Physical and Physiological Basis for the Reflectance of Visible and Near-Infrared Radiation from Vegetation

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Abstract

Knowledge of how solar radiation interacts with vegetation is necessary to interpret and process remote sensing data of agricultural and many natural resources. A plant leaf typically has a low reflectance in the visible spectral region because of strong absorption by chlorophylls, a relatively high reflectance in the near-infrared because of internal leaf scattering and no absorption, and a relatively low reflectance in the infrared beyond 1.3 μ because of strong absorption by water. The reflectance of a plant canopy is similar, but is modified by the nonuniformity of incident solar radiation, plant structures, leaf areas, shadows, and background reflectivities. Airborne sensors receive an integrated view of all these effects, and each crop or vegetation type tends to have a characteristic signature which permits its discrimination. When disease and physiological stresses directly affect the reflectance properties of individual leaves, the most pronounced initial changes often occur in the visible spectral region rather than in the infrared because of the sensitivity of chlorophyll to physiological disturbances. The primary basis for the detection of stress conditions in a crop or other plant community by aerial remote sensors often, however, is not a change in the reflectance characteristics of individual leaves, but a reduction in the total leaf area exposed to the sensors. This reduction can result from a direct loss of leaves, a change in their orientation, or an overall suppression of plant growth. In such cases the total infrared reflectance tends to be decreased relatively more than the visible reflectance because of a reduction in the infrared enhancement due to fewer multiple leaf layers and because of an increase in background exposure.

Introduction

Remote sensing of agricultural and other earth resources involves the detection of electromagnetic energy that is reflected or emitted from the complex assemblage of biological, geological, and hydrological features at the earth's surface. The data obtained can be meaningfully interpreted and processed only if we have a fundamental understanding of the energy-matter interactions at the earth's surface that account for variations in the quantity and quality of radiation recorded by the air- and space-borne sensors. This knowledge also is necessary for us to derive new applications of existing remote sensing systems and to design new systems capable of sensing and recording potential and predictable differences in data.

The purpose of this paper is to discuss the physical and physiological basis for the reflection of visible and near-infrared solar radiation from plant leaves and vegetation canopies. This discussion is particularly pertinent to the remote sensing techniques of photography and multispectral sensing for obtaining information about agricultural crops, forests, and range. This paper is not a comprehensive review of the literature on leaf reflectance. Such reviews have been prepared previously (Clark, 1946; Gates et al., 1965; Steiner and Gutermann, 1966), most recently by Myers and Allen (1968).

Leaf Reflectance Characteristics

A typical reflectance spectrum of a plant leaf is given in Fig. 1. The curve shows the percent reflectance of the energy incident to the leaf as a function of the wavelength of incident energy
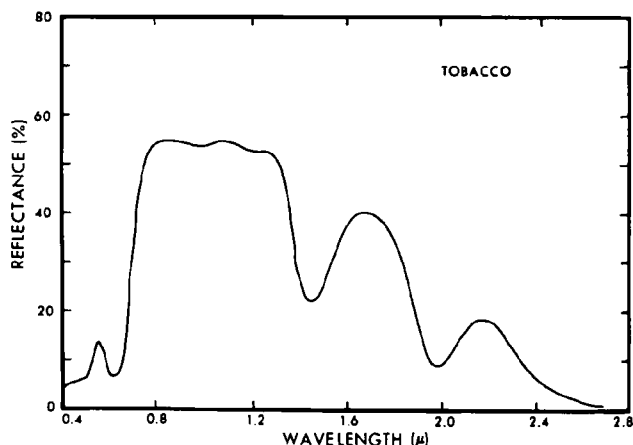

Fig. 1. Reflectance spectrum of a tobacco leaf.

over the spectral range 0.4 to 2.7 μ. In the visible part of the spectrum, 0.4 to 0.7 μ, the leaf reflectance is quite low, about 10%, with a peak at about 0.55 μ in the green region. This peak accounts for the green color of plants perceived by the human eye. The reflectance increases to a high of about 50% in the infrared over the range 0.7 to 1.3 μ, but gradually decreases to a low value at about 2.7 μ.

The spectral range 0.4 to 2.7 μ has received considerable attention from workers studying leaf reflectance, largely because incident solar radiation occurs predominantly at these wavelengths and because the spectrophotometric instrumentation is readily available for measuring reflectance in this region. Fortunately, this wavelength range includes a major portion of the leaf reflectance information that is detected by remote sensing systems. Beyond the ends of the range shown in Fig. 1, that is, in the ultraviolet at the shorter wavelengths and in the far infrared at the longer wavelengths, the leaf reflectance is at a low and relatively uniform level, generally less than 5% (Gates and Tantraporn, 1952; Wong and Blevin, 1967).

Mechanism of Leaf Reflectance

Only a part of the incident energy is reflected from a leaf. The remainder is either absorbed or transmitted. These three components are closely interrelated, and it is necessary to consider all three in order to evaluate the physical and physiological bases for leaf reflectance. Figure 2 shows the reflectance, absorptance, and transmittance over the wavelength range 0.4 to 2.7 μ. The reflectance spectrum is the same as shown in Fig. 1, but is inverted in this case. The transmittance spectrum has the same shape as the reflectance spectrum. The absorptance spectrum, however, is the opposite of the other two. Absorption is high in the visible and in the infrared beyond 1.3 μ, but is nearly zero in the infrared from 0.7 to 1.3 μ.
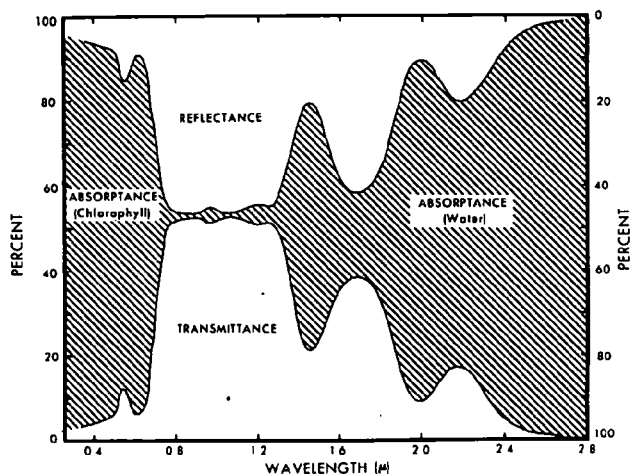
Fig. 2. Reflectance, absorptance, and transmittance spectra of a plant leaf.

Fig. 4. Reflectance spectra of the white and green portions of a variegated geranium leaf. Modified from Billings and Morris (1951).

The strong absorption by a leaf in the infrared beyond 1.3 μ is due to water (Allen and Richardson, 1968). The reflectance spectrum of a dehydrated leaf effectively illustrates this point (Fig. 3). The effect of water also is supported by theoretical considerations. On the basis of absorption coefficients of pure liquid water, Allen et al. (1969) and Gausman et al. (1970) derived the expression equivalent water thickness (EWT) to indicate the thickness of a sheet of water that can completely account for the absorption spectrum of a leaf in the 1.4 to 2.5 μ spectral range. Values of EWT calculated for turgid and mature corn and cotton leaves were about 150 μ and were in close agreement with the measured amounts of water in the leaves.

In the visible spectral region the high absorption of radiation energy is due to leaf pigments, primarily the chlorophylls, although the carotenoids, xanthophylls, and anthocyanins also have an effect (Gates et al., 1965; Rabideau et al., 1946). Numerous published absorption spectra of pigments isolated from leaves in organic solvents document this relationship, but perhaps the most striking evidence is given by the reflection spectrum of the white portion of a variegated leaf which lacks chlorophyll (Fig. 4). In this case the level of visible reflectance is at about the same high level as the reflectance of both portions
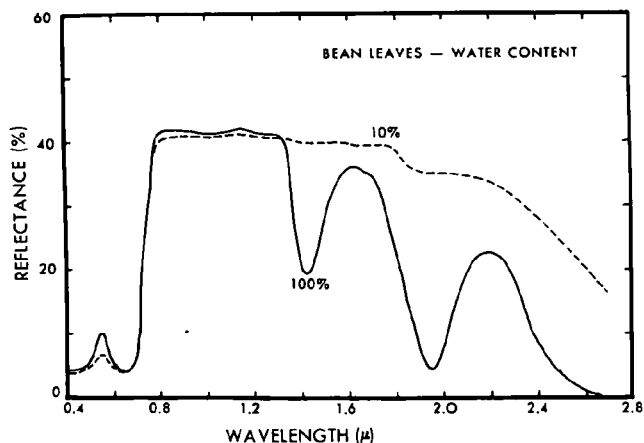

Fig. 3. The effect of leaf dehydration on the spectral reflectance of bean leaves. The numbers on the curves, 10 and 100, refer to the water content of the leaves at the time of sampling as a percentage of their water content when fully hydrated.
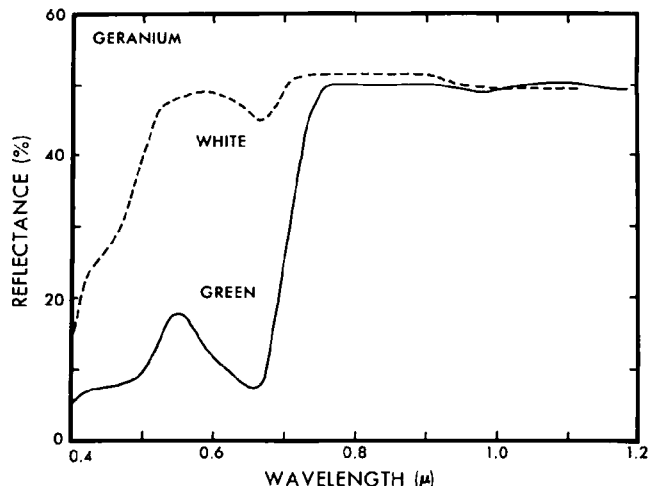
of the leaf in the near infrared. Since both parts have the same level of infrared reflectance, it can be concluded that neither the absence nor the presence of chlorophyll is responsible. This is an important point, for the infrared reflectance has sometimes erroneously been attributed to the chlorophylls. Actually, the absorption spectra of isolated chlorophylls indicate that the pigments are completely transparent to infrared radiation.

The high infrared reflectivity of leaves appears to be caused by their internal cellular structure (Mestre, 1935; Willstätter and Stoll, 1913). The cuticular wax on a leaf is nearly transparent to visible and infrared radiation, and very little of the solar energy incident to a leaf is reflected directly from its outer surface. The radiation is diffused and scattered through the cuticle and epidermis to the mesophyll cells and air cavities in the interior of the leaf. Here the radiation is further scattered as it undergoes multiple reflections and refractions where refractive index differences between air (1.0) and hydrated cellulose walls (1.4) occur. The microfibrils which make up the cell walls probably account for their surface roughness and diffusing nature (Sinclair, 1968).

Little or none of the infrared radiation in the wavelength range 0.7 to 1.3 μ is absorbed internally, but about 40 to 60% of it is scattered upward through the surface of incidence and is designated reflected radiation, whereas the remainder is scattered downward and is designated transmitted radiation. This internal scattering mechanism accounts for the similarity in the shape of the reflectance and transmittance spectra. The high levels of visible and infrared (beyond 1.3 μ) reflectance from white and dehydrated leaves suggest that the interaction of radiation of these wavelengths with the leaf structure is not really different from the interaction of near-infrared energy. However, when chlorophyll and water are present, much of the radiation energy is absorbed before it escapes the leaf. Thus pigments and water account for the spectral regions of relatively low leaf reflectance and transmittance in an indirect manner and do not themselves have these spectral characteristics.

The evidence for the internal reflection mechanism is quite strong. One of the most convincing pieces is given by the drastic reduction in the near-infrared reflectance of a leaf infiltrated with water (Fig. 5). The water fills the air cavities and forms a continuous liquid phase medium throughout the leaf. The elimination of many of the refractive index differences within
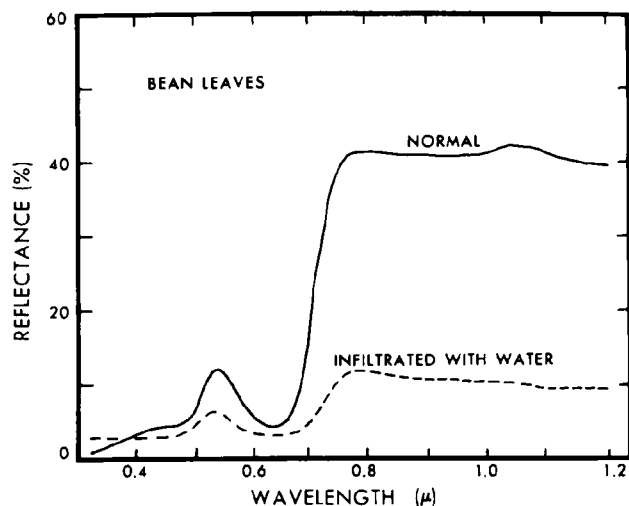
Fig. 5. The effect of water infiltration of intercellular spaces on the spectral reflectance of bean leaves.

the leaf increases the direct transmittance at the expense of scattering. The fact that chlorophylls and water in a non-infiltrated leaf absorb much of the visible and infrared energy, respectively, also can be interpreted as evidence for the internal mechanism, for the radiation must enter the leaf before it can be absorbed.

Willstätter and Stoll (1913) were the first workers to recognize the internal reflection mechanism of leaves, but they, and many other workers since, perhaps overemphasized the role of the spongy mesophyll and its large air cavities in relation to that of other interior parts of a leaf. Mathematical analyses of theoretical models (Allen et al., 1969; Gausman et al., 1970) and photomicrographs (Gausman et al., 1969a b, 1970; Sinclair, 1968 Weber and Olson, 1967) of cross sections of leaves suggest that the important parameter in determining the level of reflectance is the number or total area of the air-wall interfaces and not the volume of air space. In this regard the palisade mesophyll of a leaf probably is as important as the spongy mesophyll in the internal scattering of radiation. Many small air cavities exist between adjacent palisade cells, and the area of exposed cell walls in this region probably is as large and perhaps even larger in some cases (Esau, 1965) as in the spongy mesophyll which generally has larger air cavities and fewer cells. The orientation of the palisade air cavities probably matters little because the radiation entering the leaf is largely diffuse after passing through the cuticle, epidermis, and walls of the palisade cells. From the standpoint of chlorophyll absorption, there seemingly would be a physiological advantage to the leaf for scattering to take place primarily in the palisade region.

The expression "collapse of the mesophyll" has often been used to predict and explain decreases in infrared reflectance. It is presumed that, when leaves wilt and shrivel during senescence and dehydration, many of the reflective interfaces are eliminated as internal air space is reduced and cell walls come together. However, it is now well documented that the reflectance of dehydrating leaves increases (Sinclair, 1968; Thomas et al., 1966; Weber and Olson, 1967), and the same appears true in many cases for the initial stages of leaf senescence (Knipling, 1967, 1969). Even though the internal leaf volume decreases, micro-cavities remain between the walls and the number of interfaces may actually increase as adjacent cells split apart and as

living cell contents shrink away from interior cell walls. Also, the reorientation of the cell walls (Sinclair, 1968) and the receding of water from the wall surfaces into the microfibrillar network may increase their radiation-diffusing capacity and thus account for increases in leaf reflectance. The infrared reflectance eventually decreases in advanced stages of leaf senescence (Colwell, 1956; Knipling, 1969), but this more than likely is caused by an actual breakdown or deterioration of cell walls rather than by a collapse or reduction in the spongy mesophyll air volume.

Reflectivity of Vegetation Canopies

The reflectance properties of single leaves are, of course, basic to understanding the reflectivity of an entire plant or vegetation canopy in a field situation, but the single leaf data cannot be applied directly without modifications. There are both quantitative and qualitative differences in the two types of spectra. On a percentage basis the reflectance from a canopy is considerably less than that from a single leaf because of a general attenuation of radiation by variations in illumination angle, leaf orientation, shadows, and nonfoliage background surfaces such as soil.

The visible and near-infrared reflectance from a nearly continuous broad-leaved canopy typically might be about 3 to 5% and 35%, respectively (Steiner and Gutermann, 1966), whereas the corresponding values for a single leaf are about 10 and 50%. In this case the levels of visible and infrared reflectance from the canopy are about 40 and 70% respectively, of the levels from a single leaf. The relatively smaller reduction in infrared reflectance is due to a compensating factor. Much of the incident infrared energy transmitted through the uppermost leaves is reflected from lower leaves and retransmitted up through the upper leaves to enhance their reflectance. This effect has been illustrated both spectrophotometrically and photographically (Myers et al., 1966).

Allen and Richardson (1968) also demonstrated the infrared enhancement effect using theoretical considerations of two German physicists, Kubelka and Munk (1931), who developed a mathematical description of the attenuation of light in a diffusing medium. Allen applied the theory to a plant canopy of a given depth and random leaf orientation, and showed that the spectral reflectance and transmittance of a plant canopy are functions of total leaf area, an absorption coefficient, a scattering coefficient, and the background reflectivity. The coefficients are related to the geometry of the canopy and the optical properties of the individual leaves. This theoretical analysis of canopy reflectance also has given insight to the physical basis for the optical properties of single leaves. A similar theory was used to describe the reflectance and transmittance of a leaf in terms of the reflectivity and transmissivity of interfaces within the leaf, absorption and scattering coefficients, refractive indices, and the number of air cavity-cell wall interfaces (Allen et al., 1969; Gausman et al., 1970).

The enhancement of infrared reflectance by multiple leaf layers in a canopy seemingly amplifies the already large difference in visible and infrared reflectance of single leaves. However, an additional factor yet to be considered partially compensates for the increased difference. For the purpose of presenting the basic characteristics and mechanism of leaf reflectance, the levels of reflectance discussed to this point have been expressed as percentages. But these values do not represent the distribution of energy that actually will be reflected from a leaf

because the intensity of the incident solar energy is not uniform across the spectrum. When the incident energy is expressed as the amount per wavelength interval, the spectrum peaks in the visible at about $0.5~\mu$ and decreases to a relatively low level in the near infrared. Thus the shape of the incident energy spectrum is nearly the opposite of a leaf or canopy reflectance spectrum and therefore tends to compensate somewhat for the large difference in reflectance between the two regions. However, the infrared reflectance expressed on an energy basis is still significantly higher than the visible reflectance.

The expression of reflectance spectra on an energy basis is quite important to remote sensing applications. In fact, there is a great need for leaf and canopy reflectance characteristics to be measured and studied directly on an energy basis from aerial platforms. This will require the development and use of new and suitable energy-measuring spectrometers or spectral radiometers. All remote sensors operate on the basis of energy detection, and it is the patterns and variations of energy received by the sensors that provide the information about resource features at the earth's surface.

Agricultural Remote Sensing

Two major applications of remote sensing in agriculture and other plant sciences are the identification of land use patterns and the inventory of kinds and acreages of crops and other plant communities. The differences in reflectivity that allow discrimination of plant species or vegetation types can be traced to their leaf and canopy characteristics. The leaves of a given species tend to have a characteristic surface, thickness, internal structure, and pigment content. Similarly, the canopy, in both its horizontal and vertical extents, tends to have a characteristic structure or geometry, which is determined by the size, shape, and orientation of the plants and their leaves and by the cultural practices or environmental growing conditions. All these factors influence the leaf and canopy optical properties, and the reflection patterns received by airborne sensors represent the integration of their effects.

Detection of diseased or physiologically stressed crops is another major application of agricultural remote sensing. Its value lies in the fact that it permits corrective action to be taken and yield predictions to be adjusted. The detection of stressed plants is based on the premise that their reflectivity is qualitatively and quantitatively different from that of healthy and vigorously growing vegetation. There are experimental evidence and remote sensing data to support this view, but in some cases the physical or physiological basis for the differences has been misinterpreted.

There has been a tendency to attribute the reflectance differences between stressed and nonstressed plants largely to changes in the optical properties of individual leaves, primarily in the nonvisible spectral regions. However, critical evaluations of much of the experimental data and aerial imagery reveal several important relationships. One of them is that, when differences in the reflectance properties of individual leaves develop, the changes in the visible reflectance often occur as soon as, and are as sensitive indicators of physiological stress as changes in the infrared (Knipling, 1969). This view is supported by reports (Benson and Sims, 1967; Ciesla *et al.*, 1967; Heller, 1968) that photo-interpreters find many incipient reflective differences of vegetation apparent on conventional color as well as on color infrared photography. Even when the color differences appear earlier or more prominently on the latter type of imagery, they often can be attributed to the ability of the color infrared emulsion to discriminate more distinctly between foliage and background surfaces and to amplify the tonal renditions of visible spectral changes rather than to changes in the infrared reflectivity of individual leaves alone (Knipling, 1969). This analysis in no way detracts from the value of color infrared film, but helps to assign a meaningful reason to why it is useful.

The responsiveness of leaf reflectivity in the visible spectral region to stress conditions is caused by the sensitivity of chlorophyll to metabolic disturbances. As it deteriorates and absorbs less efficiently, the visible reflectance increases. The changes in the infrared reflectance of leaves are quite variable with the onset of disease, senescense, or stress, sometimes decreasing and other times increasing. Ultimately, in advanced stages of senescense, the infrared reflectance of leaves decreases.

Another important relationship revealed by evaluations of the imagery and reflectivity data of stressed plants, including some of those affected by diseases, insects, nutrient deficiences, drought, and salinity, is that often the predominant factor responsible for their distinction from healthy vegetation is differences in leaf area and foliage density (Thomas *et al.*, 1967). These differences may arise from a direct loss of foliage or a suppression of plant growth. Concurrent with reductions in leaf area are increases in shadows and nonfoliage surfaces, such as branches and soil, which generally have a low reflectivity. The energy reflected from such areas usually is different, both qualitatively and quantitatively, from that from healthy and vigorously growing vegetation, even though the reflectance characteristics of individual leaves may not differ greatly. However, the total infrared reflectance of the foliage component of the area viewed tends to be reduced by a relatively greater amount than the visible reflectance because the multiple leaf layers are fewer and the infrared enhancement effect is reduced.

In some cases, differences in the reflectivity of stressed plants can be attributed to changes in leaf orientation as well as to actual reductions in leaf area. An important example is the temporary wilting of leaves which occurs commonly in many crops and in the young growth on the outer fringes of forest tree crowns during hot and relatively dry midday periods. The effect here is essentially the same as a reduction in leaf area, for the drooping of the leaves reduces the amount of foliage and increases the area of background surfaces exposed to airborne sensors. The amount of water lost from leaves in the wilting range appears to have an insignificant effect on their reflectance properties as measured with a spectrophotometer (Thomas *et al.*, 1966).

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