THE CLASSIFICATION OF LAND USE CATEGORIES, CROP MATURITY, CROP TYPES, AND DISEASE STATUS BY THE ANALYSIS OF REMOTE REFLECTANCE MEASUREMENTS

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Robert W. Tinker

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ABSTRACT

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Remote visible (350-750 nm) and infrared (750-1850 nm) spectral reflectance data were acquired, throughout the 1976 growing season, from field plots of sod, soil, and various cereal and broadleaf crops located at the Central Experimental Farm of Agriculture Canada in Ottawa. Certain agronomic parameters were classified by discriminant analysis of normalized plot spectral data. Land use categories (sod, soil, crop), stages of crop maturity (vegetative, flowered), crop type (rapeseed, fababean, soybean, cereals), and disease status (diseased or healthy cereals) were classified with 95.2, 93.3, 90.7, and 67.9% accuracy, respectively. The accuracy of classification for specific cereals was low (wheat, 53.5%; oats, 67.7%; barley, 50.0%) since, in part, due to stress, the growth habit and, therefore, reflectance of these crops were similar. An attempt has been made to explain these results in terms of trends observed in the biological data (plant heights, growth stages, and leaf chlorophyll) which were acquired concurrently with plot spectral measurements.

FOREWORD

This thesis was prepared in accordance with the general regulations of the Faculty of Graduate Studies and is presented in the format outlined by the Department of Plant Science for the preparation of a paper-style thesis. The main body of this thesis is composed of a single manuscript, "The Classification of Land Use Categories, Crop Maturity, Crop Types, and Disease Status by the Analysis of Remote Reflectance Measurements", which has been submitted (February, 1978) to Agronomy Journal for publication. A second manuscript, "Improvements in Spectral Reflectance Measurements of Field Crops" (Brach et al., 1977), has been included in the appendix section to facilitate reference and to further illustrate the scope of research carried out in Ottawa during the 1976 field project.

INTRODUCTION

"The field of remote sensing is an outgrowth of aerial photographic interpretation, and has been rapidly expanding and evolving since the term was first coined by Evelyn Pruitt in 1960. Remote sensing involves the collection of data by systems which are not in direct contact with the objects or phenomena under investigation. In many instances, technological development of remote sensing systems (sensors and platforms) has outstripped corresponding development of interpretation methodologies and techniques, which are needed to convert remotely sensed data into usable information. However, increasing attention is being directed towards the interpretative and analytical phases of remote sensing. Now emphasis is being placed on problem-oriented research and development of operational interpretation methodologies and techniques." (Estes and Senger, 1974).

The potential importance of remote sensing to agriculture was recognized early in the development of remote sensing technology. An imaginative review of this subject was published in 1970 (see Luney and Dill, 1970) which gave a comprehensive survey of the state-of-the-art at that time, the possible uses of remote sensing in agriculture, and an outline of some of the physical and physiological parameters of the agricultural environment which might be of importance to the development or application of this technology. Since 1970, however, there have been rapid advances in the areas of instrumentation, crop reflectance modeling, and data analysis. Also, it has been recognized that the task of developing an operational remote sensing system is complicated by the vast, complex, and dynamic nature of the phenomena of interest in agricultural applications.

In the case of crop production, the basic premise for the use of remote sensing is that, by the analysis of crop spectral data, it may be possible to determine important agronomic parameters which are at present difficult to determine effectively by other survey methods. Such parameters might include the estimation of crop type, maturity, acreage, stress (eg. disease, pests, nutrient deficiencies, or water stress), and predicted yield. This information, if effectively acquired, analysed and distributed, could aid in the implementation of sound cultural or marketing decisions.

The purpose of the research outlined in this thesis was to classify land use categories, crop type, maturity and disease status by the analysis of visible and infrared spectral reflectance data. These data were acquired throughout the growing season by the measurement of small-scale test plot reflectance with instrumentation contained in a mobile field spectro-radio laboratory. It was felt that the results of this study might complement the development of a remote crop survey system.

LITERATURE REVIEW

The discrimination of crop parameters through crop reflectance measurement depends on the optical character of the canopy which in turn is a function of the optical nature of the elements composing the canopy. A summary of the literature concerning the interaction of solar radiation with single leaves and canopies is thus in order.

Single Leaves

As reviewed by Sinclair et al. (1973), most current hypotheses concerning the path of visible and infrared radiation through leaves are based on the findings of Willstätter and Stoll (1918) for visible radiation. Their theory took into account the concept of internal reflectance (Coblenz, 1913) and the absorptive role of leaf chlorophyll. Due to the prevailing refractive indices and the broad range of incident angles possible, Willstätter and Stoll proposed that the cell wall-air interfaces of the spongy mesophyll best met the conditions needed for critical reflectance within leaves. It was proposed that the observed diffuse reflectance and transmittance characteristics of leaves were due to a multitude of critical reflectance and transmittance events which occurred as light was incident with the irregular cell wall-air interfaces of the spongy mesophyll.

Sinclair et al. also pointed out that "Mestre (1935) recognized that reflectance of solar radiation occurred at both the leaf surface and within the internal structure." The reflectance could be either specular in nature in glossy leaves and follow Fresenel's law of reflectance, or diffuse in the case of tomentose leaves and obey Lambert's cosine law. It was also deduced that the scattering of light within the leaf was due to the internal reflections, proposed by Willstätter and Stoll, since there was no tendancy for increased reflectance at shorter wavelengths as would be the case if scattering by small particles was occurring.

In 1941, Dinger found that in the near infrared wavelengths (750-2600 nm) chlorophyll absorbed none of the incident radiation; that leaf reflectance and transmittance were high between 800 and 1300 nm; and that absorption increased above 1300 nm, especially in the waterbands at 1500 and 2000 nm.

Obaton (1941, 1944) found leaves to be highly reflective in the near infrared. From coefficients of reflection for leaves from different ecosystems, he concluded that there was no consistent pattern with leaf type and that neither the cuticle nor the epidermis greatly affected reflectance in the near infrared.

Gates and Tantaporn (1952) showed that the ventral sides of leaves were more reflective than the dorsal side. They reasoned that the small amount of absorption allowed the infrared radiation to readily penetrate the pallisade tissue into the spongy mesophyll where internal reflectance occurred. These observations were felt to support the Willstätter and Stoll theory. The authors also reported that a waxy leaf cuticle seemed to enhance reflectivity.

Colwell (1956) found that rust infected wheat leaves had markedly lower reflectivity in the infrared. He proposed that hyphae of the invading fungus filled the intercellular spaces and prevented internal reflectance. The actual structural changes in these leaves were not studied.

In 1965 Gates et al. published a comprehensive review on the spectral properties of plants throughout the solar spectrum. They concluded that internal reflectance was due to critical reflectance at the cell-air cavity interfaces in the spongy mesophyll of leaves. Absorption at some wavelengths would reduce the reflectance and transmittance. They also showed that, in maturing oak leaf tissues, as the chlorophyll pigments developed there was a deepening of the 680 nm absorption band, an increase in green reflectance at 550 nm, and a decrease in the reflectance beyond 740 nm. As the green pigmentation darkened, the reflectance at 550 nm diminished and the reflectance at the infrared wavelengths increased. Gates et al. proposed that the spectral changes in the visible region for the maturing leaf were related to pigment development. The changes in the infrared were probably a function of changes in cell shape and size. The immature leaf was felt to have mesophyll tissues that were highly ramified with air spaces. As the leaf matured, these spaces were thought to decrease with increasing cell size, accounting for the decreased infrared reflectance. Finally, in the mature, differentiated leaf, the intercellular relationship in the spongy mesophyll becomes favorable to increased infrared reflectance (i.e. increased air-cell wall interfaces).

Gates et al. also studied the differences in the spectral properties of ventral and dorsal sides of leaves. In the visible wavelength region, higher reflectance was observed from the dorsal surface. It was concluded that visible radiation incident to the lower surface of the leaf interacted with the spongy mesophyll tissues without being affected as greatly by chlorophyll which was more prevalent in the pallisade layers. The infrared reflectance was approximately equal from both sides of the leaf. It was also stated that the internal reflectance within the leaf would certainly involve some scattering or diffraction by particles such as grana or chloroplasts. However, it was observed that whatever scattering existed was not strongly wavelength dependant.

The reflectance, transmittance, and absorptance of plants whose leaves were progressively darker and thicker was also measured by Gates et al. It was noted that: the visible absorptance increased substantially from the lighter to the darker leaves; the near infrared absorptance was highest in the thinner leaves; the infrared transmittance was greater than reflectance in thinner leaves; and the infrared reflectance drastically increased with leaf thickness. It was concluded that qualitatively all green leaves have similar spectral characteristics which quantitatively may differ considerably.

Thomas et al. (1966) observed that leaves of plants grown in either low nitrogen or chloride concentrations had higher reflectance in the visible and lower reflectance in the infrared, as compared to normal leaves. When the relative turgidity decreased, an increase in leaf reflectance was observed which was most noticeable in the 1450 nm water absorption region. It was pointed out that the reflectance was more related to absolute water content than relative turgidity.

Gausman et al. (1970) measured the reflectance of single leaves and field plots of cycocel-treated cotton over the 500 to 2500 nm wavelength region. Cycocel had been found to increase leaf area and thickness by increasing the number of intercellular spaces in the mesophyll. An increase in leaf chlorophyll content was also noted. Spectrophotometric measurements from single, treated leaves exhibited a 5% increase in reflectance over the 500-1300 nm region and a 6% decrease in transmittance over the entire 500-2500 nm interval when compared with untreated leaves. Increased reflectance and decreased transmittance over the 750-1300 nm interval were mainly associated with an increased number of spaces in the leaf mesophyll. Decreased transmittance of treated leaves in the wavelength intervals 500-750 and 1350-2500 nm was due to increased chlorophyll and water contents, respectively.

Knipling (1970) reviewed the physical and physiological basis for the reflectance of visible and near infrared radiation from vegetation. He stated that "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." He also proposed that internal reflections and subsequent scattering or diffusing of radiation took place in the mesophyll tissues, but noted, from work carried out by Sinclair (1968), that the radiation entering the leaf would also be diffused by the epidermis and pallisade cell walls. The microfibrillar structure of the cell walls was stated to "account for their surface roughness and diffusing nature." Knipling felt that many workers had possibly "overemphasized the role of the spongy mesophyll and its large air cavities in relation to that of other parts of the leaf." He felt that the number or total area of interfaces and not the volume of air spaces were important in determining the levels of leaf reflectance. This probably would give the pallisade tissues, with many small air cavities, as important a role in leaf reflectance as the mesophyll. He pointed out that it would be physiologically advantageous, in terms of chlorophyll absorption, to have scattering occurring primarily in the pallisade tissue. It was also stated that "the 'collapse of the mesophyll', which was often used to predict and explain decreases in infrared reflectance due to the elimination of air-wall interfaces or dehydration, actually caused an increased infrared reflectance (Sinclair, 1968)." As the "internal leaf volume decreases, micro-cavities between the walls remain and the number of interfaces may actually increase as adjacent cells split apart and as the living cell contents split away from interior cell walls. Also, the reorientation of cell walls (Sinclair, 1968) and the receding of water from the wall surfaces into the microfibrillar network may increase their radiation-diffusion capacity and thus account for increases in leaf reflectance." The eventual decrease of infrared reflectance, in advanced senescence, was thought to be due to an actual break down or deterioration of cell walls rather than by collapse or reduction in spongy mesophyll air volume.

Breece and Holmes (1971) proposed a multi-layered leaf model to explain the diffuse transmittance and bidirectional (diffuse and specular) reflectance of green soyabean and corn leaves in the visible and infrared wavelength regions. They noted that a bidirectional characteristic of leaf reflectance at 540 nm was observed by Seybold (1933) and that the transmission characteristic seemed to have both diffuse and refractive components. From their own research, they found that corn and soybean leaf reflectance in the visible wavelength (375-750 nm) was quite specular in nature, while near infrared (750-1000 nm) reflectance was diffuse. The visible reflectance observed from the underside of soyabeans was more diffuse than the upper surface reflectance; while in the undifferentiated tissues of the corn leaf, the reflectance was similar for either side. The corn leaves, however, exhibited a variation in reflectance and transmittance components depending on the orientation of leaf veins in relation to the angles of the source and detector.

By means of an approximated solution to the radiation transfer theory, Breece and Holmes calculated that, for a leaf consisting of m-layers of air-cell wall interfaces, the observed diffuse or Lambertian reflectance of infrared radiation was related to the number of layers on which the radiation was incident and the probability of reflectance or refractance at each interface. In the visible wavelength regions, where the pigments are more absorptive, the specular nature of the observed reflectance was interpreted to be due to the high absorptance of the upper layers of tissue. If there is some scattering within the upper layers of a tissue, the deeper the radiation passes, the greater the diffusion. However, the incident radiation that is reflected from the first few layers would emerge as a dispersion about a specular angle. Thus, the pallisade layers of soyabeans, having denser chloroplast concentrations, would have fewer interface interactions prior to reflectance and this reflectance would be more specular in nature as was observed in the experiments.

Sinclair et al. (1973) proposed a modification of the hypothesis for the path of solar radiation through leaves to include the diffusive reflectance properties of cell walls. They proposed that "the microfibrillar structure of cell walls presumably induces the scattering necessary to have diffuse reflectance, as defined by Lamberts cosine law....The total thickness of the cell wall material, largely a function of the number of walls incident radiation encounters, would determine the intensity of the observed reflectance." They felt that "the concept of the path of radiation through leaves must be revised to include diffuse as well as specular reflectance."

In 1973, Gausman related the reflectance, absorptance and transmittance characteristics of spinach leaves to the optical characteristics of their subcellular particles over the 500-2500 nm wavelength interval. When particulate size was of comparable size to the wavelength of light, the interaction of light with a particle was strong; the Lorenz-Mie scattering formulation described the differential light scattering pattern. It was concluded that chloroplast and mitochondria interact strongly with visible and near infrared radiation in vitro. Therefore, the subcellular particles of intact leaves contribute to the reflectance and absorptance of infrared light. However, the contribution of subcellular particles in leaves to the reflectance of infrared light is small compared with the reflectance caused by cell wall-air interfaces.

Gausman and Allen (1973) published the optical parameters of leaves from thirty plant species at 550, 650, 850, 1450, 1650, 1950, and 2200 nm.

They concluded that the interactions of plant species with the wavelengths, in terms of infinite reflectance, absorption, and scattering (reflectance and transmittance), were highly significant. Considering the mean optical measurements at all wavelengths, infinite reflectance, absorption, and scattering, respectively, were negatively, positively, and not highly correlated with leaf thickness. The relation of scattering with leaf thickness was interpreted to mean that leaf structure and not thickness played an important role in light scattering.

In 1977, Gausman reported that leaf components such as stomata, nuclei, cell walls, crystals, and cytoplasm contributed to the near-infrared reflectance of leaves, particularly over the 700-1100 nm wavelength interval. Also in 1977, Thomas and Gausman reported that the 550 nm wavelength seemed superior as compared with the 450 and 670 nm wavelengths for relating leaf reflectance to total chlorophyll or carotenoid concentrations. For most crops investigated, chlorophyll was the most important independent factor affecting visible reflectance. However, later in the growing season, it was felt that carotenoids may become more effective in determining reflectance.

Thus the current concept of the path of solar radiation within leaves incorporates specular and diffuse reflectance components of the microfibrillar cell wall structure and the cell wall-air interfaces. The observed reflectance and transmittance from a leaf is thought to be the net result of the scattering of radiation within the leaf and the absorption of radiation in some spectral regions by plant pigments and water. Observed specular reflectance components from some leaves are thought to be due to the reflective properties of the upper pallisade, epidermis, and cuticular layers of the leaf.

Canopy Reflectance

Knipling (1970) noted that "although 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, ...the single leaf data cannot be applied directly without modification." A combination of factors, including single leaf optics, is responsible for the reflectance from a vegetation canopy.

Myers (Myers, et al. 1966; Myers, 1970) reported that the stacking of leaves in layers from two to six leaves in thickness caused an enhancement of the infrared reflectance and no change in the visible reflectance when compared to that of a single leaf layer. It was concluded that as the number of leaf layers increased, the infrared radiation lost by transmittance from a single layer would be partially reflected and reradiated from subsequent layers. The upward reradiated energy would enhance the reflectance of the surface layer. The surface layer was concluded to be responsible for the observed visible reflectance. Myers predicted that, in a field situation, the infrared reflectance from a canopy would be greater than that of single leaves. The amount of enhancement would be related to the leaf area index of the canopy. The visible reflectance from a canopy would give an indication of the pigment content of the upper leaf layers. It was noted, however, that environmental factors, such as soil background radiance and atmospheric absorption and scattering, would affect reflectance measurements in a field situation.

Gausman et al. (1970) noted that the infrared reflectance of single leaves from cycocel-treated plots was greater than that of leaves from untreated plots. In the field, however, colour infrared photography indicated that the treated plot had lower reflectance than the untreated plot. Also, the infrared reflectance of stacked leaves from the treated plot was slightly greater than that of stacked leaves from the untreated plot. It was concluded that many factors such as canopy type (geometry), background soil reflectance, and differences in the maturity of leaves on a plant mask the contribution of a single leaf to the reflectance of light from a canopy.

A number of workers (Allen et al., 1964; Williams et al., 1965; Monteith, 1965; Baker and Meyer, 1966; Loomis and Williams, 1969; Monteith, 1969; Idso and de Witt, 1970; and Ross, 1975) have attempted to describe the radiation interception efficiency of plant canopies by modified solutions of the radiation transfer theory (Kubelka and Munk, 1931). Allen and Richardson (1968) applied a solution of the radiation transfer theory to a canopy of given depth for which there was assumed to be a random leaf orientation. It was deduced that the spectral transmittance and reflectance of a plant canopy were functions of total leaf area, an absorption coefficient, a scattering coefficient, and the background reflectivity. The coefficients were related to the geometry of the canopy and the optical properties of single leaves.

Ross (1975), however, pointed out that radiative transfer in a plant stand was a complicated problem for which no satisfactory general solution had been found. The main complications were felt to be the large variability and inhomogeneity of the architecture of the plant stand as well as of individual plants. Changes in the direction and strength of the incident solar radiation were felt to add to the complications. Ross summarized the factors affecting the radiation regime within a plant stand to include:

1) conditions of the incident radiation (diffuse sky, direct solar);
2) optical properties of the stand (component interaction with radiation);
3) optical properties of the ground surface (especially in sparse canopies); and
4) stand architecture (most important single factor: relates canopy architecture, spatial distribution of plants, and distribution size, and orientation of leaves).

In remote sensing, however, the reflectance of the canopy, subsequent to the interaction of solar radiation with the canopy components (including non-leaf structures), is the quantity of interest. Therefore, factors affecting the measurement of canopy reflectance should be considered in addition to the interaction of radiation within the stand.

Egbert and Ulaby (1972) demonstrated the effect of solar altitude, incidence look angle, and azimuth look angle on the spectral reflectance of a grass canopy. It was concluded that, in addition to atmospheric effects, the angular reflectivity variations from a canopy surface should be considered in remote reflectance measurements. They felt that such considerations would aid in the determination of optimum conditions for collecting remote reflectance data.

Suits (1972a, 1972b), using a variation of the radiation transfer theory, developed a model to describe the directional reflectance characteristics of vegetation canopies. In this model, the canopy was assumed to consist of layers containing distinct mixtures of biological components. The components were idealized to consist of three flat Lambertian plane sections; found by taking three mutually orthogonal projections of each component. The spectral qualities of the Lambertian plane sections were derived from those of the biological components which they represented. The layers of components and their horizontal and vertical projections defined the canopy model. The radiant flux field within the canopy was described as consisting of upward and downward directed, diffuse, spectral flux densities from canopy-radiation interactions, and a downward, specular flux density from the external sky or solar source. Observed canopy radiance was proposed to be due to the interaction of the diffuse and specular flux fields with the component layers of the canopy.

Suits concluded that the azimuthal variations of canopy radiance were due to the diffuse transmittance or reflectance of specular flux by the vertical components of the canopy when the polar angle of view or solar incident angle were large. It was noted that for large polar angles of view, common in ground based observations, the biomass of the canopy would have little effect on the observed radiance. Most aerial remote sensing studies, however, due to the vertical view angle and solar angle near the zenith, were felt to have negligible directional radiance variations. Suits did state, however, that if an azimuthal variation aided canopy discrimination techniques, the specular flux field contribution to canopy radiance as a function of azimuth should be determined. It was also noted that, even in highly reflective canopies, the azimuthal variations would be moderated by the azimuthally symetric skylight and diffuse flux field of the canopy.

The bidirectional canopy reflectance model (Suits 1972a, 1972b) has been tested by a number of workers. Colwell (1974) described the effects of a number of parameters on the bidirectional reflectance of a crop canopy. He defined bidirectional reflectance as π times the ratio of radiance from a canopy at a particular polar look angle and the irradiance, on a horizontal datum, from a source at a particular polar zenith angle and azimuth angle. It was stated that the bidirectional reflectance of a canopy determined its relative tone or radiance in the 0.3-3.0 μm portion of the spectrum. The bidirectional reflectance was felt to be estimated most accurately when measurement included a sufficiently large portion of the canopy to account for its inherent random, systematic, and stochastic variations. From empirical measurements and modelling, Colwell concluded that the factors affecting canopy reflectance included: a) leaf hemispherical reflectance and transmittance, b) leaf area, c) leaf orientation, d) hemispherical reflectance and transmittance of supporting structures, e) effective background reflectance, f) solar zenith angle, g) look angle, and h) azimuth angle. Since the relative importance of each of these factors could vary significantly, depending on the prevailing conditions of measurement, it was felt that, ideally, all of the factors should be considered in attempts to establish the cause of observed canopy reflectance.

Bunnik and Verhoef (1974 ; Verhoef and Bunnik, 1975) studied the spectral directional reflectance of agricultural crops, and the relations between crop characteristics and canopy spectral reflectance. The studies incorporated Suits' bidirectional canopy reflectance model which was compared with empirical measurements from the field.

A number of conclusions were drawn from the comparison of measurements and model estimations of the directional reflectance of wheat and grass canopies (Bunnik and Verhoef, 1974). In wheat, the canopy directional reflectance varied with stage of crop development. The intrinsic radiance of the crop depended on the angle of view. It was noted that crop heterogeneity produced stochastic changes of the spectral signature while angular or directional differences led to systematic variation. The vertical components of the canopy were, as predicted, important to bidirectional character of canopy reflectance.

Grass canopy reflectance was shown to be estimated most accurately by a single layer solution of Suits' model. The grass canopy had fewer vertical components than wheat and, thus, less angular variation. At complete cover, the leaves were approximately horizontal, and the canopy reflectance was Lambertian,varying stochastically with variations in leaf densities. The measurement of canopy reflectance, in a field situation, from wheat and grass canopies thus supported Suits' model.

In a later study, Verhoef and Bunnik (1975) related canopy reflectance, measured in the field under fixed illumination and viewing conditions, to a number of canopy characteristics. The model was modified to define the canopy reflectance in terms of a model leaf area and leaf inclination angle, instead of the vertical and horizontal projections used by Suits. It was felt that, for erectophile, planophile, and plagiophile canopies, these terms would give a close approximation of the actual leaf area index and leaf inclination angle.

Field reflectance studies were again supportive of the model. It was found that most reflectance changes in the field could be accounted for by simulated differences in leaf area, leaf inclination, or soil moisture content. It was found that the infrared plateau reflectance increased, and the visible and water absorption band reflectance decreased with increasing leaf area index up to a leaf area at which reflectance was insensitive to further change. The limiting leaf area depended on the wavelength and leaf inclination angle, and was reached earliest in planophile, highly absorptant canopies. Increased vertical leaf orientation caused a decrease in canopy reflectance over most spectral regions due to a shadowing effect. However, in the case of a canopy with a small leaf area index, the reflectance increased in regions of high leaf absorption with increasing leaf angle. In this case the contribution of soil reflectance overwhelmed the shadow effect. When cover was low, the red 670 (nm) reflectance of the canopy was most sensitive to changes in vegetation cover while, at higher leaf area indices the near infrared (870 nm) was most sensitive.

In a hypothetical canopy of infinite leaf area index and horizontal green leaves, most information concerning leaf type was found in the green (550 nm) and water absorption (1450 and 1950 nm) bands. For a canopy of known green leaf and dry soil optical characteristics, the most information about canopy structure (leaf area and average inclination) was found in the red (670 nm) and water absorption bands. The reflectance difference of a canopy due to moist or dry soil background was greater in the infrared plateau than in the visible region.

It was noted by the authors, that, due to the controlled illumination