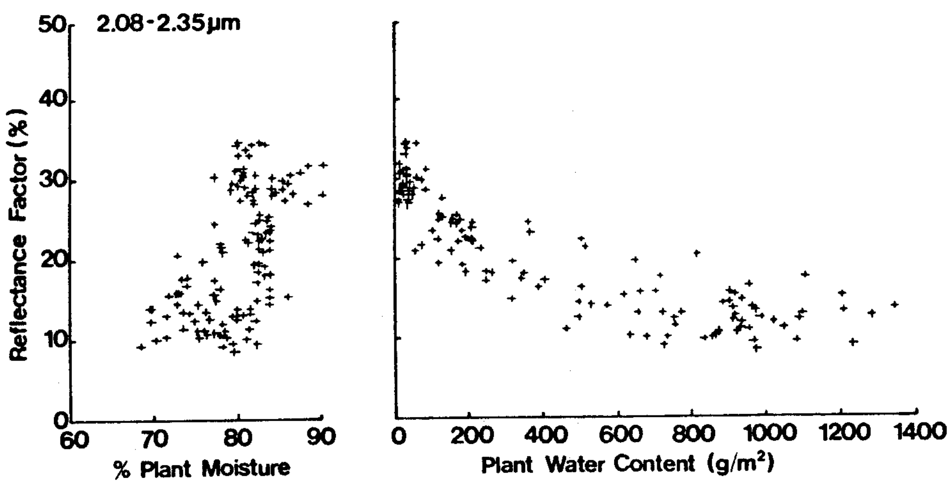


Figure 5. Relationship of percent moisture and moisture content and middle infrared reflectance of spring wheat canopies.

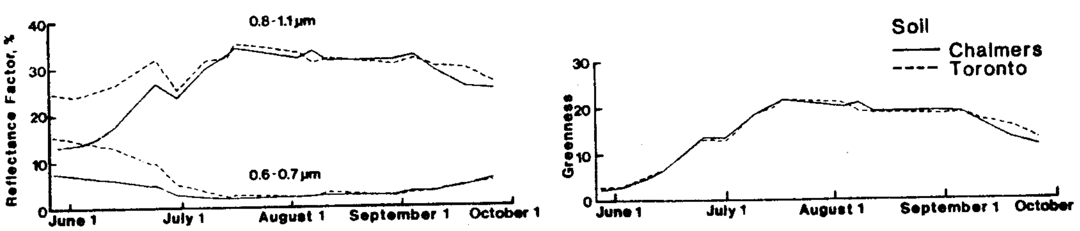


Figure 6. Effect of soil background on the red and near infrared reflectance and greenness transformation of corn canopies. Chalmers is a relatively dark soil and Toronto is a light color.

reflectance) for a given soil type. Use of the near infrared/red ratio and the greenness transformation, however, have been found to essentially eliminate variation in spectral response of canopies due to differences in soil reflectance.

7. EFFECTS OF CULTURAL PRACTICES

If multispectral remote sensing is to be successfully used to monitor and inventory crops, it is important to quantify and understand the sources of variation in spectral responses of crops. Some variation may be associated with important agronomic factors which it may be desirable to identify (e.g. dryland vs. irrigated cropland). Other variation may be associated with a factor, such as cultivar, which probably would not be monitored. In our experiments we have tried, while emphasizing the determination of relationships of reflectance to variables such as LAI, to select experimental factors representative of farming practices in order to quantify the magnitude of variation likely to be encountered in a future remote sensing-based crop inventory system.

The percent of variation associated with several agronomic factors, including planting date, row spacing, plant population, cultivar, available soil moisture, and soil type, for several corn, soybean and wheat experiments is summarized in Table I. Early in the growing season soil background tends to be the dominant source of variation. As canopies begin to develop, row spacing, plant population, fertilization, and soil moisture availability become important factors influencing

Table I. Percent of variation in red (0.6-0.7 µm) and near infrared reflectance (0.8-1.1 µm) and the greenness transformation of corn, soybean, and spring wheat canopies associated with soil type and cultural practices on several dates (development stages).

Agronomic Factor	Spectral Variable											
	Red Reflectance				Infrared Reflectance				Greenness Transformation			
	Corn											
	6/11	7/15	8/22	9/26	6/11	7/15	8/22	9/26	6/11	7/15	8/22	9/26
Soil type	56	25	3	2	51	21	5	-	16	-	2	-
Plant population	-	8	22	-	1	33	36	4	1	31	47	2
Planting date	12	38	7	53	24	8	14	76	39	61	9	82
	Soybeans											
	6/18	7/17	8/22	9/26	6/18	7/17	8/22	9/26	6/18	7/17	8/22	9/26
Soil type	13	15	-	-	15	11	-	-	2	-	-	-
Planting date	13	63	52	87	44	69	10	85	82	90	12	87
Row width	8	-	9	-	2	5	29	1	-	4	29	-
Cultivar	1	-	6	-	2	-	16	10	-	-	16	8
	Spring Wheat											
	6/1	6/23	7/7	7/20	6/1	6/23	7/7	7/20	6/1	6/23	7/7	7/20
Soil moisture	2	16	73	52	9	28	69	36	8	41	87	63
Cultivar	-	1	-	2	-	10	4	4	-	9	2	3
N fertilizer	-	9	3	1	-	1	3	4	-	6	3	3
Planting date	36	5	7	27	85	35	4	6	42	12	-	21

†Models include variation due to treatments. Total variation is due to blocks, treatments, and experimental error. Interaction terms and percentages less than 1.0 are omitted for clarity, but were included in model.

spectral response. At the end of the season, cultivar and planting date, because of their influence on date of maturity, are major sources of variation.

8. EFFECTS OF STRESS

Stresses such as nutrient or moisture deficits can substantially alter the growth of crop canopies. These changes, particularly in canopy variables, such as LAI, percent cover, and chlorophyll concentration, are manifested in the spectral responses of the canopies. The presence of moisture and nitrogen deficiencies reduces leaf chlorophyll concentration, LAI, percent soil cover, and plant water content (i.e. smaller, chlorotic plants) causing increased visible and middle infrared reflectance and decreased near infrared reflectance (Figure 7). We have conducted experiments with two levels of available soil moisture for spring wheat and varying levels of nitrogen fertilization for corn and winter wheat and found significant differences throughout the growing season in the reflectances of the canopies (Figure 8).

9. RELATION OF CANOPY REFLECTANCE AND YIELD

A major objective of agricultural remote sensing is to use remote sensing to predict crop yields. Development of a capability to spectrally estimate variables such as LAI, solar radiation interception, and degree of stress (i.e. inputs to crop condition and yield models) is one approach. We have also found, as shown in Figure 9, strong relationships between a spectral variable integrated over the season and

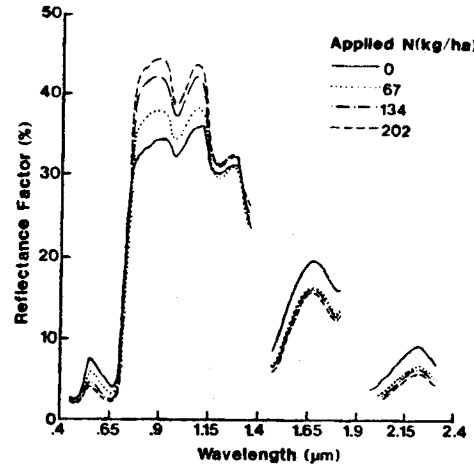


Figure 7. Reflectance spectra during the grain filling stage of corn canopies with varying levels of nitrogen fertilization.

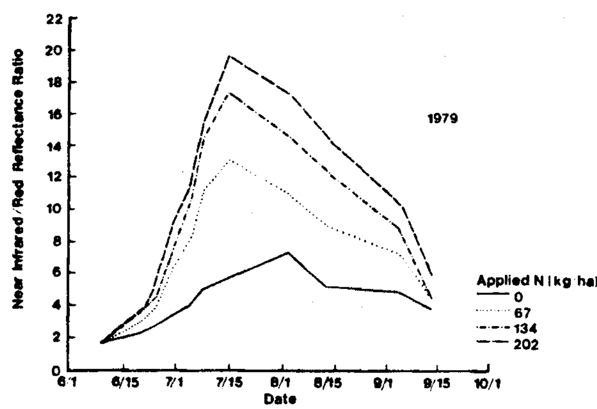


Figure 8. Temporal measurements of the near infrared/red reflectance ratio for corn canopies with varying levels of nitrogen fertilization.

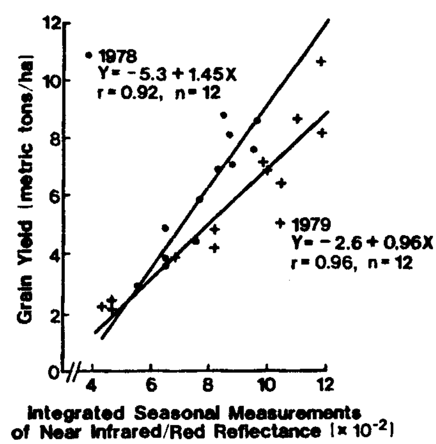


Figure 9. Relation of corn grain yield to measurements integrated over the growing season of near infrared/red reflectance ratio.

grain yield of corn and winter wheat canopies. And, in another experiment, reflectance measurements at the time of heading of spring wheat were highly correlated with grain yield. These results are highly dependent on differences in LAI and related canopy variables which in turn were related to yield. Although positive relationships between spectral variables and grain yield have been found in several instances, we have not concluded that yields can be directly predicted from spectral measurements. Canopies having similar LAI and reflectance could be exposed for only a few days to two different environments (for example, moisture or temperature stress at the time of pollination) which cause large differences in grain yields, but not in reflectance. The results do, however, indicate that multispectral response is a potential new source of information related to the potential grain yield of crop canopies.

Much of our present research is directed at combining spectral, meteorological and soil productivity data to predict grain yield. These approaches combine the high spatial resolution of Landsat spectral data, allowing individual fields over large geographic areas to be observed, with the high temporal (low spatial) resolution of meteorological data.

10. SUMMARY AND CONCLUSIONS

Based on the analysis of several thousand reflectance spectra of corn, soybean and wheat canopies, the following relationships and effects have been found:

* The three different reflective regions of the spectrum respond to different canopy properties. The properties to which the visible, near infrared and middle infrared regions are most sensitive are amount of leaf chlorophyll, leaf area index and percent soil cover, and plant water content, respectively. Reflectance is relatively unrelated to variables such as plant height, percent green leaves and percent moisture.
* Early in growing season, up to LAI of 2 and soil cover of 20 to 30 percent, soil background dominates the spectral reflectance, but the near infrared/red ratio and greenness transformation are relatively insensitive to soil color and moisture. Later in the growing season, row spacing, plant population and development stage are the primary agronomic factors causing variation in the reflectance of canopies. At the end of the season differences in cultivars due to varying rates of senescence and maturity are important.
* The above agronomic factors cause differences in leaf area index, percent cover, and water and chlorophyll contents which in turn are manifested in the canopy spectral responses.

The overall conclusions are that several key agronomic variables, including leaf area index, development stage and degree of stress are strongly related to spectral reflectance and that it should be possible to estimate these descriptors of crop condition from satellite-acquired multispectral data for use in crop simulation models.

11. ACKNOWLEDGEMENTS

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