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SPECTRAL INTERRELATIONSHIPS BETWEEN VEGETATION AND THE SOIL BACKGROUND

by

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ABSTRACT

The spectral characteristics of vegetation have been studied intensively for many years and much has been learned concerning the interrelationships between reflectance and the pigmentation, moisture content, and internal structure of leaves. Much of the early work was conducted using laboratory of equipment, largely because suitable radiometers for obtaining *in situ* field spectra were not available. However, accurate and efficient field spectral radiometers have become available during the past few years, and have enabled a significant improvement to be achieved in our understanding the spectra of soils and vegetation, and their interrelationships.

Analysis of *in situ* field spectra indicate that proper consideration of the spectral characteristics of the soil background may be critical for many agricultural and rangeland applications of multispectral scanner data. This paper discusses the key factors which influence the spectral characteristics of vegetation and soil, and the impact that the soil background can have on the integrated spectral response measured by multispectral scanner systems. The implications of the soil background are discussed in relation to applications involving the use of MSS data to evaluate crop disease situations and to estimate rangeland biomass.

INTRODUCTION

The advent of Landsat-1 heralded a new age in data collection and analysis techniques for any types of resource inventories. There have been numerous studies to identify the type and condition of croplands, forests, and rangelands using Landsat and other types of remotely sensed data. Because the Landsat multispectral scanner system simultaneously obtains data in different wavelength bands, there has been increased attention given to understanding the spectral characteristics of various earth surface features. Although much is known concerning the spectral characteristics of vegetation, soil and water features, there are still many aspects of the spatial and temporal variability in spectral response that are only poorly understood. The understanding of such spatial and temporal variations is often essential to effective use of remotely sensed data, particularly to determine the condition or yield of various types of vegetative cover. Frequently, attention has been focused on the reflectance characteristics of the vegetative cover types of interest, but insufficient attention has been given to the soil background. It is our belief that because multispectral scanner data represents the integrated reflectance from the vegetation (both the green, living and the dry, dead components), the soil background, and also the shadows, attention must be given to all aspects of the scene which influence this integrated spectral response. Particular attention should be given to the spectral characteristics of the soil in situations where the vegetative canopy is relatively sparse.

Before addressing the question of intregrated scene characteristics, a brief review of the factors dominating spectral reflectance from vegetation and soil appears appropriate.

SPECTRAL REFLECTANCE OF VEGETATION

The spectral reflectance of green vegetation is quite distinctive and varies considerably as a function of wavelength. Figure 1 shows a typical spectral reflectance curve for healthy, green vegetation, and indicates that the reflective portion of the spectrum from 0.4-2.5 μm can be divided into three major regions, based upon energy-matter interactions. In the visible wavelengths (0.38-0.72 μm), the plant pigments (especially chlorophyll) will absorb most of the energy impinging on green vegetation. There is a low reflectance in the chlorophyll absorption bands at approximately 0.45 and 0.65 μm, but less absorption and therefore higher reflectance in the green wavelengths (approximately 0.55 μm) between the two chlorophyll absorption bands. In the near-infrared region (approximately 0.72-1.3 μm) only very small amounts of energy are absorbed, and nearly all the energy is either reflected from or transmitted through the leaf. The level of reflectance is largely controlled by the internal structure, or histology, of the leaf [1, 2]. In the middle-infrared wavelengths (approximately 1.3-3 μm), most of the energy not absorbed by the water in the leaf will be reflected, leaving relatively small amounts to be transmitted. In these wavelengths, the amount of energy absorbed is a function of total water content of the leaf, which is related to both the percent moisture content and the leaf thickness [3].

Interrelationships between the amount of energy being absorbed, transmitted, or reflected from a leaf can be defined using the energy balance equation:

$$I_\lambda = R_\lambda + A_\lambda + T_\lambda \qquad (1)$$

where I = incident energy at a particular wavelength, λ
R = reflected energy
A = absorbed energy
T = transmitted energy

As indicated above, plant pigments control the spectral response in the visible portion of the spectrum. Generally, chlorophyll is the dominant pigment, but other pigments can cause distinct differences in reflectance, but only in the visible wavelength.

Figure 2 is an excellent example of pigmentation effects. These curves were obtained from a single leaf of a variegated coleus plant, different portions of the leaf containing distinct differences in pigmentation. Since there were no differences in internal cell structure or moisture content between areas on the leaf, there were no significant differences in reflectance in the near-infrared or middle-infrared portions of the spectrum.

Differences in the internal structure of vegetation can cause distinct and often significant differences in the level of reflectance in the near-infrared portion of the spectrum. Figure 3 shows cross-sections of corn and soybean leaves to illustrate the differences in internal cell structure that are found between these two species of plants. As can be seen, the internal structure of the leaves is significantly different, particularly in that the dicotyledonous plants (e.g. soybeans) have layers of vertically-oriented palisade cells near the top of the leaf whereas monocotyledonous plants (e.g. corn) have an undifferentiated mesophyll. Figure 4 contains the averaged spectral reflectance curves for 308 soybean and 382 corn leaves, all obtained for leaves in a green healthy condition and having moisture contents ranging from 66-80%. The curves are very similar throughout the visible wavelengths, but in the reflective infrared wavelengths the soybeans have a significantly higher reflectance than the corn. This is caused primarily by the structural difference between the monocotyledonous (e.g. corn) and dicotylendonous (e.g. soybean) leaves, the dorsi-ventral structure of the dicotyledonous leaves usually causing a higher level of reflectance.

The fact that very little energy is absorbed in the near-infrared wavelength regions results in significantly higher levels of reflectance in the near-infrared region due to an additive reflectance phenomena from multiple leaf layers. Since approximately half of the energy impinging upon a leaf is transmitted through the leaf, and half is reflected, one finds that multiple leaf layers will have an additive effect upon the total level of near-infrared relectance from a plant canopy. This multiple-leaf-layer effect is clearly indicated in Figure 5, which shows that as more leaf layers are added (up to a maximum of about six layers according to Myers [6]), dramatic increases occur in the level of near-infrared reflectance.

Reflectance of vegetation in the 1.3-3 μm middle-infrared region is dominated by the total water content present in the leaves [3]. As leaves undergo senescence, the moisture content of the foliage decreases, thereby causing distinct increases in reflectance, not only in the water absorption bands but in the wavelengths in between the water absorption bands. This phenomena is shown in Figure 6, in which averaged corn leaf spectra are shown for four different moisture content groupings. At the very low levels of moisture content associated with the top two curves, the plants were dead or dying and the increase in reflectance is significant throughout the entire reflective portion of the spectrum. The increase in reflectance in the middle-infrared region was due to the decreased moisture content in the leaves; in the near-infrared, the increased reflectance was caused by a collapse of the internal cell structure of the leaves; and in the visible wavelengths, the increased reflectance was caused by the decreased chlorophyll content of the vegetation.

It is clear from the above discussion that variations in pigmentation, the histologic and morphologic characteristics of the vegetation, and the moisture content of the foliage can cause distinct variations in spectral reflectance from vegetation. However, it is important to note that most remote sensing applications are involved with turgid green vegetation in a healthy condition. In these situations, we do not see the distinct differences in pigmentation shown in Figure 2, nor do we see the distinct differences due to senescing vegetation shown in Figure 6. Instead, we are looking for spectral differences between species or vegetative cover types (i.e., groups of species commonly found in association with each other). Usually, the differences in spectral response between the cover types of interest are relatively modest, as was shown in Figure 4. Figure 7 shows the reflectance curves for three species of trees, and we see that the differences in spectral response between these three species is not very great. In general, one could say that turgid green vegetation of one species tends to look very much like turgid green vegetation of another species, the differences between species being rather subtle!

SPECTRAL REFLECTANCE OF SOIL

As discussed in the preceding section, different species of vegetation tend to have very similar spectral reflectance characteristics when the vegetation is in a normal healthy green condition. With different soils, this is not the case in that different soil types will tend to have striking differences in spectral response, as can be seen in Figure 8. One of the most outstanding features of spectral reflectance from dry soils is the generally increased level of reflectance with increased wavelength throughout the 0.4-2 μm portion of the spectrum. As compared to vegetation, spectral reflectance curves for most soil materials are generally much less complex. Since all incoming energy impinging upon a soil surface will be either absorbed or reflected, the energy-matter interactions are also less complicated for the soil materials than they are for vegetation. However, the soil itself is a very complex mixture for inorganic and organic materials having various chemical and physical properties which can significantly affect the absorption and reflectance characteristics of the soil. Therefore, although the shape of the curves shown in Figure 8 are somewhat similar, one must consider several important properties of the soil which can cause significant differences in the amplitude of the spectral response. The key factors influencing spectral response from soil include both temporary influences and relatively permanent physical characteristics of the soil. Temporary influences of significance include the moisture content of the soil and the roughness of the soil surfaces. Relatively permanent soil characteristics of importance include the soil texture (i.e., relative percentages of sand, silt and clay in the soil) as well as the amount and condition of organic matter and iron oxide.

Figure 9 is an excellent example of the relationship between moisture content and reflectance characteristics of a silt loam soil. As indicated in this figure, there is also a hydroxyl absorption band at approximately 2.2 μm which is apparent in the spectral reflectance curves of many soils.

It is important to note that even though there is a distinct relationship between moisture content and reflectance of a particular soil type, different soil types may cause confusion. An example of this is shown in Figure 10 in which two different soil types, one in a dry and one in a wet condition, have almost identical spectral reflectance characteristics. Therefore, before one could simply relate the amplitude of reflectance to moisture content, one would first need to know the soil type involved.

The second temporary factor that often influences the amplitude of reflectance from a soil surface involves the surface roughness of the soil. Figure 11 shows field spectra of a crusted soil surface and then the same area a few minutes later after the soil crust had been broken, thereby creating a relatively rough soil surface condition. The relatively smooth crusted soil surface produces a much higher level of reflectance than the rougher broken soil surface. This type of phenomena is often observed on aerial photos and satellite data while spring plowing is underway.

Turning now to the permanent soil characteristics of significance, the first factor to consider is that of texture of the soil. Soil texture affects the spectral reflectance because of the influence on the moisture holding capacity of the soil and also because of the size of the soil particles themselves. Very fine textured soils, such as clays, have a high moisture holding capacity and therefore the water absorption bands will be distinct, even for soils in air-dry condition. As can be seen in Figure 12, the water absorption bands discussed previously are very apparent for both clay and sandy soils that are in a moist condition, as well as for the clay soil in an air-dry condition. The sandy soils in the air-dry condition retain very little of the moisture content and therefore the water absorption bands are not apparent. Soil texture also influences the general reflectance level of the surface soil. If other factors are constant, as the particle size of the soil is decreased, the soil surface will become smoother, causing less incoming energy to be trapped between the soil particles and creating shadow effects between the soil particles, thereby allowing a larger proportion of the incoming energy to be reflected. Bowers and Hanks [7] calculated that an increase in particle size from 0.22 to 2.65 mm would cause at least a 14% increase in absorption of incoming solar radiation.

The organic matter content present is another soil property that can significantly influence the reflectance characteristics of a soil. Organic matter contents found in most temperate regions range from approximately 0.5 to 5%, and a soil having a 5% organic matter content will normally appear rather black or dark brown in color [10]. Lower amounts of organic matter content will result in gray or lighter brown colors. The relationship between organic matter content and reflectance in the visible portion of the spectrum is clearly shown in Figure 13. This relationship between organic matter content and reflectance is not constant, and the drainage condition and climatic region in which the soil of interest is located must also be considered, since the degree of decomposition of the organic matter will influence the color. In tropical regions, for instance, soils that are very black in color may have a significantly lower organic matter content than would be the case for a similarly dark colored soil located in a tropical region.

A fifth factor that can significantly influence the spectral reflectance characteristics of soils is iron oxide. The red colors of many soils are generally related to unhydrated oxide, although partially hydrated iron oxide and manganese dioxide can also cause this red coloration in the soil [10]. As shown in Figure 14, an increase in iron oxide can cause a very significant decrease in reflectance, at least in the visible portion of the spectrum.

To summarize this discussion of soil reflectance characteristics, we have seen that an increased reflectance is often highly correlated with decreased moisture content, decreased roughness of the soil surface, decreased soil texture particle sizes, decreased organic matter content, and decreased amounts of iron oxide present in the soil. Although some of these effects are temporary in nature, many are permanent and are the cause of very distinct differences in the level in spectral reflectance, as was shown in Figure 8.

RELATIONSHIPS BETWEEN VEGETATION AND SOIL REFLECTANCE

Thus far, we have discussed the characteristics of vegetation and soil reflectance. Next, let us examine how vegetation and soil spectral reflectance interrelate to influence remotely sensed imagery.

A set of curves which show the generalized relationship between reflectance characteristics for vegetation and soil is shown in Figure 15. These are field spectra showing a fairly typical reflectance curve for green vegetation (corn in this case), curves representing a relatively light colored soil and a very dark colored soil, and also curves for clear and turbid water. As can be seen, the differences in level of reflectance between the green vegetation and dark colored soil are relatively small in the visible wavelengths but are very large in the near-infrared. The reverse is true for the light colored soil, which is distinctly different from the vegetation in the visible portion of the spectrum but rather similar in the near-infrared. In the middle-infrared wavelengths, both the light and dark colored soils tend to have distinctly higher levels of reflectance than the vegetation.

The spectra in Figure 15 point out a very interesting relationship. If you are interested in determining the relative amount of vegetative ground cover in a particular area, your success in accurately determining the vegetative ground cover will largely be dependent upon the soil background in relation to the wavelength band with which you are working. For example, if you are working in a very dark colored soil in the visible portion of the spectrum, the soil and vegetation would tend to blend together and you would not be able to obtain an accurate measurement of percent ground cover. On the other hand, for the same dark soil situation, data obtained in the near-infrared portion of the spectrum would very clearly show the difference in spectral response between the vegetation and the soil. Thus, the percent ground cover could be accurately defined in the near-infrared but not the visible wavelengths. The reverse would be true for situations involving light colored soils. In these cases, the near-infrared would not be effective in that the soil and vegetation would have approximately the same level of response, whereas in the visible part of the spectrum the soil would be a much lighter tone than the dark, low reflecting vegetation, and therefore one could clearly differentiate the vegetation from the soil in the visible wavelengths.

An example of vegetation/soil differentiation in the near-infrared portion of the spectrum is shown in Figure 16. These photos show an area in which bud blight in soybeans was being studied. The black and white infrared photo on the left was obtained from an altitude of 2,250 feet above the ground, whereas panchromatic and black and white infrared photos on the right were obtained from an altitude of 500 feet. As can be seen in the photo on the left, there is a marked difference in tonal response between the diseased and healthy soybean plots, the alternating plots of diseased soybeans having a much lower response on this infrared photo. Since the literature often indicates that diseased vegetation has a lower reflectance in the near-infrared portion of the spectrum, one might conclude that the photo on the left is a good illustration of such a phenomena since the diseased plots seem to have a distinctly lower level of reflectance. However, our analysis of the original photos shown on the right indicated that both the diseased and healthy soybean plants had approximately the same high level of reflectance in the near infrared portion of the spectrum, but the diseased plants were much smaller than healthy plants and therefore a much greater percentage of dark soil is visible between the rows of diseased soybeans. On the infrared photos, the larger amount of dark soil being sensed within the diseased plots causes an overall lower response of these plots as compared to the plots of healthy soybeans. This emphasizes that in order to properly interpret any type of remote sensing sensor imagery, we must consider the spectral reflectance characteristics of both the vegetation and the soil, as well as the percentage of the soil surface being covered by the vegetation.

The statement has often been made that diseased vegetation will have a lower response on black and white infrared photography. As was shown in Figure 6, however, senescencing vegetation has an increased reflectance in the near-infrared portion of the spectrum. Similar results have been found in a number of studies in which the reflectance of individual diseased leaves have been measured [6, 15]. This apparent increase in reflectance is opposite to what one would expect based upon the findings of photo-interpreters working with black-and-white as well as color infrared photos. It is our belief that this apparent contradiction does not represent a difference in results but rather indicates that on aerial photography, or spacecraft data, one is seeing the effects of the disease on the plant as a whole. When plants become diseased, the entire morphologic structure of the plant often changes, frequently resulting in a decreased amount of vegetative ground cover and an increased amount of soil being sensed. Therefore, if the soil is relatively dark, one would expect that the overall response on remotely sensed data would show a decreased level of reflectance even though individual leaves might, in fact, have a slight increase in reflectance. Again, one must take into account the soil background and the percent canopy cover in order to properly interpret the spectral response observed from the vegetation and soil combination.

RESULTS OF FIELD SPECTRORADIOMETER STUDIES

During the past several years a number of in situ studies of the spectral responses of crops, particularly wheat, corn, and soybeans have been conducted [15]. Field spectra of data acquired on spring wheat canopies at Williston, North Dakota are shown in Figure 17, and illustrate the changes in spectral reflectance caused by increasing amounts of vegetation and development stage. The changes in spectral response that occur throughout the growing season are dramatic, going from essentially bare soil to dense vegetation and back to dry vegetation (which closely resembles the spectral response for bare soil).

In the summer of 1979, spectral reflectance measurements were made at the Purdue Agronomy Farm to study the effect of soil background, crop density and stage of development on the spectral response of corn and soybean canopies. Plots were established on two soil types: Chalmers silty clay loam, a dark-colored Mollisol, and Fincastle silt loam, a light-colored Alfisol. On each soil type, three planting dates (May 2, 16, and 30), each with three planting densities (25, 50, and 75 thousand plants per hectare) were used in the corn experiment. Spectral reflectance measurements were made at approximately weekly intervals throughout the summer. Along with the radiometric data, photos were obtained for each plot on each of the data collection missions, and reference data were collected on the leaf area index, percent ground cover, stage of development, dry biomass, and condition of the crop.

Reflectance spectra similar to those shown in Figure 17 were developed to show the changes in spectral response that were obtained as a function of growth stage. Another way of looking at the change in level of reflectance throughout the growing season is shown in Figures 18a and b, for corn planted on May 16 at a density of 50,000 plants per hectare. These curves show the change in spectral response throughout the growing season for both soil types, at two specific wavelengths. Figure 18a shows the data for the 0.6-0.7 μm visible wavelengths, while Figure 18b shows the response in the 0.8-1.1 μm near-infrared portion of the spectrum. As shown in Figure 18a, as the canopy cover becomes more complete, (Development Stages 1-3), the relatively low reflectance of the vegetation causes the overall response from the moderately light soil to decrease until a maximum level of canopy cover has been reached (Development Stage 4) and spectral response in this wavelength band is minimal. The moderately dark soil, on the other hand, has a lower response to begin with, and as the vegetative cover increases, the low-reflecting vegetation and the low-reflecting soil blend together, and one sees less of a change in spectral response as a function of plant development. At Development Stage 4 (16 leaves) the amount of vegetative cover or canopy closure (70%) has nearly reached its maximum and the level of response is very low for both soil types. The reflectance remains relatively low through Development Stage 10 when the corn is maturing, but the level of response increases rather dramatically beyond this point as chlorophyll content decreases and more soil is being sensed.

Figure 18b, based on data obtained in the 0.8-1.1 μm wavelength band, also demonstrates the effect the soil background has on the overall level of spectral response. In this case, however, the medium-light colored soil has a moderately high level of reflectance at the beginning of the growing season and as the amount of vegetation increases, the level of spectral response almost doubles, (because the corn has a much higher level of reflectance than the Fincastle silt loam in these near-infrared wavelengths). The corn planted in the dark colored soil has a very low spectral response initially, since the measurements are in fact primarily from the soil. Then, as the percentage of vegetative cover increases, the overall level of reflectance almost triples, until the percentage of ground cover and amount of leaf area has reached maximum, at which time the level of reflectance is essentially the same as that of the canopy over the light soil. At this point, (Development Stage 4), we see no difference in the level of reflectance between the light and dark soil.

These curves clearly show that the soil background has a major impact on the level of reflectance that one sees for vegetative situations in which the canopy closure is not complete. Once the ground cover has reached a maximum, however, there is little difference in the level of reflectance due to soil type. But until canopy closure has reached approximately 70-80%, the soil background will have a major impact on the overall level of response observed in either the visible or near-infrared portion of the spectrum.

A considerable amount of work has been done with ratios of the visible and infrared wavelength bands. Interestingly, by obtaining a ratio of the infrared to visible reflectance, the influence of the soil background is considerably reduced since the ratio value is related primarily to the amount and density of the vegetative cover present.

The potential for ratios to nullify the effect of the soil background on spectral response levels is shown in Figure 19. In this case the infrared-to-visible ratio has been calculated for both the dark and light soil background situations shown in Figures 18a and b, and we see that the ratio values are nearly identical for the two soils throughout the various stages of crop development. However, it is also significant to note that the ratio value changes with increasing canopy density. This relationship is similar to the spectral parameter referred to as "greenness" by Kauth and Thomas [15].

Figures 18 and 19 indicate a rather significant point involving the analysis of remotely sensed data, namely the differences that are encountered when manually interpreting remotely sensed data as opposed to using computer-aided analysis techniques for processing multispectral scanner data. In manually interpreting data from areas with different soil backgrounds, the influence of the soil background on the overall spectral response would be clearly seen and this would have to be taken into account in attempting to evaluate the vegetative density for that particular area. By using computer analysis techniques, the ratio of the infrared and visible wavelengths or other spectral parameters can be easily determined to minimize the soil background effects and display ratio values which are more directly related to differences in vegetative density, regardless of the color of the soil background. It is therefore very clear that ratioing near-infrared and visible data for purposes of assessing vegetative density is one computer analysis technique that has a great deal of potential, particularly in the use of Landsat data to assess the density and condition of rangeland vegetation.

We believe that an understanding of the relationship between spectral reflectance and the canopy coverage or density of the vegetation is very important, since attempts to predict crop yields using satellite data often involve correlations between the measured reflectance and crop canopy factors such as leaf area index, percent canopy closure, vegetative biomass, etc. In addition to crop yield predictions, the relationship between reflectance and biomass is of importance in rangeland and forestry applications. In situations involving forest cover, differences in crown closure or density of the forest stand will cause distinct variations in level of reflectance. This has been shown to be true for both infrared and visible wavelengths, as is indicated in Figure 20. This figure was generated using Landsat data from the San Juan Mountains in southwestern Colorado, in an area of Engelmann spruce-subalpine fir forest cover. In this data, the forest canopy has a relatively low response in both the visible and the near-infrared wavelengths as compared to the highly reflecting dry, dead grass beneath the forest canopy. As is shown, the actual Landsat response values for the partial canopy coverage situations indicate a slightly higher level of reflectance in the infrared bands than had been predicted. Although the relationship is not linear, this example does point out that distinct differences in reflectance will be encountered for forest stands having different densities, at least for situations in which the understory cover has spectral reflectance characteristics which are considerably different from those of the forest canopy itself. It is important to note that if crown closure is complete, there seems to be no indication that the level of reflectance measured with multispectral scanners will be highly correlated with biomass of forest canopies. Because of recent questions involving the increased levels of CO_2 in the atmosphere throughout the world, the potential for measuring vegetative biomass is receiving increased attention. We believe that the relationship between level of reflectance in the optical portion of the spectrum and the biomass in forest canopies where the crown closure is complete and the foliage is dense (such as would be the case in tropical forest areas) would be relatively poor. It is possible that different wavelength bands and polarizations of synthetic aperture radar (SAR) data might allow a better opportunity to correlate biomass and remotely sensed measurements. We believe this to be an area in need of additional investigation.

SUMMARY AND CONCLUSIONS

Reflectance from vegetation varies considerably as a function of wavelength, and is primarily controlled by the pigmentation, histology, and moisture content of the foliage. Soil reflectance tends to vary more uniformly throughout the reflective wavelength region, and is largely controlled by soil texture, the content and condition of both the organic matter and the iron oxide, as well as the surface soil moisture and surface roughness.

Since the multispectral scanners measure the integrated reflectance from the vegetation, soil, shadows and litter, proper interpretation of such data must include consideration of all components of the scene. Many applications are involved with the type and condition of the vegetation present, but it is clear that the soil background will have a very significant influence on the overall spectral response, at least when there is not complete canopy coverage. Light colored soils will influence the overall spectral response more in the visible and middle-infrared wavelengths, whereas dark soils will have greater influence on the near-infrared response.

The use of ratios of near-infrared to visible response values provides a potential for more effective estimates of canopy coverage to be achieved, regardless of the soil background. However, if one is using manual photo interpretation techniques, the color of the soil background can cause significant differences in overall response in either the visible or near-infrared portion of the spectrum.

These results indicate that studies involving the collection and analysis of spectral data obtained in the field for various types and conditions of vegetation and soils are a critically important ingredient in developing our ability to effectively interpret and analyze data obtained from satellite altitudes. More work is needed in both the optical and microwave portions of the spectrum on a variety of crops and soils, forest types, and rangeland conditions to develop a better understanding of the energy/matter interrelationships involved. This knowledge is essential to effective assessment of the capabilities as well as the limitations for using data acquired from space.

ACKNOWLEDGEMENTS

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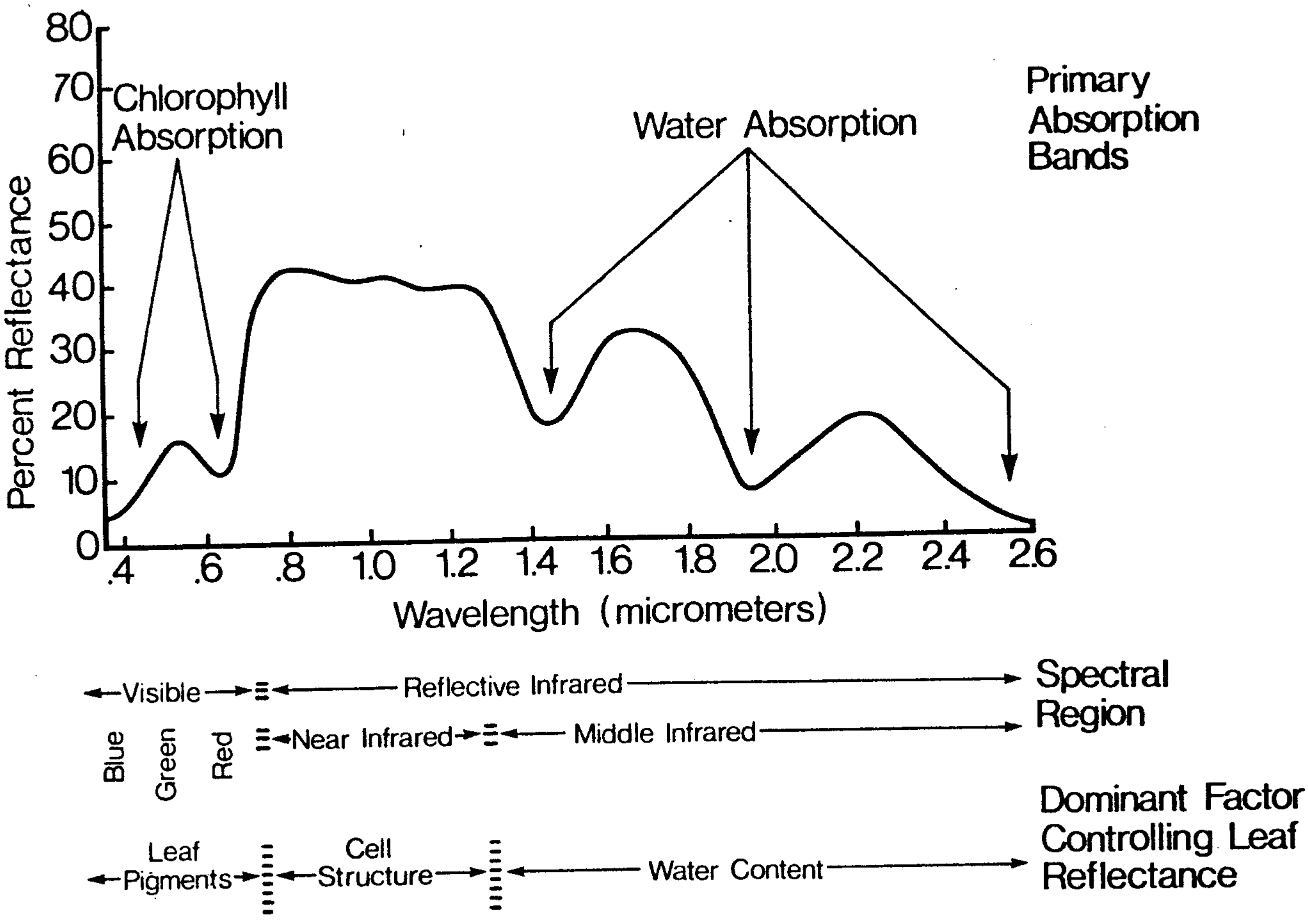


Figure 1. Spectral reflectance characteristics of green vegetation [after 4].

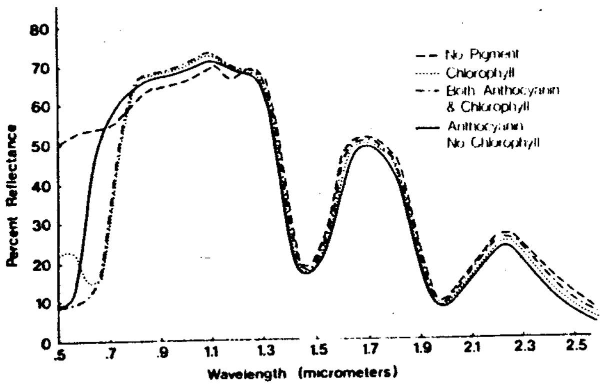


Figure 2. Effects of pigmentation on spectral reflectance [after 4].

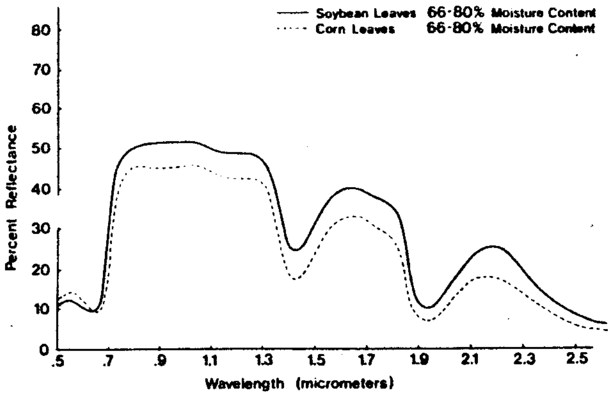


Figure 4. Spectral reflectance of soybean and corn leaves [after 4].

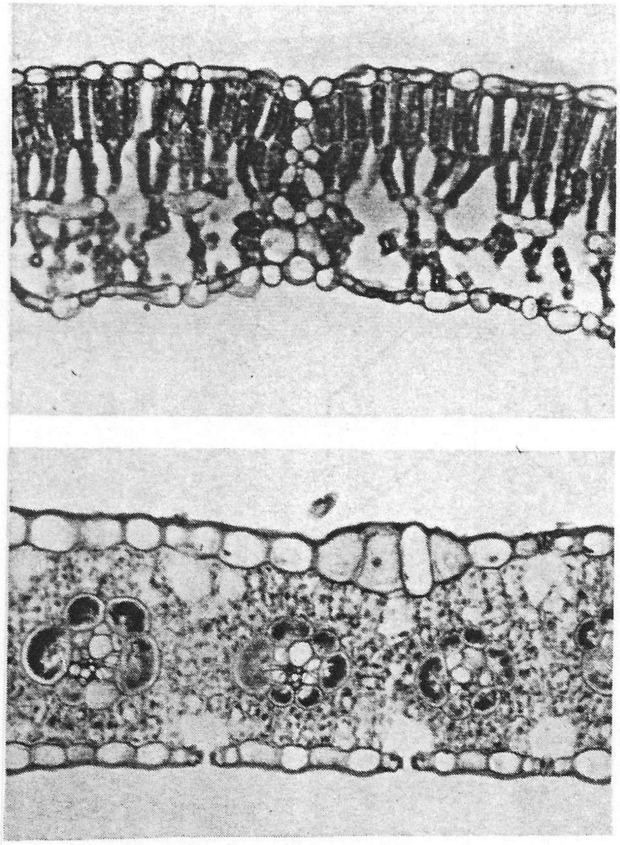


Figure 3. Cross sections of portions of a soybean leaf (top) and a corn leaf (bottom) [from 5].

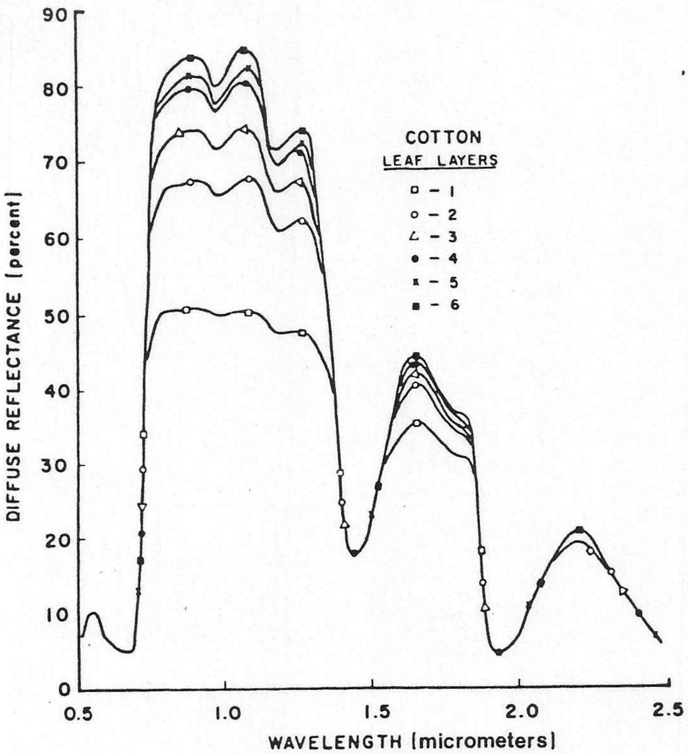


Figure 5. Effects of multiple leaf layers on spectral reflectance [from 6].

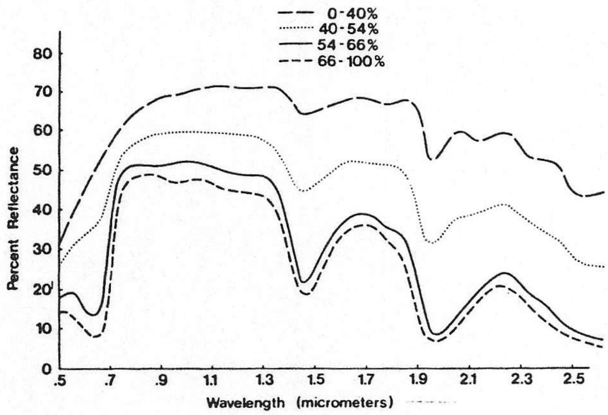


Figure 6. Effects of senescense on reflectance of corn leaves [after 4].

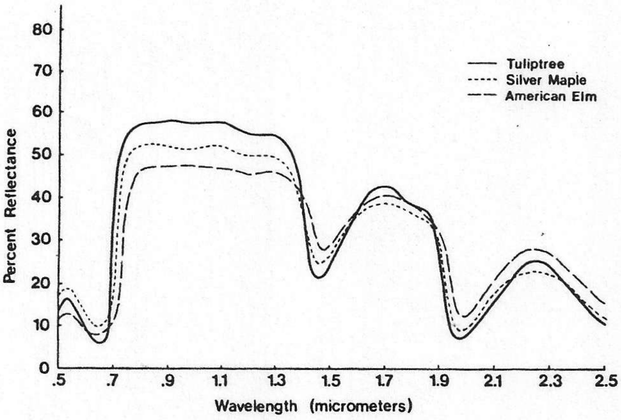


Figure 7. Spectral reflectance for three species of trees [after 4].

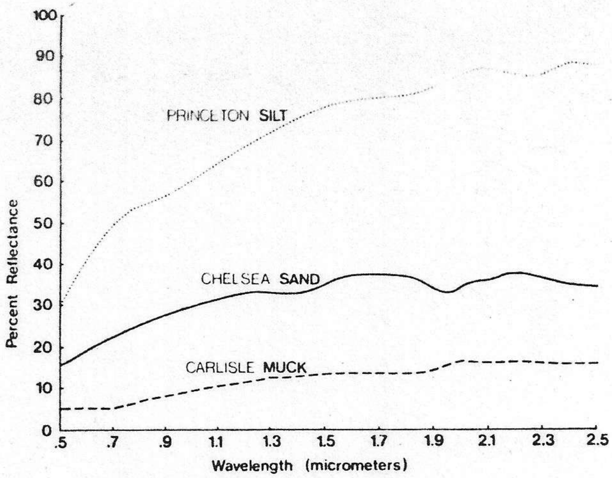


Figure 8. Spectral reflectance for three soil types, all at an air-dry moisture content [after 3].

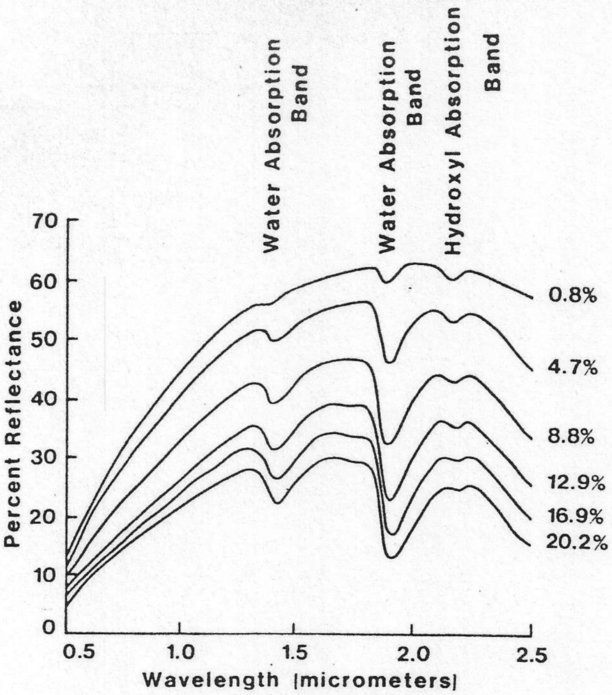


Figure 9. Spectral reflectance of Newtonia silt loam at different moisture contents [after 7].

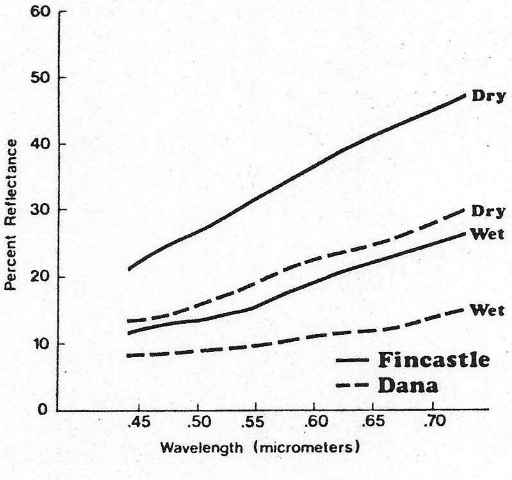


Figure 10. Field spectra of two different soil types at different moisture contents [after 8].

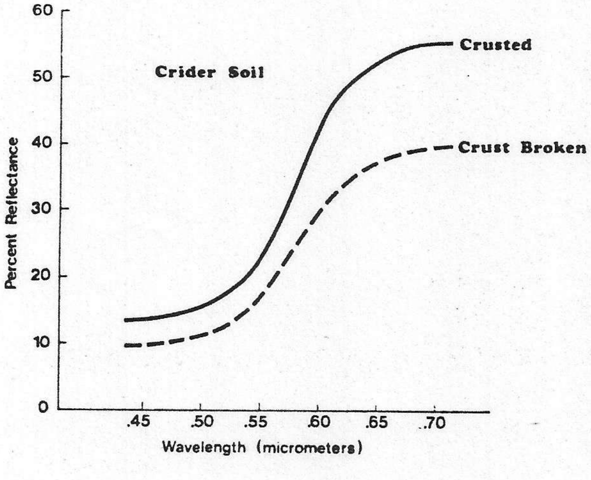


Figure 11. Effect of a crusted surface on soil reflectance [after 8].

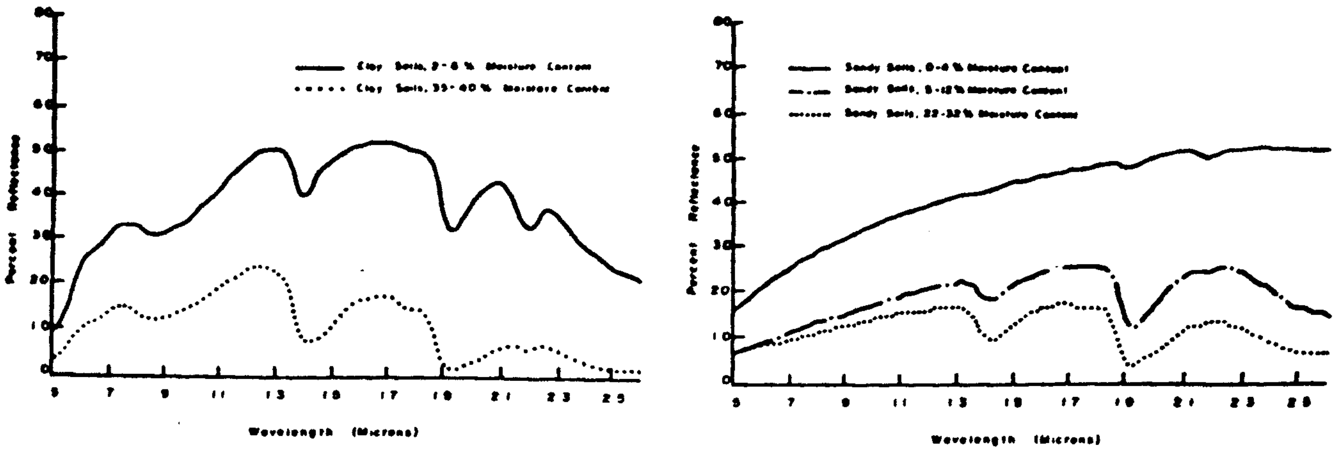


Figure 12. Spectral reflectance of a typical clay soil at two moisture contents (left) and a typical sandy soil at three moisture contents [after 4].

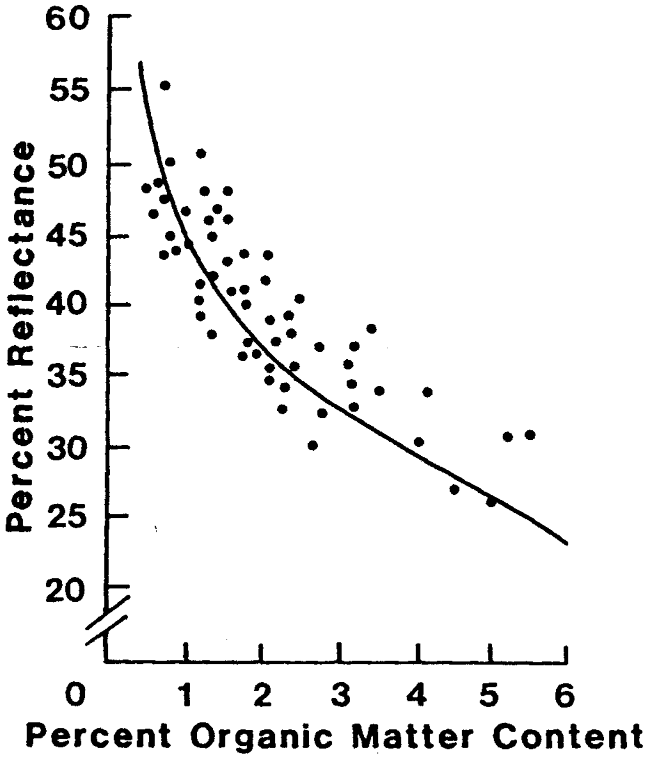


Figure 13. Relationship between reflectance and organic matter content in soils [after 11].

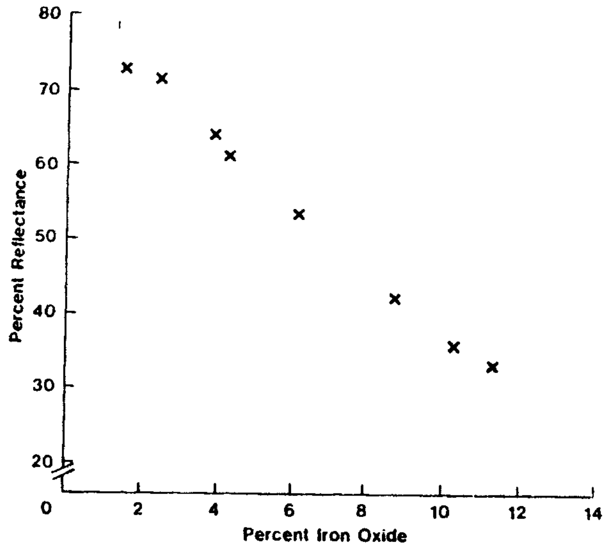


Figure 14. Relationship between iron oxide and soil reflectance [after 12].

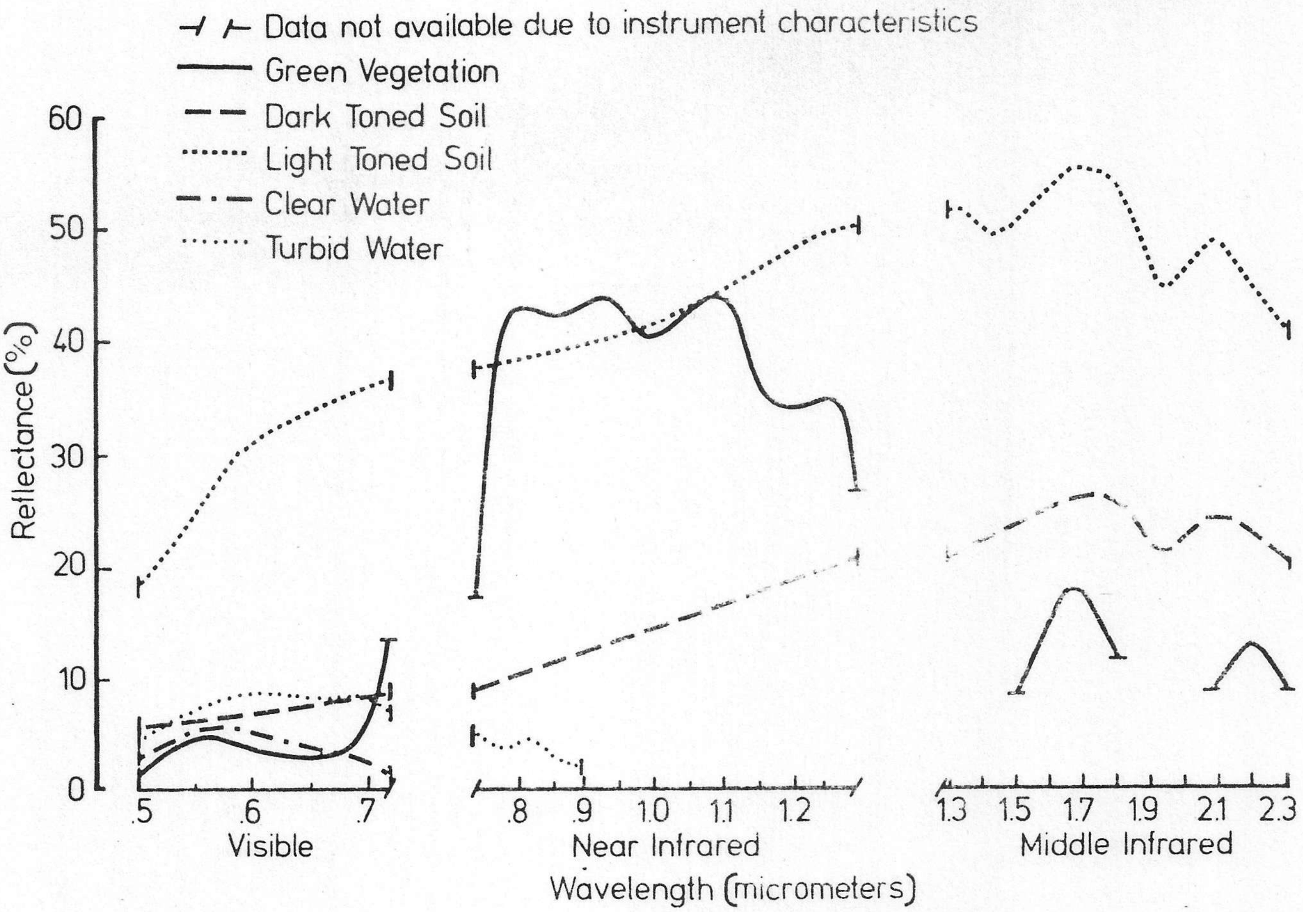
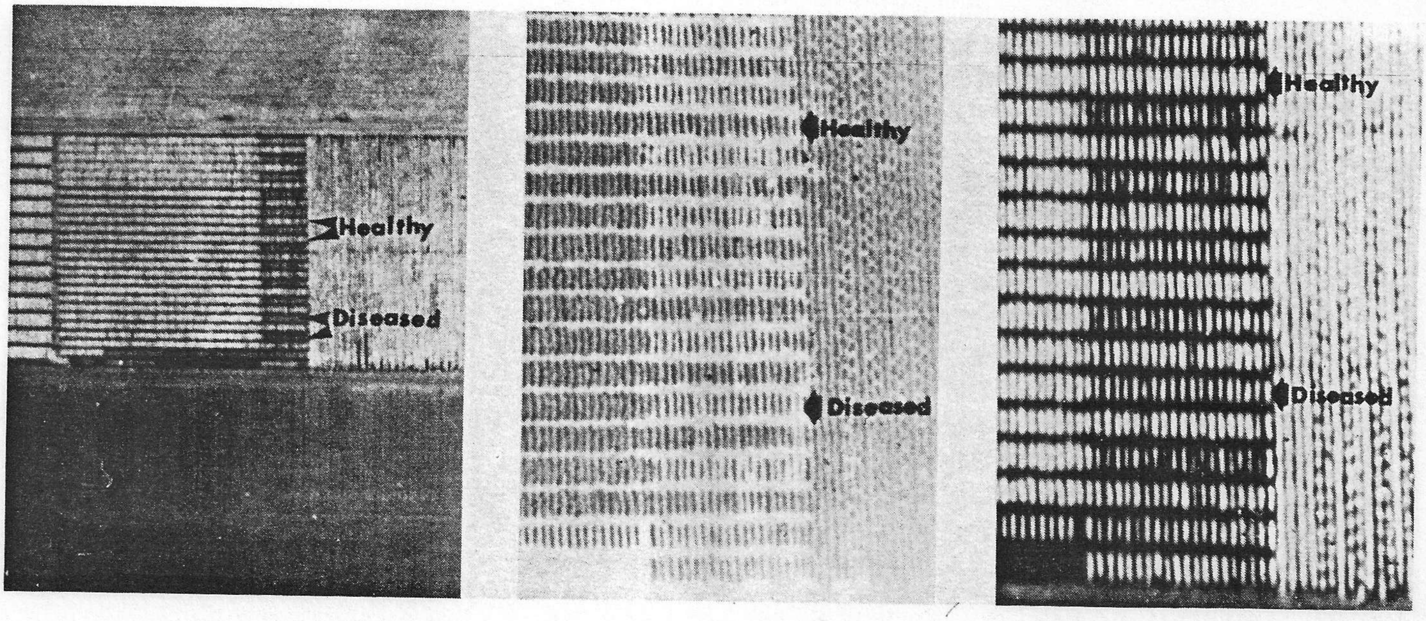


Figure 15. Field spectra of green vegetation, light and dark soil, and clear and turbid water [after 3].



0.7–0.9 μm
(2,250 ft)

0.4–0.7 μm

(500 ft)

0.7–0.9 μm

Figure 16. Photos of diseased and healthy soybean plots obtained at two scales [from 14].

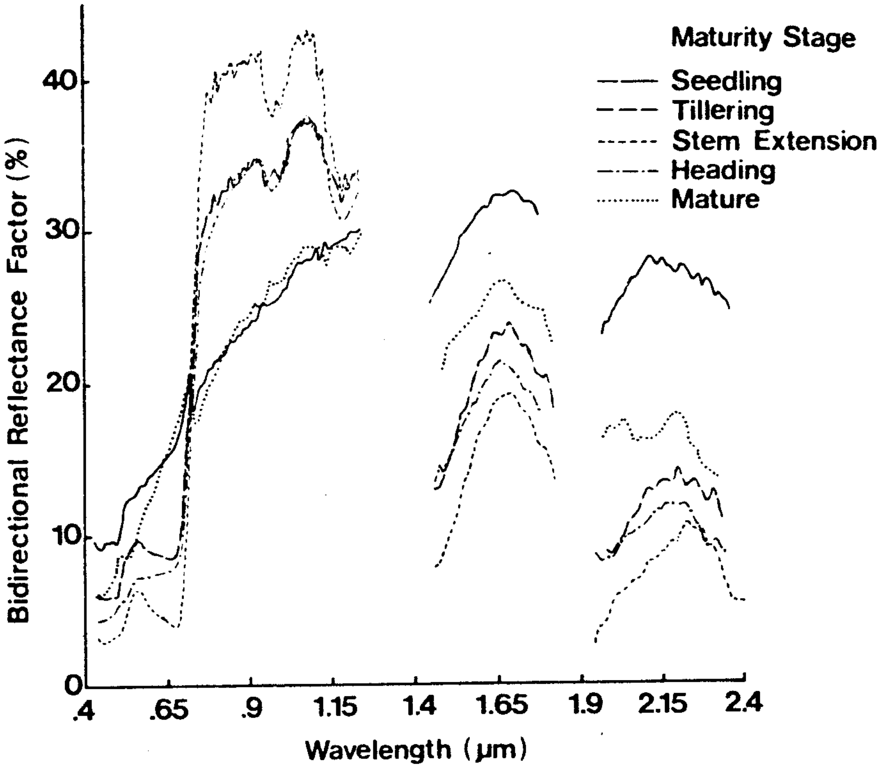


Figure 17. Spectral reflectance of spring wheat canopies at several maturity stages [from 16].

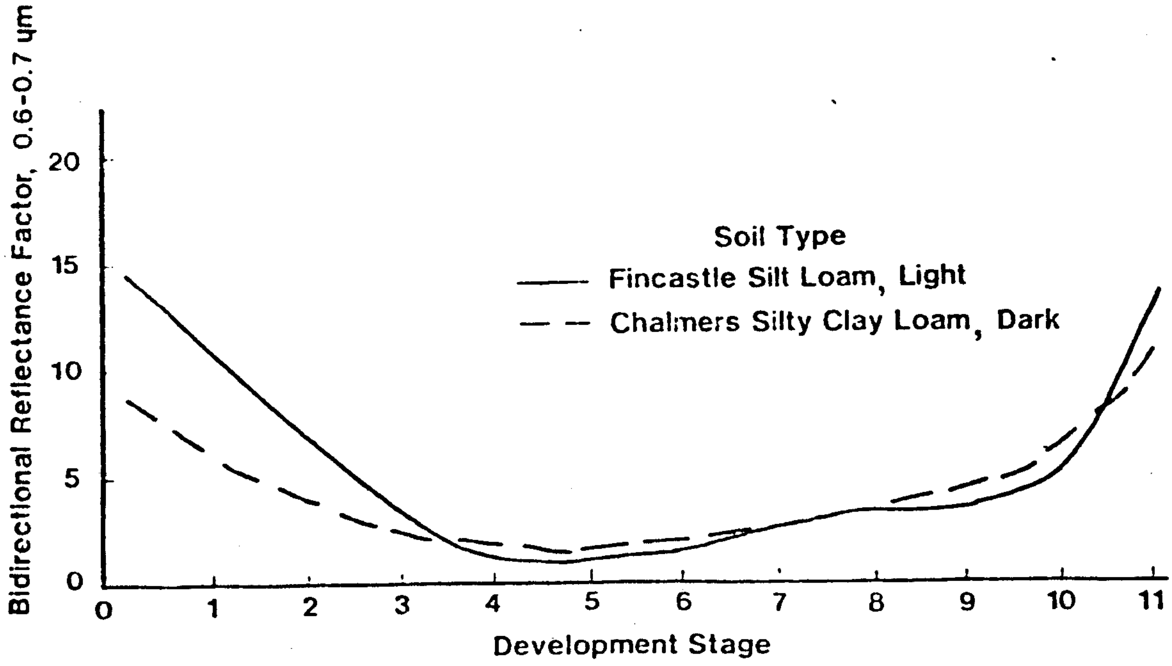


Figure 18a. Relationship between reflectance and development stage of corn in the 0.6–0.7μm wavelength band.

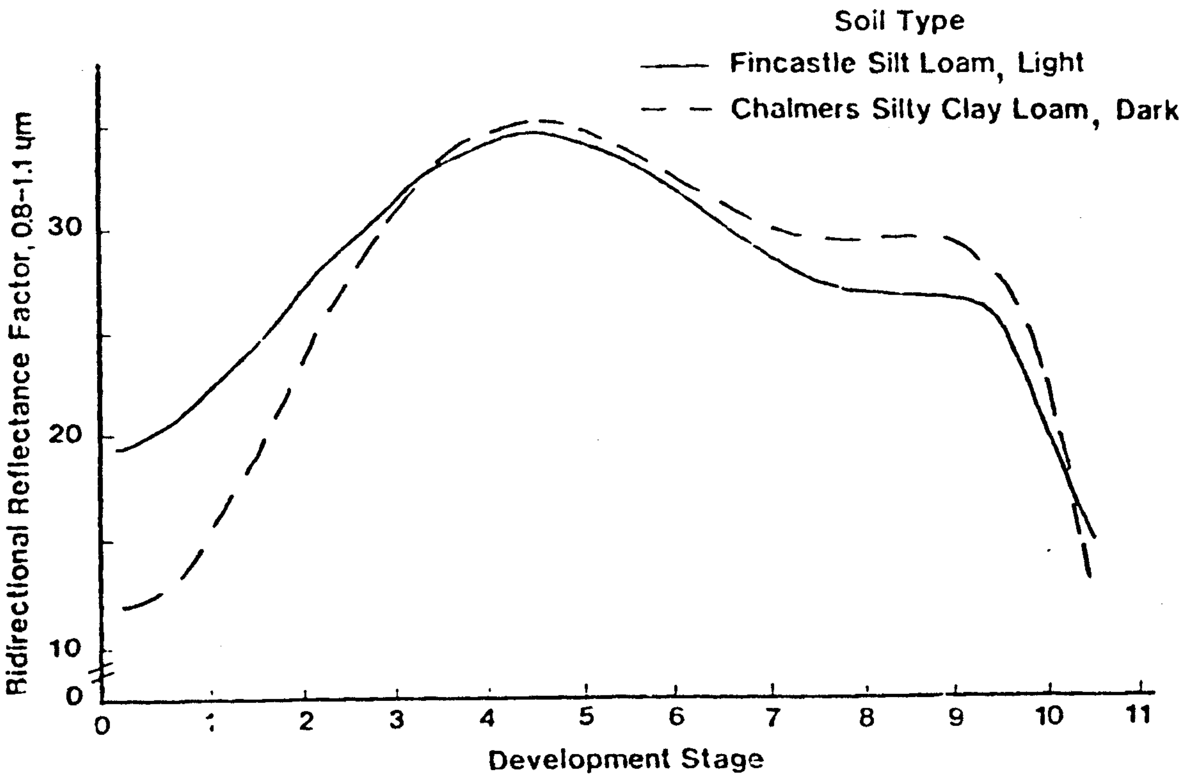


Figure 18b. Relationship between reflectance and development stage of corn in the 0.8-1.1µm wavelength band.

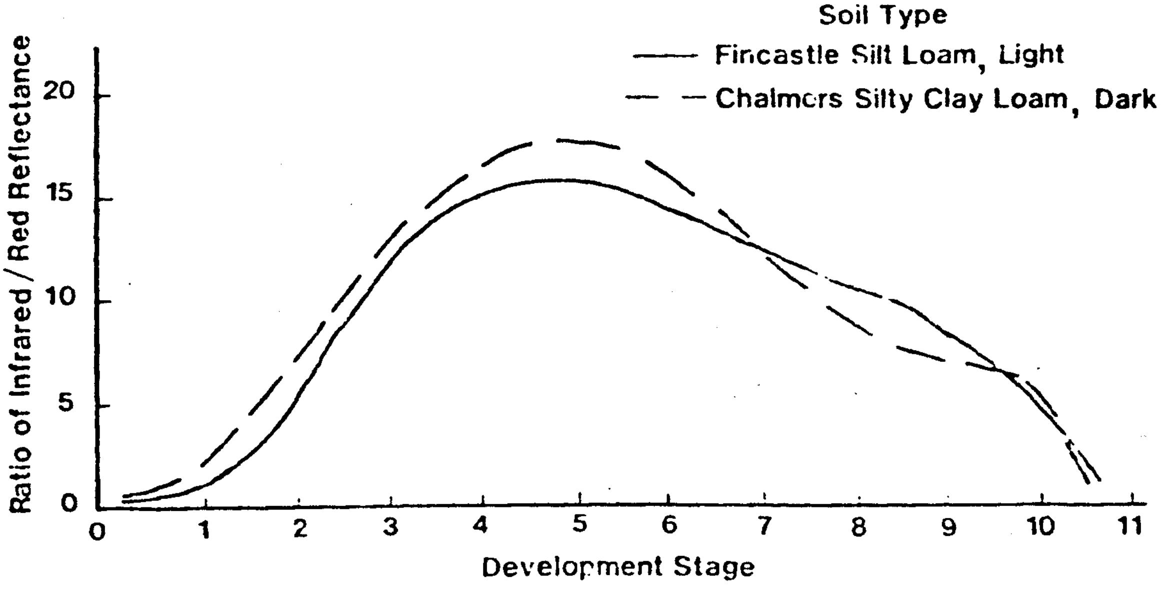


Figure 19. Relationship between development stage of corn and infrared to red reflectance ratio values.

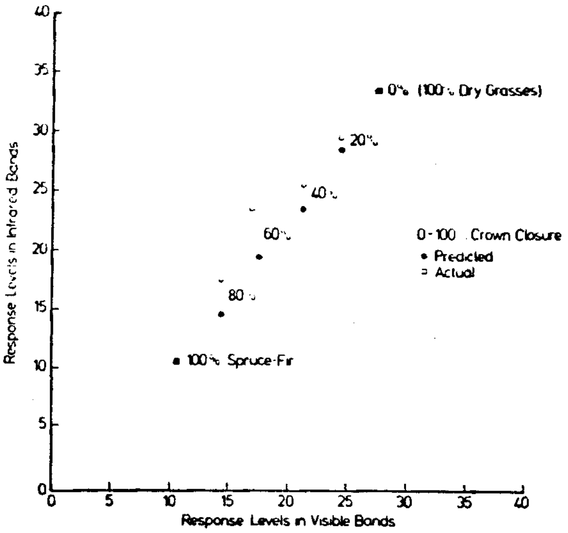


Figure 20. Spectral response in relation to percent crown closure for the spruce/fir cover type [from 16].