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Spectral Properties of Agricultural Crops and Soils Measured from Space, Aerial, Field and Laboratory Sensors

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

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16. Abstract

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Abstract

To develop the full potential of multispectral measurements acquired from satellite or aircraft sensors to monitor, map and inventory agricultural resources, increased knowledge and understanding of the spectral properties of crops and soils is needed. This paper reviews the present state of knowledge, emphasizing current investigations of the multispectral reflectance characteristics of crops and soils as measured from laboratory, field, aerial and satellite sensor systems. The relationships of important biological and physical characteristics to their spectral properties of crops and soils are addressed. The paper concludes with discussion of future research needs.

Introduction

Mankind is becoming increasingly aware of the need to better manage the resources of the earth--atmosphere, water, soils, vegetation and minerals. As the world's population increases and a higher standard of living is sought for all, more careful planning and effective use of these resources, particularly soils, vegetation and water, is required to produce adequate food supplies. Agricultural crop production is highly dynamic in nature and dependent on complex interactions of weather, soils, technology and socio-economics. Accurate and timely information on crops and soils on a global basis is required to successfully plan for and manage food production. The repetitive, synoptic view of earth provided by satellite-borne sensors such as Landsat MSS provide the opportunity to obtain the necessary information on soil productivity and crop acreage and condition. For example, the recently completed Large Area Crop Inventory Experiment established the applicability of multispectral remote sensing to inventory and monitor global wheat production (1).

But, to fully develop the potential of multispectral measurements acquired from satellite or aircraft sensors to monitor, inventory and map agricultural resources, increased knowledge and understanding of the spectral properties of crops and soils in relation to physical, biological and

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*Research agronomist, research engineers, and research agronomist, respectively. The authors gratefully acknowledge the support of the NASA Johnson Space Center, contract NAS9-15466.

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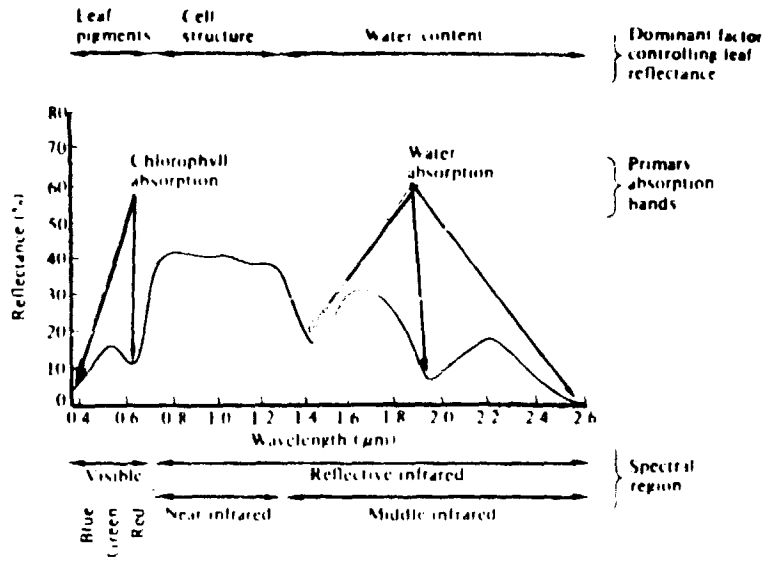

Figure 1. Significant spectral reflectance characteristics of healthy, green vegetation.

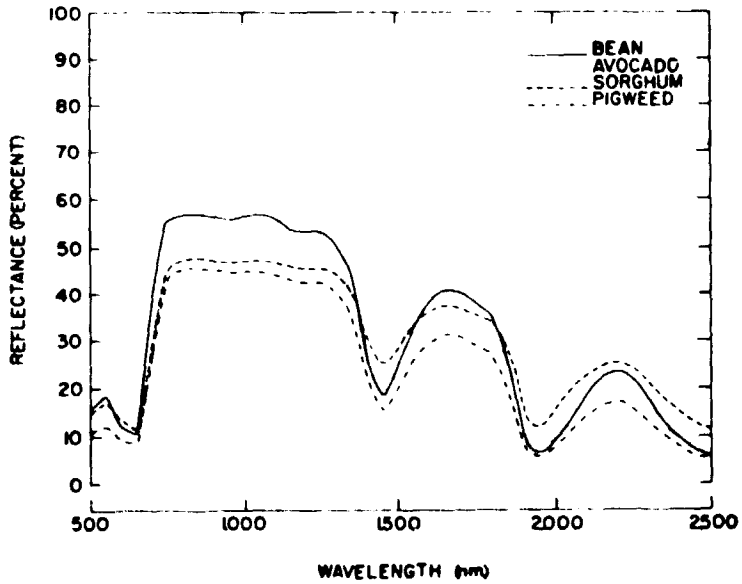

Figure 2. Reflectance spectra of leaves of four crops. Pigweed and sorghum have compact mesophylls; bean and avocado leaves have dorsiventral mesophylls (from Gausman et al., 5).

agronomic characteristics is needed. The purpose of this paper is to review, emphasizing current investigations, the multispectral reflectance properties of crops and soils as measured from laboratory, field, aerial, and satellite sensors. Although the measurements at the longer thermal and microwave wavelengths contain additional important information about condition of crops and soils, only the reflective region of the spectrum (0.4-2.4 μm) will be considered in this paper. The paper is organized in four parts: (1) spectral properties of leaves, (2) reflectance properties of soils, (3) reflectance characteristics of crop canopies, and (4) large area applications of spectral measurements. It concludes with a brief discussion of future research needs.

Spectral Properties of Leaves

We will begin with a brief discussion of the optical properties of plant leaves since they are the dominant plant component influencing the spectral properties of crop canopies. Several excellent reviews of the spectral properties of leaves and plant canopies have previously been published by Gates et al. (2), Knipling (3) and Gausman et al. (4). The spectral reflectance of green vegetation is distinctive and quite variable with wavelength. A plant leaf reflects, absorbs and transmits incident radiation in a manner that is uniquely characteristic of pigmented cells containing water (2). Figure 1 shows a typical spectral reflectance curve for green vegetation and identifies the spectral response regions of major importance. The amount of energy that plant leaves reflect is a function of three factors: the incident solar radiation, the amount of energy absorbed and the amount of energy transmitted. The amount of energy reflected at a specific wavelength is equal to the incident radiation minus the sum of the energy which is either absorbed or transmitted at that wavelength.

The reflectance of leaves is relatively low in the visible portion of the spectrum. The low reflectance (and transmittance) in the visible region is attributed to absorption by leaf pigments. Chlorophyll absorbs most of the incident energy in the blue and red wavelength bands centered at approximately 0.45 and 0.67 μm. A relative lack of absorption in the region between the two chlorophyll absorption regions results in a reflectance peak at about 0.54 μm, the green wavelength region. A plant stress which reduces chlorophyll production will cause leaves to absorb less in the chlorophyll absorption bands; such leaves will have a higher reflectance, particularly in the red region, and will appear yellowish or chlorotic. Other pigments of interest include the carotenes and zanthophylls which are yellow pigments and anthocyanins which are red pigments. Chlorophyll, however, generally masks the presence of these pigments except during senescence when the chlorophylls have no significant effect on reflectance in either the near- or middle-infrared.

In the near-infrared there is a marked increase in reflectance. Leaves typically reflect 40 to 50 percent and absorb less than 5 percent of the incident energy in these wavelengths. The high reflectance, as well as transmittance, in the near-infrared "plateau" between 0.7 and 1.3 μm is explained by multiple reflections in the internal mesophyll structure, caused by the differences in the refractive indices of the cell walls and intercellular air cavities. Since the internal structure of leaves often varies considerably among species, differences are frequently greater in the infrared than in the visible wavelengths (Figure 2).

In comparison to the reflectance of a single leaf, multiple leaf layers result in increasing levels of reflectance in the near-infrared portion of the spectrum until a stable reflectance, called infinite reflectance (R_∞), is reached (6). In the visible and middle-infrared R_∞ is reached with two layers, while six to eight layers are needed to reach R_∞ in the near-infrared region (Figure 3).

In the middle-infrared portion of the spectrum the reflectance of green vegetation is dominated by strong water absorption bands which occur near 1.4, 1.9 and 2.7 μm; however, the regions between these absorption bands are also strongly influenced by water content of leaves. In this region leaf reflectance is inversely related to the total amount of water present in leaf. Gausman et al. (7) showed that in this region the spectral absorption characteristics of leaves can be simulated by the absorption of an equivalent water thickness.

Reflectance, transmittance and absorption by leaves depend on the concentration of pigments and water, along with the internal cell structure of each species. These physiological and morphological quantities depend on leaf type, stage of matruation, and senescence. Concerning leaf type, there are significant differences in the reflectance characteristics, particularly in the near-infrared region, of monocotyledon leaves with undifferentiated mesophyll and dicotyledon leaves having a dorsiventral mesophylls (5). As leaves mature, their visible reflectance decreases and near-infrared reflectance increases. Gausman et al. (7) attributed this effect to the greater number of intercellular air spaces in the mesophyll of mature leaves, compared to those of more compact young leaves. Senescence produces the opposite effect of maturation, i.e., visible reflectance increases due to loss of chlorophyll and infrared reflectance decreases, although relatively less than the increase in visible reflectance.

The optical properties of plant leaves are also affected by various kinds of stresses including nutrient deficiencies, salinity, and damage by insects and disease (3). These stresses are typically accompanied by reduced chlorophyll production causing an increased level of reflectance in the visible region. In the infrared, reflectance is typically reduced by these types of stresses, although a stress causing a loss of water will results in increased infrared reflectance. However, changes in reflectance are not substantial until the leaves reach about 75 percent relative turgidity (Figure 4).

In the preceding paragraphs only total reflectance and transmittance by leaves were considered. In a now classic study, Breece and Holmes (8) investigated the directional or spatial distribution of reflectance and transmittance of corn and soybean leaves. They found that the specular contribution to reflectance increased with the angle of incidence, but that transmittance was nearly Lambertian in nature (Figure 5).

In summary, the optical behavior of leaves in the visible region is determined by the concentration of chlorophylls and other pigments; the near-infrared is affected by leaf mesophyll structure; the middle-infrared is dominated by the optical properties of water in the tissue. Several theories and models have been developed to describe the optical properties of leaves, including the work by Sinclair et al. (9), Kumar and Silva (10), Allen et al. (11) and Gausman et al. (7).

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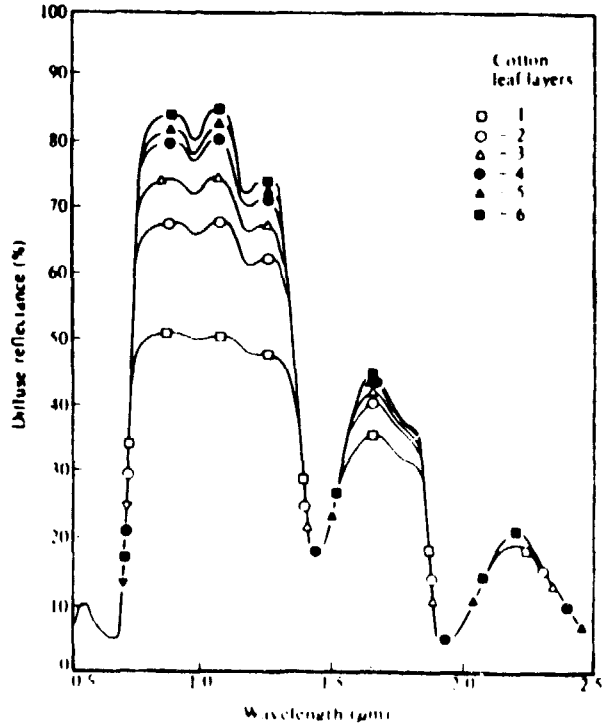

Figure 3. Reflectance from combinations of cotton leaves stacked on one another, up to six deep (from Allen and Richardson, 6).

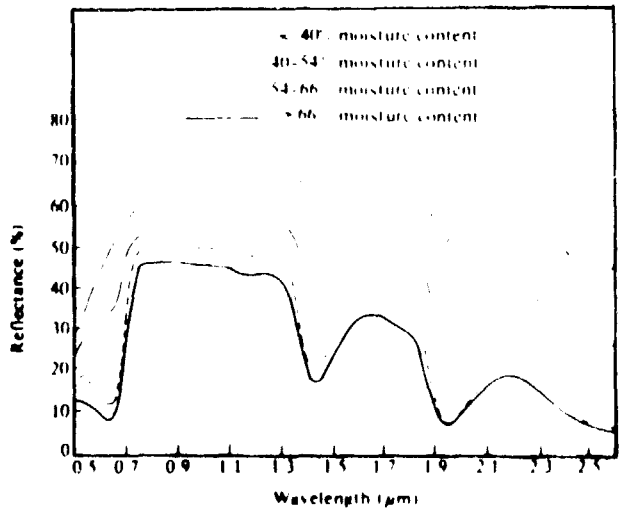

Figure 4. Effect of moisture content on reflectance of corn leaves (from Hoffer and Johannsen, 14).

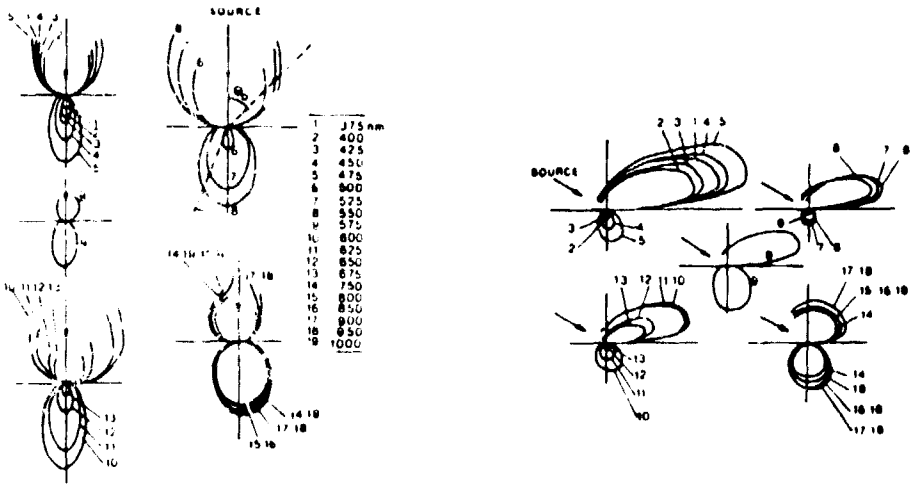

Figure 5. Polar diagrams of the directional reflectance and transmittance at perpendicular incidence (left) and 60° zenith angle of incidence (from Breece and Holmes, 8).

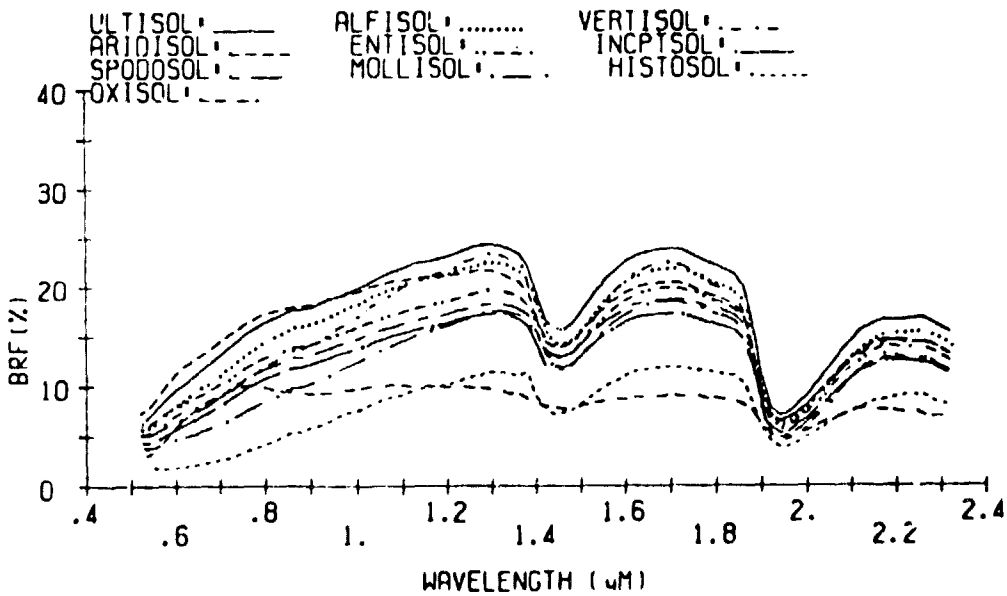

Figure 6. Averaged reflectance spectra for soils representing ten orders of soil taxonomy (from Stoner and Baumgardner, 12).

Spectral Characteristics of Soils

Spectral reflectance curves of soils are generally less complex than those of vegetation (Figure 6). As these curves demonstrate, one of the characteristics of soil reflectance curves is a generally increasing level of reflectance with increasing wavelength. Energy-matter interactions of soils are perhaps less complicated than for vegetation because all of the incident radiation is either absorbed or reflected. However, the soil itself is a complex mixture having various chemical and physical properties which affect the absorption and reflectance of soils. Therefore, although the reflectance curves are similar in their general shape, there are a number of interacting properties which determine the amplitude of reflectance, including moisture content, organic matter content, iron oxide content, texture and surface roughness. A very thorough review of the physical-chemical factors affecting soil reflectance properties has recently been completed by Stoner and Baumgardner (12).

As shown in Figure 7 most soils appear darker when wet than when dry and the decrease in reflectance with increasing moisture is apparent throughout the reflective wavelengths (13, 14). The amplitude and shape of soil reflectance curves is affected by the presence of strong water absorption bands at 1.45 and 1.95 μm. Bowers and Smith (15) found a linear relationship between soil moisture and absorbency and Peterson et al. (16) demonstrated that the loss of reflectance from the oven dry state to field capacity for 15 surface Mollisols and Alfisols from Central Indiana is linearly related to the oven dry reflectances of these soils. This relationship held true for visible as well as near- and middle-infrared reflective bands. These results point to the existence of orderly relationships among soil moisture tensions and soil reflectance values.

Soil organic matter content and composition of organic constituents are known to strongly influence soil reflectance. A general observation has been that as organic matter content increases, soil reflectance decreases throughout the 0.4 to 2.5 μm wavelength range (14). Al-Abbas et al. (17) found that organic matter plays a dominant role in bestowing spectral properties to soils when the organic matter content exceeds two percent. As the organic matter drops below two percent, it becomes less effective in masking out the effects of other soil constituents. Although it was not recognized by Condit (18), his Type 1 and Type 2 curves corresponded respectively to the reflectance curves of high surface organic content Mollisols and low surface organic content Alfisols (19). Organic constituents including humic and fulvic acid and nonspecific compounds including decomposing plant residues are known to influence soil reflectance to differing degrees, although the contribution of each has been difficult to quantify.

Iron oxide content can also have a significant influence on the spectral reflectance of soils. An increase in iron oxide can cause a decrease in visible reflectance. Obukhov and Orlov (20) reported that soils with an elevated content of iron could be easily distinguished by the inflection characteristic for pure Fe_2O_3; they found the intensity of the reflection in the region from 0.50 to 0.64 μm inversely proportional to the iron content.

Soil texture (particle size) as well as the size and shape of soil aggregates resulting from moderate crushing appear to influence soil reflectance in varying manners. Bowers and Hanks (13) measured the

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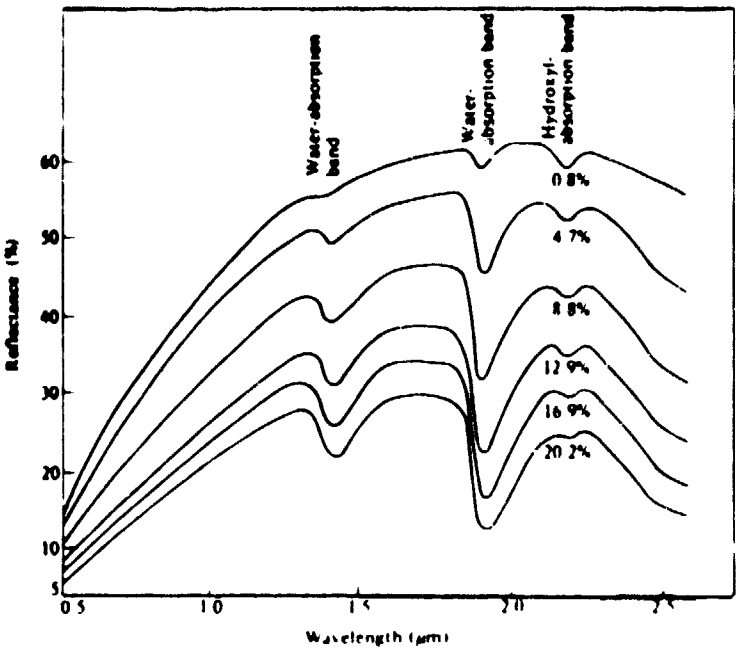

Figure 7. Spectral reflectance curves for Newtonia silt loam soil at various moisture contents (from Bowers and Hanks, 13).

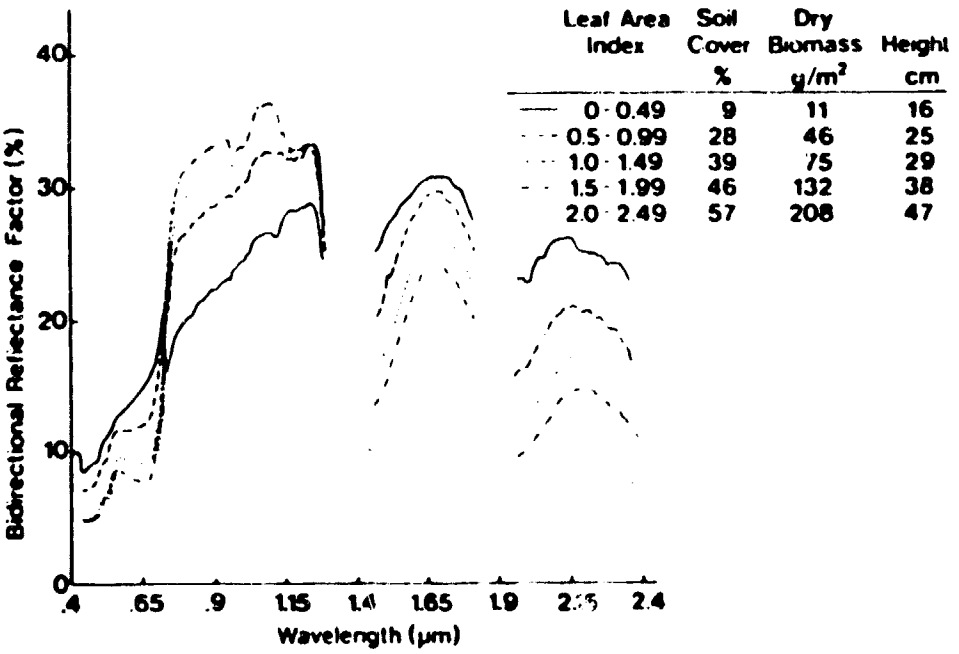

Figure 8. Effect of amount of vegetation on spectral reflectance of spring wheat. Data were acquired at Williston, North Dakota on May 28- June 18, 1976 for plots with different soil moisture levels, planting dates, nitrogen fertilization and cultivars (from Bauer et al., 25).

reflectance of pure kaolinite in size fractions from 0.022 to 2.68 mm diameter (coarse silt to very coarse particle size classes) and found a rapid exponential increase in reflectance at all wavelengths between 0.4 and 1.0 μm with decreasing particle size. The most notable increases in reflectance occurred at sizes less than 0.4 mm diameter (approximately medium sand particle size class and finer). It was felt that particles or aggregates larger than 2-3 mm diameter would have little influence on additional absorption of solar energy. Montgomery et al. (21) found that the amount of silt present was the major factor influencing the level of reflectance in both visible and infrared wavelengths, with an increase in the amount of silt causing increases in reflectance.

Surface roughness also affects the reflectance of soils. Coarse aggregates, having an irregular shape, form a complex surface with a large number of interaggregate spaces where much of the incident energy is absorbed. The structure determines the percentage of shadow generated at the soil surface. Cipra et al. (19) showed that there are dramatic differences in the reflectance of crusted and uncrusted soils.

Stoner et al. (22) have recently completed development of a comprehensive data base for investigation of the reflectance properties of soils. It includes reflectance measurements of over 200 soils from 39 states of the continental United States. Physicochemical characteristics measured were organic matter content, particle size distribution, cation exchange capacity, and iron oxide content. Site characteristics of soil temperature regime and moisture zone were used as selection criteria for soils included in the study, while parent material and internal drainage were noted for each soil. From this data set, Stoner and Baumgardner (12) identified at least five general types of soil reflectance curves based primarily on the presence or absence of probable ferric iron absorption bands at 0.7 and 0.9 μm, but also based upon organic matter content and soil drainage characteristics. While generally confirming relationships identified by previous investigators, their results, based on a large, representative sample of soils, significantly increase our understanding of the spectral properties of soils.

In summary, it has been found that increased soil moisture causes decreased reflectance throughout the reflective region; that reflectance increases as particle size decreases; and that increases in organic matter and iron oxide contents cause decreases in reflectance.

Spectral Characteristics of Crop Canopies

To realize the full potential of remote sensing for crop identification, condition assessment and yield prediction, it is important to understand and quantify (1) the relationship between agronomic (e.g., leaf area index) and reflectance characteristics of crop canopies and (2) the effect of various cultural and environmental factors on crop reflectance properties. Although knowledge of the reflectance characteristics of plant leaves and soils, as reviewed above, is basic to understanding the reflectance properties of crop canopies in the field, there are significant differences between the spectra of foliage and soil and the spectra of canopies.

The reflectance characteristics of canopies are due fundamentally to three factors, the optical properties of the component parts of the canopy,

canopy morphology, and view/illumination directions. The canopy component properties, the spectral characteristics of leaves and soils, were discussed above. The canopy morphology, the geometrical arrangement of the foliage in space, varies with changes in such agronomic variables as maturity stage, leaf area index, and percent soil cover and cultural and environmental factors such as planting date, seeding rate, row spacing, species, and cultivar. The geometric characteristics of a canopy also change with the wind and plant phototropic responses.

Consideration of the third factor, the directions of view and illumination of the canopy, is necessary when measuring the canopy reflectance characteristics. Even if the first two factors, canopy morphology and component optical properties, are constant for a canopy throughout the day, the canopy reflectance characteristics will change with not only the changing illumination direction but also with view direction. This is supported by both theoretical arguments and empirical evidence (23, 24). Such reflectance variations are due in part to the proportions of shaded and sunlit foliage changing with view/illumination directions. The view/illumination factor is potentially important for identifying particular canopy structural features such as wheat heads, a prominent part of a headed wheat canopy at large zenith view/illumination angles.

The relationship between agronomic and spectral characteristics of crops primarily involves canopy geometric properties and the optical properties of canopy components. Simple measures of the canopy geometric properties include leaf area index, percent soil cover, and biomass, each indicative of the amount of canopy vegetation present. Figure 8 from Bauer et al. (25) illustrates the effect of the amount of vegetation on the spectral response of spring wheat during the period between tillering and the beginning of heading, when the maximum green-leaf area is reached. As leaf area and biomass increase, there is a progressive and characteristic decrease in reflectance in the chlorophyll absorption region, increase in the near-infrared reflectance, and decrease in the middle-infrared reflectance. The relationships of percent soil cover, leaf area index, fresh biomass, and plant water content with reflectance in selected wavelength bands are shown in Figure 9.

To further quantify the relationship between canopy morphology and reflectance characteristics, Table 1 lists the linear correlations of the five canopy variables with reflectances in the proposed thematic mapper (Landsat-D) and Landsat MSS bands. The correlations and plots include data for the stages of maturity when the canopy is green, seedling through flowering. Fresh biomass, dry biomass, and plant water content correlate most highly with reflectance in the middle-infrared band, 2.08 to 2.35 μm. Percent soil cover and leaf area index are most highly correlated with reflectance in a near-infrared band, 0.76 to 0.90 μm. The visible wavelengths were less sensitive to leaf area and biomass; infinite reflectance was reached at a leaf area index of about two in the visible wavelengths, but had not been reached at the maximum LAI of 3.5 in this data set. Other canopy variables, analyzed but found poorly correlated with reflectance, were plant height, percent green leaves and percent plant moisture. These and other results indicate that the amount of photosynthetically active (green) vegetation has a dominant influence on the reflectance characteristics of crop canopies. Similar results have been reported by Colwell (26) and Tucker (27).

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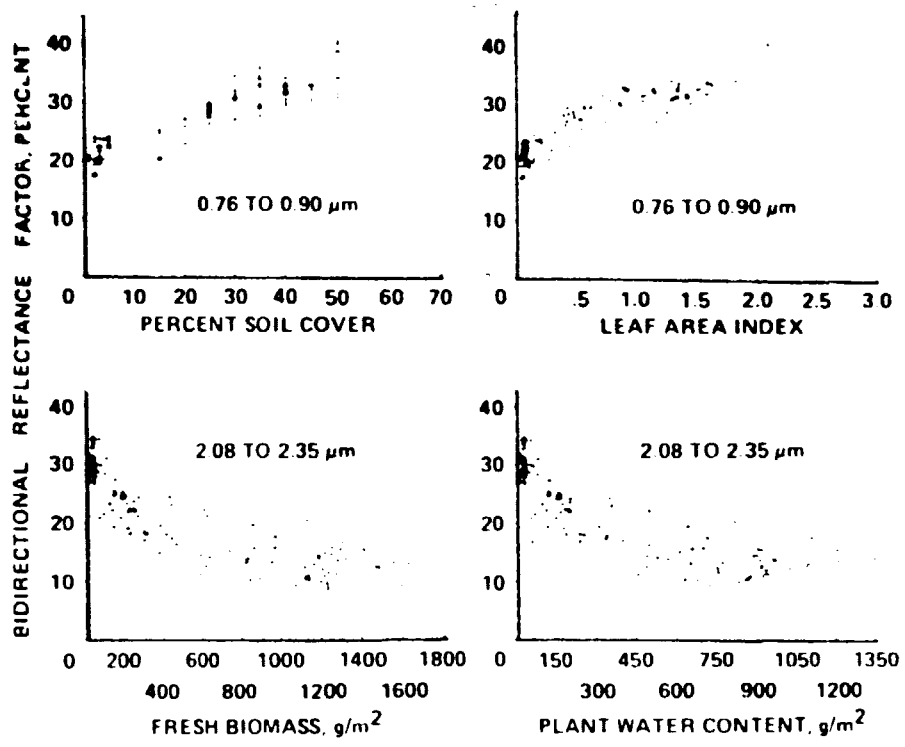

Figure 9. Relationship of percent soil cover, leaf area index, fresh biomass, and plant water content to reflectance in selected wavelength bands (from Bauer et al., 25).

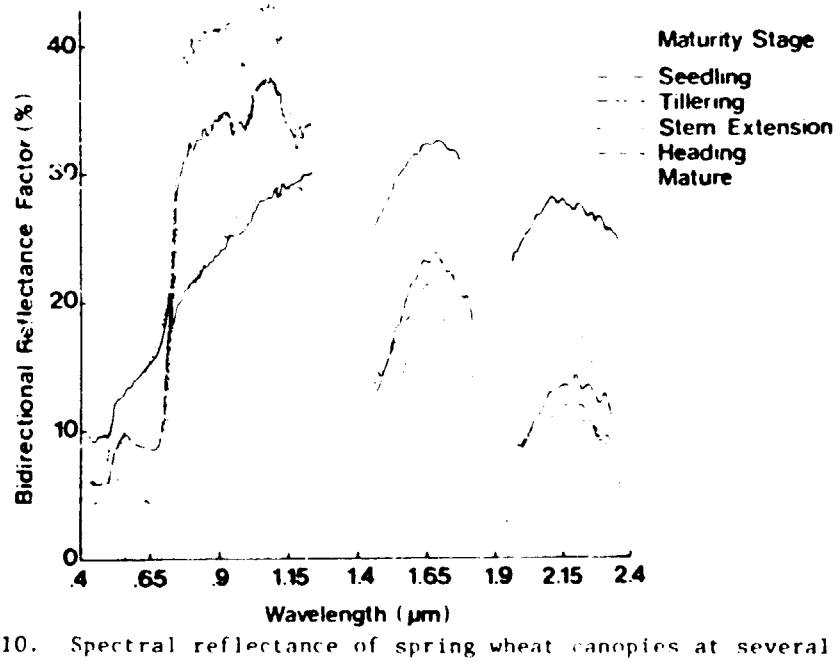

Figure 10. Spectral reflectance of spring wheat canopies at several maturity stages. Measurements were made at Williston, North Dakota during May-August, 1976 (from Bauer et al., 23).

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Plant development and maturity (as opposed to growth or increase in size) result in many changes in canopy geometry and pigmentation of leaves. Figure 10 shows the spectra of spring wheat at several different maturity stages and Figure 11 illustrates the changes in temporal-spectral trajectories of small grains as a function of development stage. Leamer et al. (28) have also studied the effect of development on the spectral reflectance of winter wheat.

The effects of several cultural and environmental factors on the reflectance of spring wheat were investigated with data acquired at Williston, North Dakota by Bauer et al. (23). The effects of available soil moisture on plant growth and spectral response were quite significant. Wheat, planted on land that had been fallow the previous year, had more tillers and, therefore, greater biomass, leaf area, and percent soil cover than the wheat crop grown on land that had been cropped the previous year. These differences caused decreased visible reflectance, increased near-infrared reflectance, and decreased middle-infrared reflectance for the fallow treatment. Planting date caused differences in the amount of vegetation present, as well as differences in maturity stage, which in turn influenced the spectral reflectance. 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, i.e., 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 apparent but were not statistically significant.

In other field experiments conducted by Purdue/LARS (unpublished data) the reflectance of corn canopies affected by H. maydis (southern corn leaf blight) and nitrogen deficiency were measured. The nonsystemic stress of blight and the systemic stress of nitrogen deficiency both affected the spectral response. Compared to healthy corn, blighted corn displayed increased reflectance in the chlorophyll absorption wavelengths and decreased reflectance in the green and reflective infrared wavelengths (Figure 12). The changes in reflectance were attributed to changes in canopy geometry as well as reflectance of individual leaves. Nitrogen deficiency caused increased reflectance in the visible wavelengths and reduced the infrared reflectance compared to the reflectance of canopies with adequate nitrogen fertilization. The changes in reflectance were attributed to lower levels of chlorophyll in the leaves and less leaf area and ground cover. Idso et al. (29) found that varying rates of senescence of winter wheat resulting from different degrees of moisture stress could be determined from visible and near-infrared reflectance measurements of the canopies (Figure 13) and in turn related to grain yield.

Several investigators have used canopy reflectance models, such as the deterministic model of Suits (30) or the probabilistic model of Smith and Oliver (31), to good advantage in promoting our understanding of the spectral properties of crop canopies. The models are particularly useful for studying the effects of altering the values of the input variables (the optical, geometric and directional parameters). The work of Bunnik (34) who investigated the relationships between crop variables, soil background, and geometrical variables and spectral reflectance of crop canopies using the Suits model along with experimental measurements is particularly significant. As a part of his work, Bunnik suggested several spectral parameters or transformations of reflectance measurements in the green, red and near-infrared wavelengths which are related to key agronomic varaibles

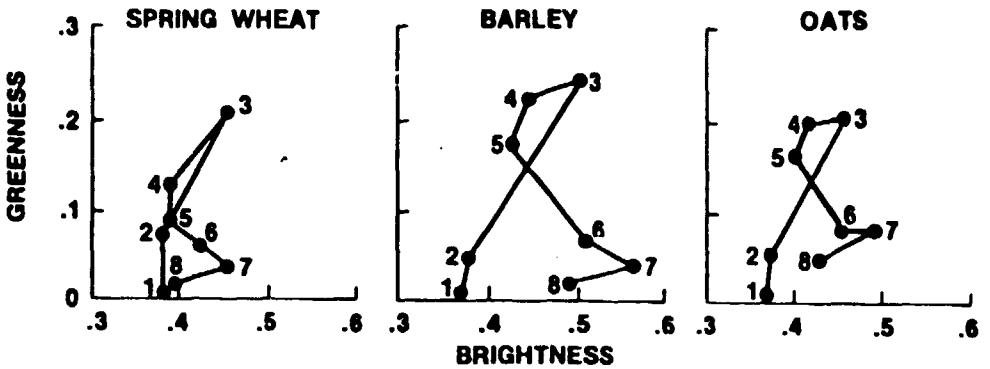

Figure 11. Comparison of selected greenness-brightness trajectories of spring wheat, barley, and oats. The growth stages are (1) seedling, (2) tillering, (3) jointing, (4) heading, (5) milk, (6) dough, (7) ripe, (8) ripe (from Bauer et al., 25).

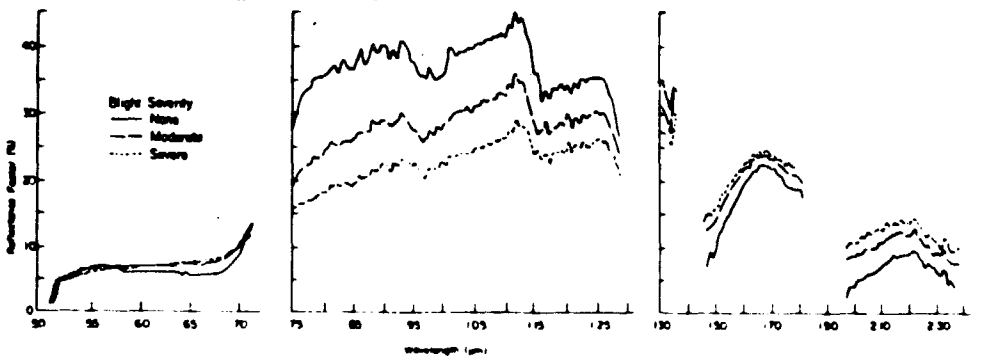

Figure 12. Reflectance characteristics of corn canopies with three levels of leaf blight infection as a function of wavelength (Purdue/LARS unpublished data).

Table 1. The linear correlations (r) of reflectances in the proposed thematic mapper and Landsat MSS wavelength bands with percent soil cover, leaf area index, fresh and dry biomass, and plant water content (from Bauer et al., 25).

Wavelength band, μm	*Percent soil cover*	*Leaf area index*	*Fresh biomass*	*Dry biomass*	*Plant water content*
		Thematic mapper			
0.45 to 0.52	−0.82	−0.79	−0.75	−0.69	−0.76
0.52 to 0.60	−.82	−.78	−.81	−.77	−.82
0.63 to 0.69	−.91	−.86	−.80	−.73	−.81
0.76 to 0.90	.93	.92	.76	.67	.79
1.55 to 1.75	−.85	−.80	−.83	−.79	−.84
2.08 to 2.35	−.91	−.85	−.86	−.81	−.86
		Landsat MSS			
0.5 to 0.6	−0.82	−0.79	−0.81	−0.76	−0.81
0.6 to 0.7	−.90	−.85	−.81	−.74	−.82
0.7 to 0.8	.84	.84	.57	.46	.60
0.8 to 1.1	.91	.90	.77	.68	.79

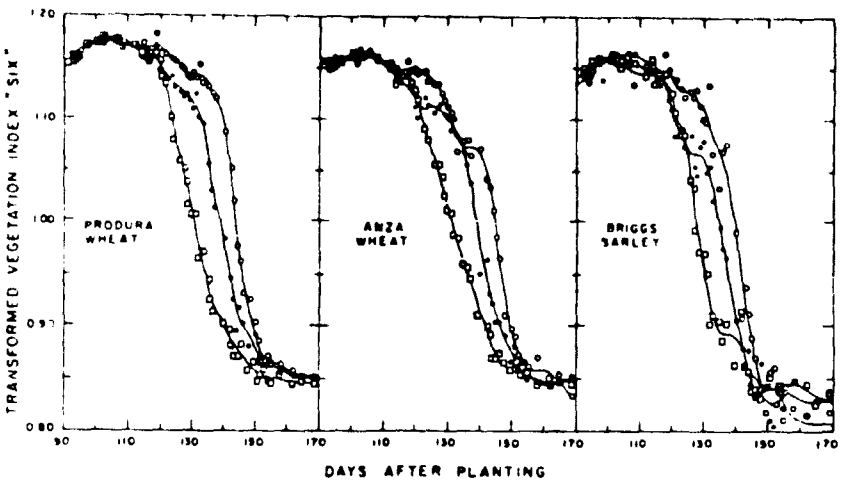

Figure 13. Representative plots of TVI6, a transformation of green and red reflectances, of wheat grown at Phoenix, Arizona with high (o), moderate (·), and low (□) water treatments (from Idso et al., 29).

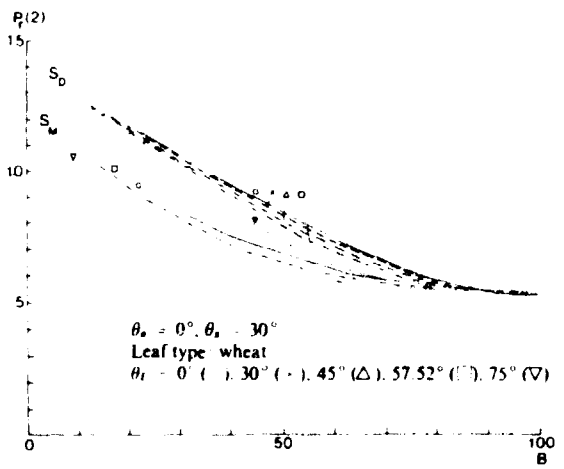

Figure 14. Ratio of canopy reflectance in red and green wavelengths (Pr(2)) as a function of soil cover percentage (B) for dry and moist soils illustrating the use of a canopy reflectance model to evaluate spectral parameters (from Bunnik, 32).

such as leaf area index and percent soil cover, while at the same time being relatively insentive to other factors such as variations in soils background or leaf angle distributions.

Large Area Applications of Remote Sensing

Many investigations of the potential utility of spectral measurements covering large geographic areas have been made since 1972 when the Landsat satellite with a four-band multispectral scanner (MSS) was launched. Only a few of these for crop condition assessment and soil mapping will be cited here. Thompson and Wehmanen (33) developed a technique utilizing transformed Landsat MSS data for detection and monitoring of agricultural drought in the U.S. Great Plains and the Soviet Union. The technique, green index number, agreed well with a ground-based crop moisture index. Wiegand et al. (34) showed that leaf area index (LAI) of wheat might be estimated from Landsat MSS data and for the first time enable LAI inputs to crop evapotranspiration, growth and yield models for large geographic areas.

Analyses of satellite-acquired multispectral data should aid soil scientists a great deal. Landsat data provides information in the visible and near-infrared portion of the spectrum with a synoptic view over a much greater area than is possible with aerial photography. Early Landsat research showed that gross variations in soil features could be identified. The synoptic view enabled the observation and delineation of repeating soil patterns, land use, slope effects, and drainage patterns. Soil association maps have been prepared by Westin and Frazee (35) from interpretations of Landsat imagery and more recently Weismiller and Kaminsky (36) demonstrated how computer-aided classifications of Landsat MSS data, together with ancillary data maps such as topography or parent material, can be used as field mapping aids by the soil surveyor.

Reflections on Future Research

Major advancements have been made in the development and application of remote sensing of agricultural scenes during the past decade. Although the interaction of radiation with plant leaves and soil is reasonably well known, the physical-biological meaning of variations in the spectral responses of crops and soils in the field is less clear. Planned improvements in the spectral, spatial, and temporal resolution satellite sensor system will certainly improve the capability to identify, monitor, and map agricultural crops and soils; however, research, both applied and basic, will be needed to fully realize the potential value of multispectral remote sensing. Recommended areas of research include:

-- Continued development of data bases containing agronomic, spectral, and atmospheric-meteorological measurements and observations acquired under carefully controlled, well documented conditions. Measurements for a wide variety of crop, soil, and environmental conditions, including normal and stressed, are needed. Spectral measurements should include the reflective, thermal and microwave regions. Polarization measurements should also be considered along with off-nadir view angles.

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-- Rigorous analysis and physical modeling is needed to quantify the optical, geometric and agronomic properties of crops and soils. A combined approach of modeling and field experiments is recommended. Model development should occur at scene, canopy, and subcanopy levels. Models for row crops and "mixture" pixels are particularly important.

-- New spectral parameters or feature sets utilizing transformations of spectral measurements with which to identify and describe specific crop-soil classes such as development stage, leaf area index, degree of stress, or surface soil moisture level should be investigated.

In summary, we believe that an increased understanding of the spectral properties of crops and soils will lead to significant applications of multispectral remote sensing in identifying, monitoring and mapping agricultural crops and soils.

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