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

A Thesis

Submitted to the Faculty

of

Graduate Studies

The University of Manitoba

by

Robert W. Tinker

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

Department of Plant Science

April 1979

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ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to Dr. Lucien Lacroix for his continued support and encouragement throughout the course of this study.

Mr. E. J. Brach and Dr. A. R. Mack are thanked for their generous guidance and for the research facilities made available to me during my work at the Central Experimental Farm of Agriculture Canada in Ottawa.

I would also like to thank Mr. G. T. St.Amour and Mr. G. Poushinsky for the considerable time and effort they invested in the operation of the electro-optical system, and the analysis of the spectral data, respectively.

Finally, I would like to express my deepest appreciation to my wife, Laurie, for her unending moral support and understanding during the course of this program.

This project was supported by an operating grant from Agriculture Canada.

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ABSTRACT

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Major Professor: L. J. Lacroix

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 and viewing conditions of the study, the results presented should be interpreted only as being indicative of some canopy parameters that may be discerned by remote reflectance measurements. It was felt that no optimal wavelength band choice existed for the determination of given set of crop characteristics since spectral reflectance sensitivity to canopy change varied with the parameter of interest, and the prevailing atmospheric and canopy conditions. The manipulation of raw spectral data by mathematical or statistical methods was felt to be a possible means of optimizing the discrimination of canopy parameters.

Chance (1977) noted that, although Suits' model had been verified by field experimentation, little had been done to demonstrate that, once the model parameters were established for a given crop, they could be applied to other cultivars of the same crop and growth stage. Established parameters for a four-level canopy of cv. Penjamo wheat, at 100 day after planting, were applied to the reflectance measurements recorded for cv. Scout wheat by Kanemasu (1974). The canopy reflectance of Scout was in close agreement with that predicted by the model for Penjamo. Thus, it seemed the model could be applied to cultivars of the same crop once the parameters were established for a given cultivar.

Chance also estimated the effect of hypothetical, "mirror-like", and black soil backgrounds on the predicted wheat canopy reflectance. It was shown that, at the growth stage studied, soil background had no effect on the visible reflectance of the wheat canopy. In the infrared region, the upper and lower limits of the effect of soil background on canopy reflectance were delineated. The range of reflectance amplitude between these limits was not great and was proposed as the range of reflectance amplitudes that would be expected for a wheat canopy at that growth stage, regardless of soil background.

In summary, canopy reflectance, as observed by remote sensing techniques, has been proposed to consist of two component parts:

a) that which is due to atmospheric and background radiation interactions, and the angular conditions of measurement; and

b) that which is due to canopy-radiation interactions and depends solely on the optical character of the canopy and its components.

Procedures to discriminate differences between, or within canopies should at first correct for that portion of the observed reflectance which is due to non-canopy-radiation interactions. The "net" canopy reflectance (b) above) will depend on the pigmentation, water content, and morphology of the canopy elements, and the frequency and orientation of these elements within the canopy. The ability to discriminate specific canopy parameters from the "net" canopy reflectance will depend on: a) the accuracy of the atmospheric and angular corrections that were used to derive "net" reflectance, b) the sensitivity of the analysis employed, and c) the unique and absolute sensitivity of "net" canopy reflectance to the parameter of interest.

Applied Research

Studies which have been undertaken to discriminate specific crop parameters from the analysis of remote canopy reflectance measurements fall into two categories. Large area crop survey programs, such as LACIE, have been initiated "to evaluate and demonstrate the capability of existing remote sensing, data processing, and associated techniques to supply world wide crop production information in a cost-effective manner" (MacDonald, 1974). The applications, however, have been limited by the spectral sensitivity and surface resolution capabilities of the onboard instrumentation, and the availability of information concerning the cause-effect relations between canopy reflectance and crop parameters. Therefore, small scale, ground based canopy reflectance studies have become instrumental in defining the discernable crop parameters, the spectral information needed for discrimination, and the data correction and analysis techniques that could be employed in larger survey programs.

In the previous sections, it was shown that factors such as leaf inclination angle, leaf area index, absolute water content, pigmentation, and leaf morphology affected the reflectance of a vegetation canopy. The discernability of these and other crop parameters by remote reflectance techniques has been investigated by a number of workers.

Kanemasu (1974) studied the midday hemispherical canopy reflectance of wheat, sorghum, and soybean throughout the growing season. It was proposed that a reflectance ratio of 545 to 645 nm wavelengths, which seemed insensitive to solar elevation angle, could be used as an indication of percent cover and physiological stress. It was pointed out, however, that it was not possible to determine crop type from the reflectance ratios. Also, neither the ratio nor the infrared reflectance offered a unique equation for the relation of leaf area to canopy reflectance for all crops.

Verhoef and Bunnik (1974) noted that the differences among spectral signatures of different crops seemed to be caused mainly by differences in canopy structure. The spectral signatures were at least as much influenced by growth stage as by crop type. Differences in spectral signatures in the visible wavelengths were mainly caused by differences in pigment and ground cover. It was also noted that disease infected potato plots showed dramatic decreases in reflectance at the infrared plateau.

It was found that normalized reflectance values, in spectral bands, gave better classification results than absolute reflectance values. Spectral parameters such as normalized data or ratios showed a strong dependance on growth stage and were interrelated to a large extent. The classification of crop types at all stages of growth required at least four spectral parameters (ratios) to be employed; the composition of which depended on the component being classified. An accurate classification of a number of crop types and growth stages were obtained under the controlled conditions of this study. It was pointed out, however, that systematic effects such as angular conditions and atmospheric radiation interactions would modify the results of classifications obtained under more realistic experimental conditions. Verhoef and Bunnik did conclude, however, that the classification of certain crop types and growth stages was possible by remote reflectance measurements, and that this information could be applied in crop type and status inventories.

Pederson (1976) used a multispectral sensor (500-900 nm) to study the relation between reflectance and the yield and disease status of barley plots. It was concluded from preliminary results that, at 900 nm, reflectance differences between diseased and disease-resistant barley plots were positively correlated to visual disease ratings and negatively correlated with plot yields.

Tucker (1977) studied the relation of grass canopy reflectance at a number of wavelenth bands (0.35 to 0.80 μm) to the proportion of standing live and standing dead vegetation late in the growing season. It was found that the total wet or dry biomass was best estimated in the 0.35 to 0.44 μm region due to differences in chlorophyll and carotenoid content of the vegetation. Leaf water content and, thus, photosynthetically active tissue was best estimated in the 0.43 to 0.50, 0.63 to 0.69, and 0.74 to 0.80 μm regions due to strong chlorophyll absorption in the visible bands and the high infrared reflectance of living tissue.

Brach and Mack (1977) measured the spectral reflectance of a number of crops throughout the growing season. Variances due to solar irradiance and solar angles were partially normalized by the measurement of radiance from a standard grey card and by the use of spectral ratios in the analysis. It was found that for corn and cereals prior to heading, radiance in the blue regions increased more rapidly than in the green and red wavelengths. After heading, the red radiance increased more rapidly than other visible bands due to the decreased absorptance by chlorophyll. Brach and Mack also concluded that normalization and a number of spectral ratios would be necessary to classify crop types over a wide range of growth stages.

Rao et al. (1978), used an extensive method to statistically describe the radiance differences between a number of crops from the booted or flowered to mature growth stages. By this method, it was possible to show the spectral regions of maximum discriminability for certain crop types. It was shown that the differences in radiance variation occurred in the spectral regions of minimal absorption by plants, of absorption by chlorophyll, and plant water, respectively. It was not, however, demonstrated that the radiance variation differences were species or cultivar specific, or repeatable.

Idso et al. (1977a, 1977b) showed that it was possible to predict the yield of a wheat crop at a given location and environment by measuring the albedo or canopy temperature variations of the crop throughout the growing season. These data were applied to a stress-degree-day-yield linear correlation and the yield of the crop was estimated. It was pointed out, however, that these methods were dependant on the crop cultivar studied and the prevailing environmental conditions. Models for other crops or environments would have to be developed separately.

Summary

Theories concerning the interaction of radiation with single leaves and vegetation canopies have been developed by a number of workers. Canopy reflectance models, based on developed theory and incorporating the moderating effects of the conditions of measurement, have been proposed and tested for use in the prediction of canopy reflectance. The cause-effect relation of a number of canopy parameters to the observed canopy reflectance has been studied with the aim of developing techniques for the discrimination of useful canopy information by remote reflectance measurements. Although such studies have aided in the recognition of some discernable canopy parameters, it has been pointed out that further research is necessary for the application of these techniques in an operational remote sensing program.

MANUSCRIPT

The Classification of Land Use Categories, Crop Maturity, Crop Types, and Disease Status by the Analysis of Remote Reflectance Measurements

ABSTRACT

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.

INTRODUCTION

Since its inception as a modern data acquisition system, remote sensing has been considered as a possible aid or alternative for existing crop reporting systems (Luney and Dill, 1970). The projected ability to discern crop type, acreage, status and possibly yield has been the major incentive for research in this area. The long term goal of this research has been to develop a timely, accurate, and efficient system that could supply useful crop information to a broad base of potential users (MacDonald, 1976). The success of any remote sensing program depends on its ability to characterize the phenomenon of interest by its observable spectral qualities.

The problems faced in developing a useful crop reporting system are well embedded in the complexities of the observed phenomenon. Biological systems are dynamic -- constantly changing through their growth and development, and in direct response to their environment. The radiant environment and microclimate within a crop is in turn changing on a daily and seasonal basis -- both predictably and at random. The ability to distinguish crop types and related agronomic parameters therefore depends on the extent to which the observed spectral differences may be attributed to actual crop differences.

The purpose of this study was to classify land use categories, crop maturity, type, and disease status by the analysis of normalized visible (350-750 nm) and infrared (750-1850 nm) plot reflectance data which were acquired throughout the growing season. The results of these classifications have been discussed in terms of observed trends in the biological data which were acquired concurrently with the spectral reflectance measurements. It was felt that this study would supplement the development of an operational remote crop reporting system. Certain agronomic parameters were accurately classified by the methods employed. The misclassification of other parameters was felt to be an indication that greater resolution and environmental correction might be required for their discrimination.

MATERIALS AND METHODS

Instrumentation and Measurement.

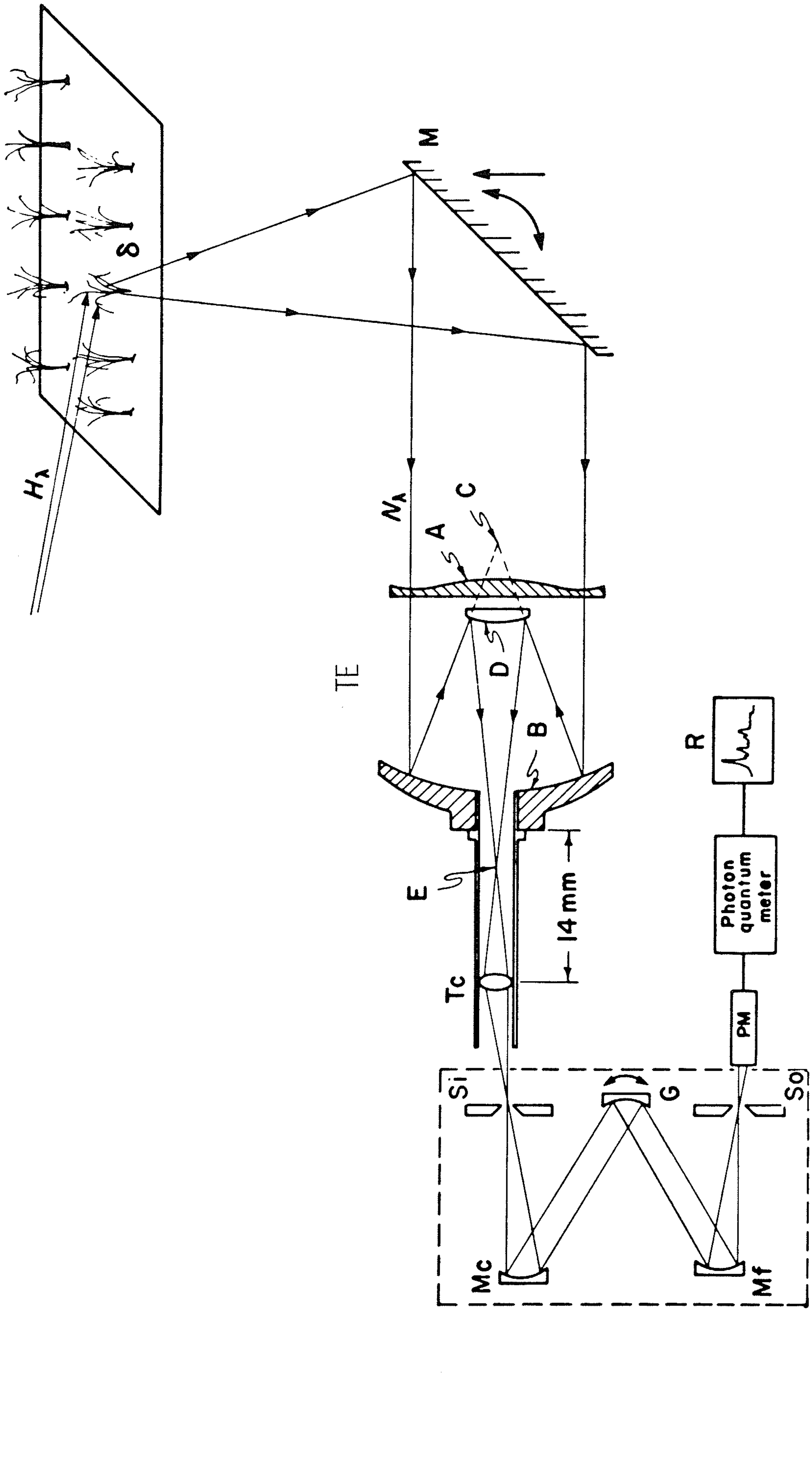
The electro-optical and environmental monitoring equipment was contained in a mobile field laboratory adjacent to the test plot area (Brach et al., 1977). Further environmental data were available from a nearby meteorological site.

The visible system (Fig. 1) consisted of a front surfaced, folding mirror (M), a Cassegrain-Schmidt telescope (TE, Celestron 8; f.o.v. 0.2834^{o}/cm), a telecompressor (TC), a monochromator (1 m focal length; McPherson model 2051, Acton Mass, 01720) for which the input and exit slits were set at 2.0 mm and 0.4 mm respectively, a photomultiplier (PM), a photon quantum meter, and digital (teletype) and analog (x-y recorder) data recording equipment. The infrared system (Fig. 2), consisting of optical components similar to those of the visible system, has been described previously by Brach et al. (1977).

The environmental monitoring components contained in the mobile laboratory consisted of a radiant energy pyranometer, a relative red (675 nm, 25 nm HBW)/blue (475 nm, 25 nm HBW) photometer, and an ambient thermometer. This monitoring equipment was mounted on the roof of the mobile laboratory and was interfaced with the data acquisition components of the visible system. Atmospheric moisture data, along with complementary temperature and radiant energy data, were acquired from the nearby meteorological site.

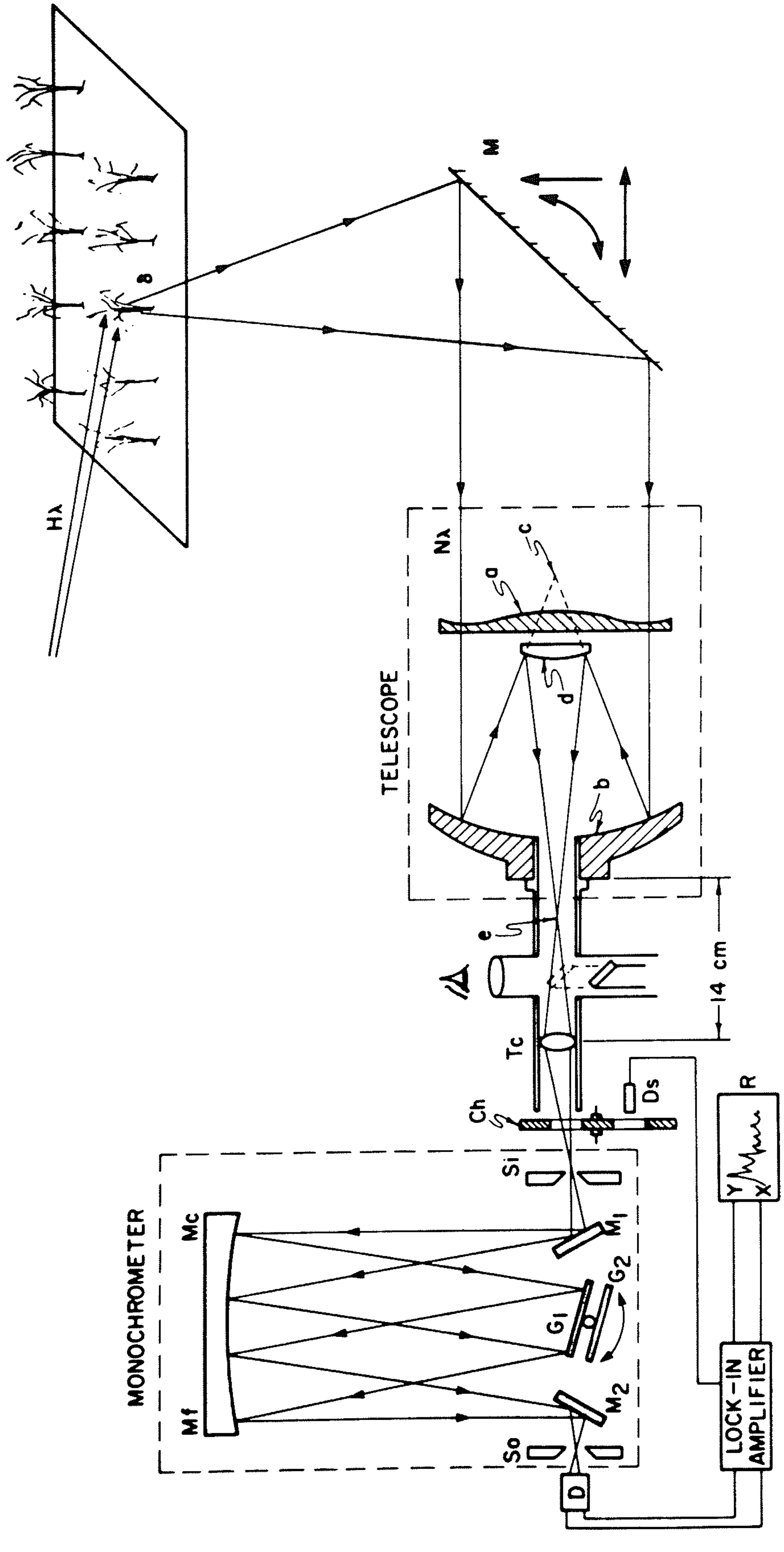
Prior to each spectral measurement the mirrors were adjusted to the proper angles and the telescopes were focussed on the plot surface. The visible measurement was electronically initiated (hardware programmed through the teletype), while the infrared measurement was manually initiated. Preliminary data including a) plot number, b) time (hour/min.), c) temperature (C), d) incident radiant energy (W cm^{-2}), and e) red and blue components of incident radiant energy (mW) were automatically recorded

Figure 1. Schematic of the Visible Spectral System.
M, folding mirror; TE, telescope; TC, telecompressor;
Si, monochromator input slit; So, monochromator output slit;
PM, photomultiplier; R, recorder.



M
δ
H_λ
N_λ
A
C
D
B
TE
E
14 mm
Tc
R
Photon quantum meter
PM
Si
G
So
Mc
Mf

Figure 2. Schematic of the Infrared Spectral System.
M, folding mirror; TC, telecompressor; Ch, chopper;
Si, input slit; So, output slit; D, PbS detector; R, recorder.


MONOCHROMETER
TELESCOPE
LOCK-IN AMPLIFIER
14 cm
Mf
Mc
M_1
M_2
G_1
G_2
Si
So
D
Ch
Ds
Tc
R
Hλ
Nλ
M

on punch tape and teletype. In the visible system, wavelengths and corresponding output were then recorded at 10 nm increments as the monochromator scanned the preset wavelength interval (350-750 nm). In the infrared system and as back-up in the visible system, a continuous plot of relative output as a function of wavelength was made by an x-y recorder.

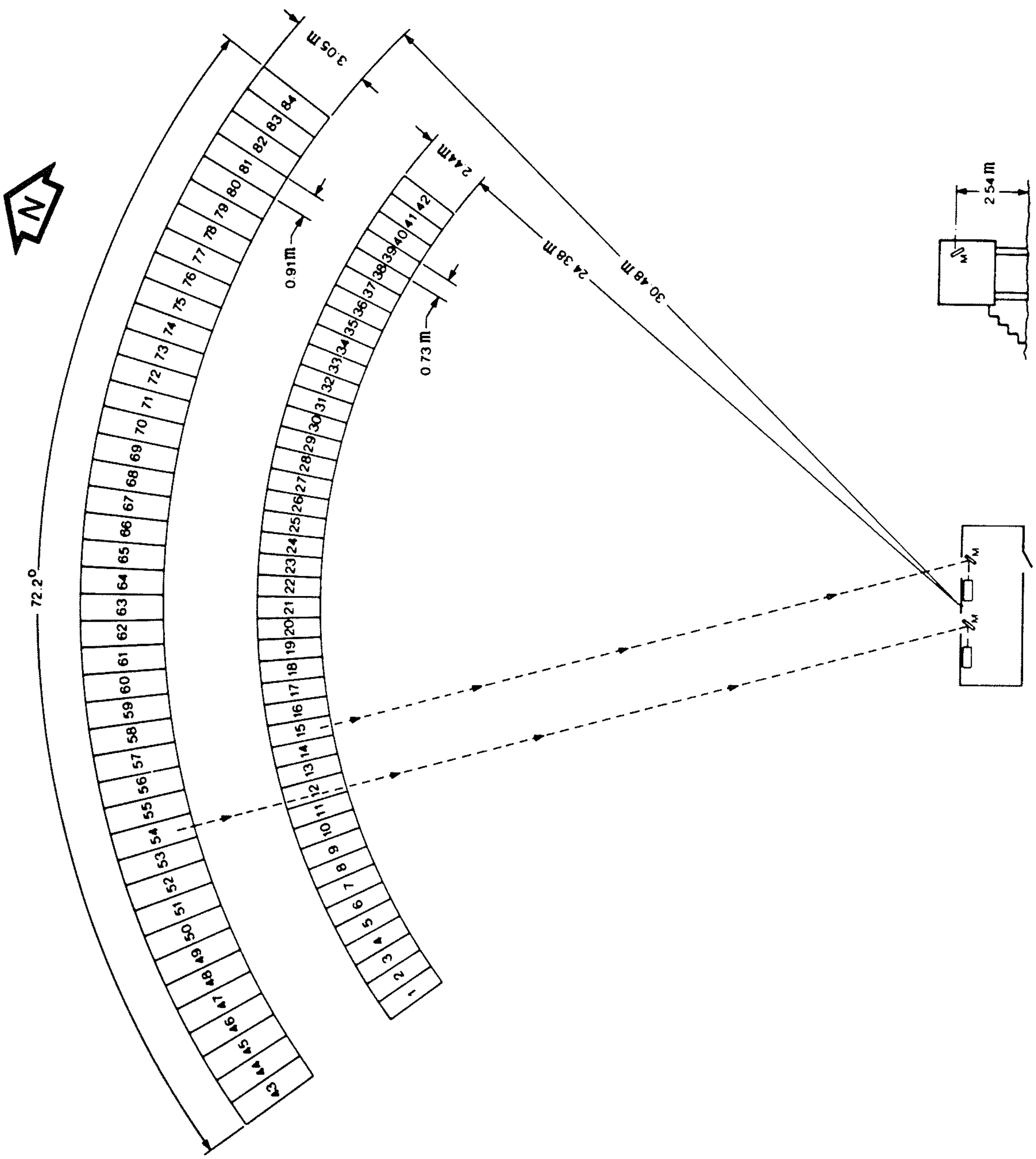
These measurements were taken throughout the growing season in accordance with a predetermined daily schedule. The measurements were postponed to the next clear day if cloud or inclement weather prevented readings from being made. In this way, it was possible to complete six measurements of each plot throughout the growing season. This data represented a wide range of growth stages for each crop.

Field Geometry - (Fig. 3).

The mobile field laboratory was located so that the optical system (2.54 m elevation) was at the geometric centre of two concentric, circular arcs (replicates) of test plots (radii 34.38 and 30.48 m). The angular width of the field test was limited to 72° to accommodate the horizontal azimuth range of the optical system (Brach et al., 1977). The azimuth angle of the line of sight from the visible mirror to the centre of plot 21 was 331.503° east of the true north. Plot dimensions of 2.44 x 0.73 m and 3.05 x 0.91 m respectively for front and rear arcs were selected so that only the reflectance of a specific plot was measured when the telescopes were focussed on a given position on the arcs.

The advantage of this field geometry was that the radiance distance for all plots within one replicate was constant. The reduction in reflected area energy over the longer distance to the outer arc was partially compensated for by the larger viewing area of the telescope which increased with distance, proportional to the ratio of the radii (r_2/r_1). The difference in viewing angle between the plots in the two arcs was small

Figure 3. Field Layout for 1976 Experiment.


N
72.2°
3.05 m
0.91 m
2.44 m
0.73 m
30.48 m
24.38 m
2.54 m

($\alpha = 1.19^{o}$ so that cos. $\alpha = 0.002$). The theoretical error was less than 1% and was ignored (Brach et al., 1977).

Experimental Materials.

In accordance with the field geometry, it was possible to fit 42 plots in each replicate arc (Fig. 3). The species and varieties selected for these plots (Table 1) included a representative range of small grains (wheat, oats and barley) and broadleaf crops (rapeseed, fababean, and soybean). By incorporating two seeding dates (D_1, May 27; D_2, June 23), selected varieties were subjected to two environmental regimes during the same growing season. Also, to observe the effects of disease on crop spectral reflectance, additional plots of wheat (cv. Marquis), oats (cv. Garry) and barley (cv. Conquest) were planted and later inoculated with stem rust (*Puccinia graminis f.s.p. tritici*), crown rust (*P.coronata cda*) and leaf blotch (*Cochiobolus sativus* (Ito and Kurib)) respectively.

A series of sod (70% Kentucky bluegrass (cv. Merion) and 30% common Kentucky bluegrass and creeping red fescue) and soil plots were included in the arcs to be used as "reflectance standards" for verification of final results. A Kodak 18% reflectance grey card was calibrated to a known xenon light source at the NRC (Canada) Physics Division by measuring the reflectance at 10 nm intervals from 350 to 1300 nm. During field measurements, this card was placed in a bracket at right angles to the viewing axis of the optical system at 331^{o} east of true north, and a distance of 15.2 m from the mirror. The card was used as a physical reflectance standard, and was measured three times daily during plot measurement periods.

Each replicate was completely randomized for all crop treatments after the sod and soil plots had been positioned to give a wide range of azimuth angles. The soil plots in the first replicate were positioned to

TABLE I RANDOMIZATION ARRANGEMENT OF CROPS, INOCULATED VARIETIES AND DATES OF SEEDING

Replicate I			Replicate II		
Plot no.	Crop type	Seeding date†	Plot no.	Crop type	Seeding date†
1	Sod		43	Barley; Conquest	D_2
2	Wheat; Hercules	D_1	44	Barley; Herta	D_1
3	Wheat; Sinton	D_1	45	Soil	
4	Oats; Garry	D_1	46	Wheat; Marquis SR6	D_2
5	Barley; Fergus	D_1	47	Oats; Garry	D_2, diseased
6	Barley; Herta	D_1	48	Barley; Conquest	D_2, diseased
7	Soil		49	Sod	
8	Oats; Hudson	D_1	50	Soybean	D_2
9	Wheat; Neepawa	D_2	51	Barley; Conquest	D_1
10	Wheat; Napayo	D_1	52	Barley; Peguis	D_1
11	Rapeseed; Tower	D_1	53	Rapeseed; Tower	D_1
12	Oats; Garry	D_1, diseased	54	Wheat; Glenlea	D_2
13	Wheat, Marquis	D_1, diseased	55	Rapeseed; Torch	D_2
14	Faba bean; Diana	D_2	56	Wheat; Marquis	D_1, diseased
15	Barley; Centennial	D_1	57	Faba bean; Diana	D_2
16	Wheat; Glenlea	D_2	58	Barley; Herta	D_2
17	Wheat; Macoun	D_1	59	Wheat; Marquis SR6	D_1
18	Barley; Conquest	D_2	60	Wheat; Macoun	D_1
19	Wheat; Marquis	D_1	61	Wheat; Sinton	D_1
20	Oats; Garry	D_2, diseased	62	Oats; Garry	D_1
21	Sod		63	Oats; Terra	D_1
22	Wheat; Hercules	D_2	64	Wheat; Hercules	D_1
23	Rapeseed; Tower	D_2	65	Barley; Fergus	D_1
24	Barley; Peguis	D_1	66	Oats; Hudson	D_1
25	Faba bean; Herz Freya	D_2	67	Wheat; Neepawa	D_1
26	Wheat; Neepawa	D_1	68	Faba bean; Herz Freya	D_2
27	Wheat; Marquis SR6	D_2	69	Barley; Conquest	D_1, diseased
28	Barley; Conquest	D_2	70	Rapeseed; Tower	D_2
29	Rapeseed; Torch	D_2	71	Wheat; Napayo	D_1
30	Wheat, Glenlea	D_1	72	Wheat; Glenlea	D_1
31	Soybean	D_2	73	Oats; Harmon	D_1
32	Wheat; Marquis	D_2, diseased	74	Oats; Garry	D_2
33	Barley; Conquest	D_1, diseased	75	Barley; Bonanza	D_1
34	Faba bean; Diana	D_1	76	Wheat; Marquis	D_1
35	Oats; Terra	D_1	77	Wheat; Neepawa	D_2
36	Oats; Garry	D_2	78	Barley; Centennial	D_1
37	Barley; Herta	D_2	79	Soil	
38	Oats; Harmon	D_1	80	Wheat; Marquis	D_2, diseased
39	Wheat; Marquis SR6	D_1	81	Oats; Garry	D_1, diseased
40	Barley, Bonanza	D_1	82	Faba bean; Diana	D_1
41	Barley; Conquest	D_1	83	Wheat; Hercules	D_2
42	Soil		84	Sod	

†D_1 — 27 May 1976; D_2 — 23 June 1976.

give a clear view of the sod plots in the second arc. After randomization certain diseased plots were relocated if it was thought necessary to decrease the interaction between diseased and healthy plots of the same or similar cultivar.

The plot area was treated with a general broadcast application of commercial fertilizer (10-10-10) and cultivated prior to seeding. The plots within each replicate were seeded with rows perpendicular to the viewing axis of the folding mirror. Plots thus presented a sufficient density of vegetation for measurements early in the growing season. Row spacing was 17.8 cm for cereals and 35.6 cm for broadleaf crops. The material was seeded by hand in accordance with normal planting densities. The perimeters, pathway and area between the laboratory and the plots were seeded with a durum wheat mixture (cv. Macoun, Lethbridge, and Wascana). This area and the sod plots were mowed regularly throughout the growing season. This maintained the sod plots at a relatively constant height (approximately 7.5 cm) and kept the test plots in clear view of the optical system.
A written and photographic record of crop conditions, heights (cm), and growth stages (Table 2; USDA-FAS-LACIE, 1976) for all crops was taken concurrently with reflectance measurements. Fresh plant samples were collected from selected plots (Table 3) for the estimation of chlorophyll a and chlorophyll b concentrations ($\mu g\ cm^{-2}$; Arnon, 1949; Sesták et al., 1971).

Analysis.

At the end of the growing season the spectral data were normalized by correcting for atmospheric moisture, sun angle and reflectance variations encountered throughout the measurement cycle (E.J. Brach, S. Elgazzar, and A.R. Mack. General software flowchart to normalize spectral curves of various agricultural crops. Computer J: sumbitted for publication). The residual spectral data were thus more representative of crop spectra and direct

Table 2. Legend to LACIE growth stage classes:

Code No.	Description
1.0	Not planted.
2.0	Planted, no emergence.
3.0	Emergence - one to three leaves.
4.0	Tillering, Preboot, Prebud.
5.0	Booted or Budded.
6.0	Beginning to head or flower.
7.0	Fully headed or flowered (Mid-pollination (flowering) for all crops).
8.0	Beginning to ripen.
9.0	Ripe - Mature.
10.0	Harvested.
11.0	Does not apply - fallow, sod, pasture.

Table 3. List of plots sampled for lab analysis.

Wheat		Oats	
Plot	Variety	Plot	Variety
2, 64	Hercules D_1†	4, 62	Garry D_1
22, 83	Hercules D_2†	12, 81	Garry D_1*
26, 67	Neepawa D_1	36, 74	Garry D_2
9, 77	Neepawa D_2	20, 47	Garry D_2*
30, 72	Glenlea D_1	Barley	
16, 54	Glenlea D_2	6, 44	Herta D_1
19, 76	Marquis D_1	37, 58	Herta D_2
39, 59	Marquis SR6 D_1	41, 51	Conquest D_1
13, 56	Marquis D_1*	33, 69	Conquest D_1*
27, 46	Marquis SR6 D_2	18, 43	Conquest
32, 80	Marquis D_2*	28, 48	Conquest D_2*

† D_1: seeded May 27th, D_2: seeded June 23rd.

*diseased plots.

comparisons could be made between measurements taken at different times or dates.

The classification of certain test plot characteristics was carried out by discriminant analysis (Klecka, 1975) of the normalized plot reflectance data. The normalized data had been partitioned into mean wavelength band amplitudes (Fig. 4a and 4b) and ratios or sums of these values (Table 4) were calculated to be used as the "discriminating" variables in the analysis. For each classification (ie. land use, crop maturity, or crop type and disease status), the "discriminating" variables of all plots in the analysis were grouped into their appropriate classes (eg. sod, soil, or crop for the land use classification), and coefficients which maximized the difference between the corresponding variables of each class were developed. Functions, consisting of the variables and their coefficients (eg. Table 5), were tested for their ability to classify all the plots in the analysis. The results presented in the following section were obtained from the classification of test plot characteristics by the "best" discriminant functions developed for each classification. In this sense "best" means that the discriminant functions were based on the variables and coefficients that maximized intergroup distances.

Figure 4a. Visible Spectral Curves for Conquest Barley, Sod and Soil Plots; and the Wavelength Bands Used for Discriminant Analysis.

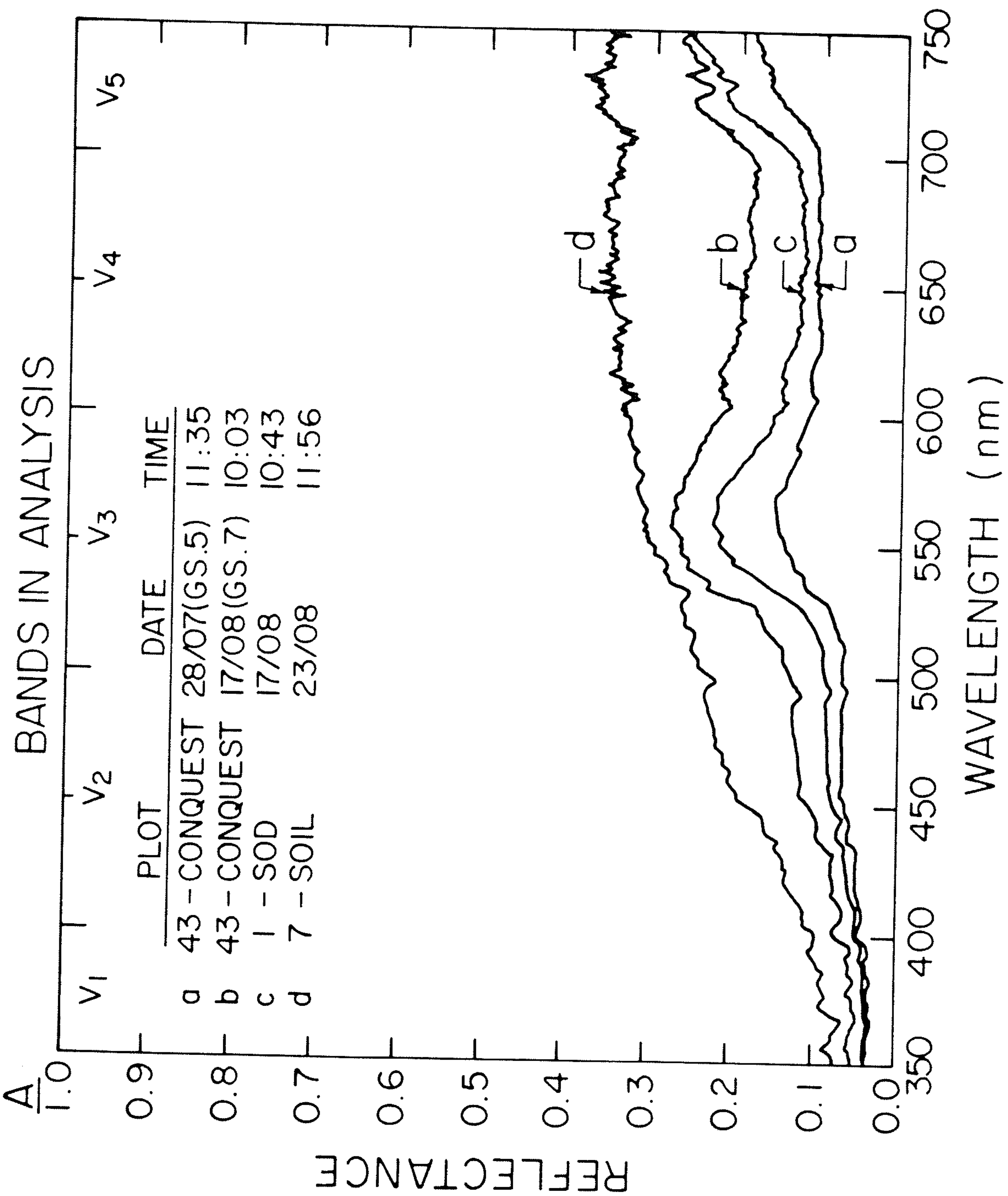

A
BANDS IN ANALYSIS
V1
V2
V3
V4
V5
PLOT DATE TIME
a 43 - CONQUEST 28/07(GS.5) 11:35
b 43 - CONQUEST 17/08(GS.7) 10:03
c 1 - SOD 17/08 10:43
d 7 - SOIL 23/08 11:56
d
b
c
a
REFLECTANCE
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
350
400
450
500
550
600
650
700
750
WAVELENGTH (nm)

Figure 4b. Infrared Spectral Curves for Conquest Barley, Sod and Soil Plots; and the Wavelength Bands Used for Discriminant Analysis.

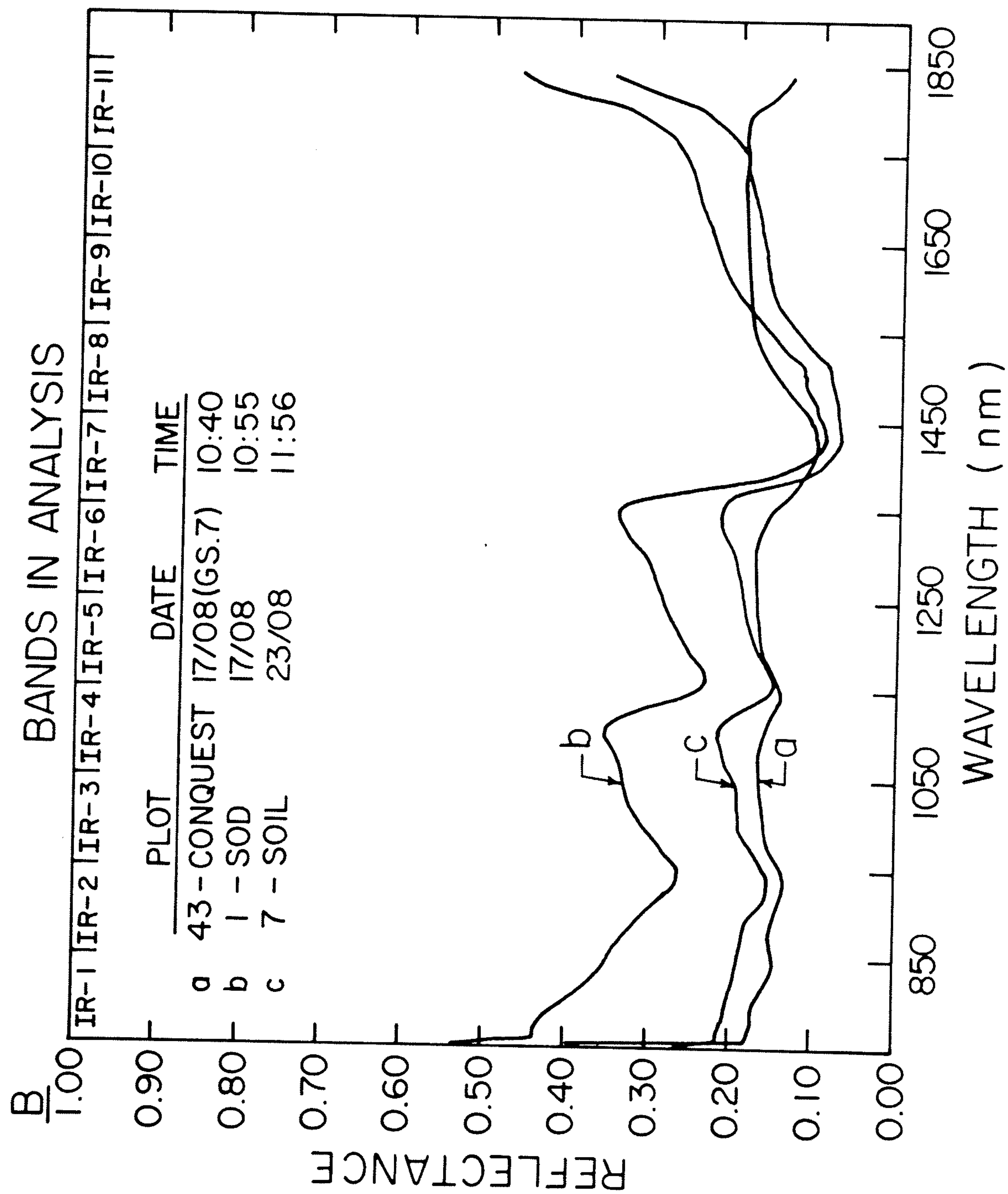

B
BANDS IN ANALYSIS
IR-1 | IR-2 | IR-3 | IR-4 | IR-5 | IR-6 | IR-7 | IR-8 | IR-9 | IR-10 | IR-11
PLOT DATE TIME
a 43 - CONQUEST 17/08 (GS.7) 10:40
b 1 - SOD 17/08 10:55
c 7 - SOIL 23/08 11:56
a
b
c
REFLECTANCE
1.00 0.90 0.80 0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00
850 1050 1250 1450 1650 1850
WAVELENGTH (nm)

Table 4. Visible and infrared "discriminating" variables.

CODE		MEAN RADIANCE BAND RELATIONSHIPS
RAT01	-	V5/V4 = (700-750 nm)/(600-700 nm)
RAT02	-	V4/V3 = (600-700 nm)/(500-600 nm)
RAT03	-	V3/V2 = (500-600 nm)/(400-500 nm)
RAT04	-	V2/V1 = (400-500 nm)/(350-400 nm)
RAT05	-	V5/V3 = (700-750 nm)/(500-600 nm)
RAT06	-	V5/V2 = (700-750 nm)/(400-500 nm)
RAT07	-	V5/V1 = (700-750 nm)/(350-400 nm)
RAT08	-	V4/V2 = (600-700 nm)/(400-500 nm)
RAT09	-	V4/V1 = (600-700 nm)/(350-400 nm)
RAT10	-	V3/V1 = (500-600 nm)/(350-400 nm)
RAT11	-	IR-6 + IR-7 + IR-8 + IR-9 + IR-10 + IR-11 = (1250-1350 nm) + (1350-1450 nm) + (1450-1550 nm) + (1550-1650 nm) + (1650-1750 nm) + (1750-1850 nm)

RESULTS AND DISCUSSION

Land Use Classification.

It was felt that, while only representing a gross characterization of the test site, the classification of general plot types (crop, sod, soil) by spectral analysis was basic to the discrimination of other plot characteristics. In an operational crop reporting system, the capability must exist to discern cropped land from other land use categories. In an abstract sense, the plot classes of crop, sod, and soil may be likened to the occurrence of cropped, pasture, and fallowed land in a large area survey.

The discriminant analysis employed in the classification of the crop, sod, and soil plots incorporated spectral data from 271 plot measurements and encompassed a crop maturity range from growth stages GS4 to GS8 (Table 2). The analysis was based on two discriminant functions which incorporated wavelength band ratios one through eight, ten, and eleven (Table 4) as the discriminant variables (Table 5). The results obtained in the land use classification (Table 6) were quite encouraging. Overall, 95.2% of the grouped cases were classified correctly. More specifically, the classification of crop, sod, and soil plots was 95.6%, 88.9%, and 100% accurate, respectively. The group cases incorrectly classified represented only 4.8% of the 271 cases analysed. This error occurred in the classification of sod vs. crop plants.

The level of accuracy obtained in the land use classification should be considered in terms of the physical and biological characteristics of the three plot types throughout the growing season. The soil plots, due to their tone, texture, and lack of vegetation, had unique spectra which were reasonably constant throughout the growing season (Fig. 4a and 4b, soil). The sod plots, which were well established prior to spectral measurements,

TABLE 5. Standardized Discriminant Function Coefficients: Land Use Classification

	Function 1	Function 2
RAT 01	0.27726	-0.86390
RAT 02	3.98726	-0.44893
RAT 03	0.76250	0.34729
RAT 04	-1.13942	-0.12298
RAT 05	-2.01452	3.34403
RAT 06	1.49733	-3.39014
RAT 07	0.60709	-0.08582
RAT 08	-4.02922	0.57715
RAT 10	0.66441	0.12931
RAT 11	0.00243	-0.29147

Table 6. Prediction Results: Land Use Classification:

Actual Group	No. of Cases	Predicted Group Membership (No. and % of Cases) Crops	Sod	Soil
Crops	227	217 (95.6%)	10 (4.4%)	0
Sod	27	3 (11.1%)	24 (88.9%)	0
Soil	17	0	0	17 (100%)

Percent of "Grouped" cases correctly classified - 95.20%

consisted of dense, green vegetation of relatively constant biomass, morphology and pigment content. As in the case of the soil plots, the reflectance of the sod plots was relatively constant throughout the growing season. However, the visible spectra of these plots exhibited the green reflectance peak of chlorophyll containing vegetation (Fig. 4a, sod). The crop plots, due to temporal variation in morphology, pigment content, and biomass, exhibited variable reflectance spectra throughout the growing season (Fig. 4a and 4b, Conquest). The misclassification of sod or crop plots was due to similarities in the reflectance of these plots at some stages of growth. Similarities in the morphology or pigmentation of these plots were felt to be responsible for the similarities in reflectance. This classification error, however, was small since only 5.1% of the 254 crop or sod plots were misclassified and the error did not occur consistently throughout the growing season. Generally, the classification of the land use categories sod, soil, and crop was quite accurate throughout the growing season.

Crop Maturity Estimation.

The ability to estimate crop maturity from remotely acquired reflectance data was felt to be a necessary requirement for the determination of a number of yield-related parameters. The period from heading to maturity (GS6 to GS9) in cereals has been found to be critical to final attained yield, while the period of floral initiation during vegetative growth has been shown to determine the maximum yield potential in a cereal crop (Idso et al., 1977a; Slatyer, 1969). It was felt that other important parameters such as time to harvest and timeliness of maturity in different cropping regions might also be determined from remotely acquired crop maturity data. Even prior to crop type classification, the estimation of general crop maturity could provide beneficial information in a crop reporting system.

The discriminant analysis employed in the crop maturity classification incorporated crop spectral data from 193 separate plot measurements encompassing a maturity range from growth stages GS4 to GS8. The analysis was based on four discriminant functions which incorporated wavelength band ratios one through seven, ten and eleven (Table 4) as the discriminant variables (Table 7). The preliminary results of the analysis (Table 8a) were not indicative of a high classifier accuracy. The "grouped " cases did not readily fall into the LACIE growth stage classes; as was evident from the 60.1% overall classification accuracy. However, when the classification groups were condensed into two classes representing growth stages GS4-5 and GS6-8 (Table 8b), the overall classification accuracy was increased to 93.3%. The specific classifications GS4-5 and GS6-8 were 81.8% and 94.0% accurate, respectively. The "grouped" cases incorrectly classified represented only 6.7% or 13 of the 193 plots measurements analysed.

It was felt that the classification results could best be explained by considering changes in canopy characteristics that would cause sufficient change in crop reflectance to allow these characteristics to be discriminated. Crop reflectance has been shown to be related to gross canopy morphology and pigmentation in the visible wavelength region (Gates et al., 1965; Knipling, 1970; Gausman et al., 1970; Thomas and Gausman, 1977). Reflectance in the infrared wavelength region has been attributed to cell wall-air interfaces, or the cellular integrity of the canopy components (Gates, 1970; Gausman et al., 1970; Sinclair et al., 1973) and gross canopy morphology and vegetation density (Myers, 1970; Colwell, 1974).

The LACIE growth stages (USDA-FAS-LACIE, 1976) were designed as a

TABLE 7. Standardized Discriminant Function Coefficients: Crop Maturity Estimation.

	Function 1	Function 2	Function 3	Function 4
RAT 01	-1.95502	3.59377	0.75340	-0.40527
RAT 02	-0.00987	1.67881	0.49149	-0.54788
RAT 03	-0.90540	-0.70827	4.87490	-2.04399
RAT 04	0.05087	-3.07175	4.22952	-3.58618
RAT 05	-0.71806	-0.36913	6.14248	-0.75425
RAT 06	2.85479	-3.22796	-7.98043	1.57176
RAT 07	-0.88099	1.19580	0.82756	-1.04358
RAT 10	0.68412	2.77788	-5.48696	4.15423
RAT 11	-0.03340	-0.09564	0.44136	0.76673

Table 8a Prediction Results: Crop Maturity Estimation

Actual Group	No of Cases	Predicted Group Membership (No. and % of Cases) GS 4	GS 5	GS 6	GS 7	GS 8
GS 4	3	2 (66.7%)	1 (33.3%)	0	0	0
GS 5	8	2 (25.0%)	4 (50.0%)	1 (12.5%)	1 (12.5%)	0
GS 6	14	2 (14.3%)	1 (7.1%)	4 (28.6%)	6 (42.9%)	1 (7.1%)
GS 7	69	2 (2.9%)	5 (7.2%)	13 (18.8%)	36 (52.2%)	13 (18.8%)
GS 8	99	1 (1.0%)	0	7 (7.1%)	21 (21.2%)	70 (70.7%)

Percent of "Grouped" cases correctly classified: 60:10%

Table 8b Prediction Results: Crop Maturity Estimation

Actual Group	No of Cases	Predicted Group Membership (No. and % of Cases) GS 4-5	GS 6-8
GS 4-5	11	9 (81.8%)	2 (18.2%)
GS 6-8	182	11 (6.0%)	171 (94.0%)

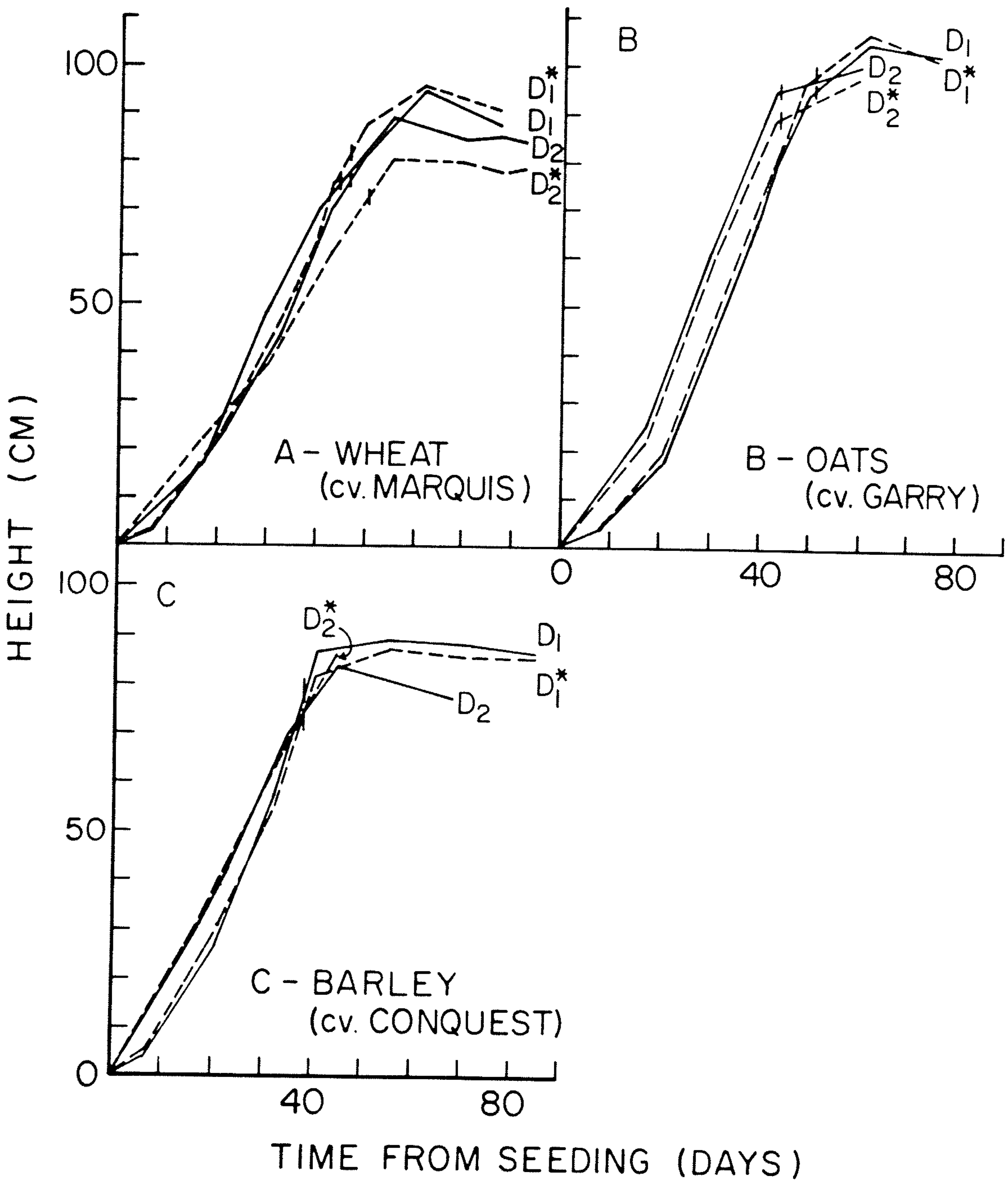
Percent of "Grouped cases correctly classified: 93.3%

guide for ground truth data collection of visually detectable crop characteristics. These stages, however, were not necessarily indicative of detectable crop canopy reflectance changes. The low classification accuracy in the preliminary analysis (Table 8a) may have been due to the characteristics of the LACIE growth stages which were used for the group structure of this classification. The small number of measurements taken during GS4 were obtained from the last portion of this growth stage when plants had reached maximum height (Fig. 5). The expansion of the upper leaf sheath during the pre-boot (GS5) stage would, therefore, have been a subtle change in canopy morphology. Also, the tissue remained green during this period, and no large change in pigment content was detectable (Fig. 6).

The first gross changes in the canopy occurred as the heads emerged from the sheath (GS6). At this stage a bi-level canopy, consisting of floral and vegetative parts, was formed, the first evidence of pigment and tissue senescence occurred (Fig. 6), and plant heights and biomass reached a plateau (Fig. 5). Therefore, when the group structure of the analysis was condensed into a vegetative (GS4-5) vs. floral (GS6-8) maturity classification, the classifier accuracy was greatly increased (Table 8b).

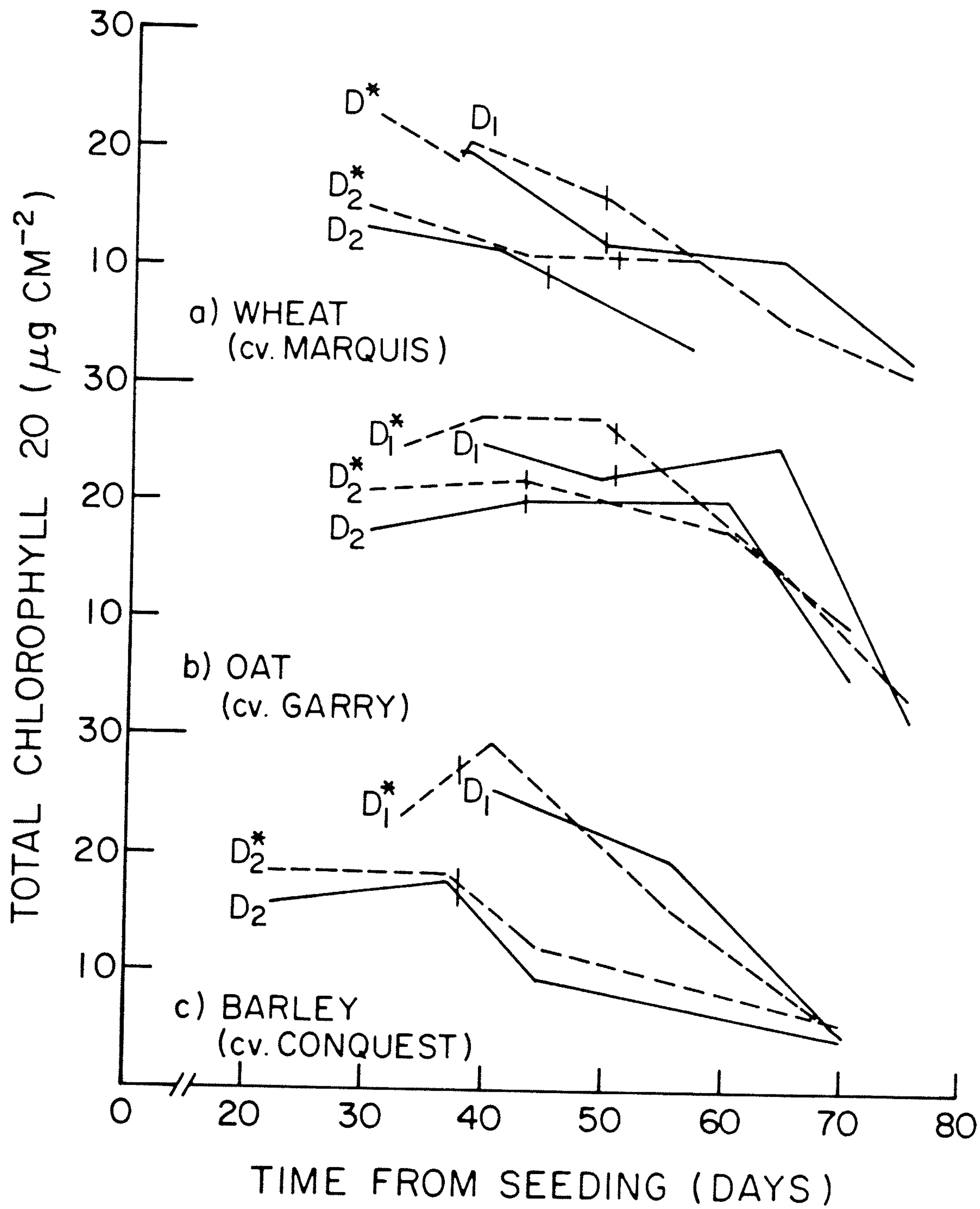
Although the maturity classification did not discriminate between specific growth stages, it did accurately separate crop growth into the two critical periods affecting yield. If accompanied by crop type, acreage, status and environmental data, this classification could aid in the estimation of final crop yields (Idso et al., 1977a, 1977b). An estimate of time to harvest or timeliness of maturity could still be acquired if the time of change from vegetative to floral growth were accurately determined.

Figure 5. Heights (cm) vs. Time from Seeding for a) Wheat (cv. Marquis); b) Oats (cv. Garry); and c) Barley (cv. Conquest). (D_1 May 27; D_2 June 23; * Diseased; 1 -Approximate Heading Time).



100
50
100
50
0
0
40
80
40
80
HEIGHT (CM)
TIME FROM SEEDING (DAYS)
A - WHEAT
(cv. MARQUIS)
B
B - OATS
(cv. GARRY)
C
C - BARLEY
(cv. CONQUEST)
D_1^*
D_1
D_2
D_2^*

Figure 6. Leaf Chlorophyll (g cm^{-2}) Concentration vs. Time from Seeding for a) Wheat (cv. Marquis); b) Oats (cv. Garry); and c) Barley (cv. Conquest). (D_1 May 27; D_2 June 23 ; * Diseased ; 1 -Approximate Heading Time).



30
20
10
30
20
10
30
20
10
0
20
30
40
50
60
70
80
TOTAL CHLOROPHYLL (μg CM^{-2})
TIME FROM SEEDING (DAYS)
a) WHEAT
(cv. MARQUIS)
b) OAT
(cv. GARRY)
c) BARLEY
(cv. CONQUEST)
D*
D_1
D_2^*
D_2
D_1^*
D_1
D_2^*
D_2
D_1^*
D_1
D_2^*
D_2

Crop Type and Disease Classification.

It was felt that the ability to classify specific crop type and stress would complete the set of discernable characteristics required for a remote crop survey system. The identification of these characteristics would allow users to make an accurate, timely, and specific assessment of crop production in a given area. Cultural decisions regarding the control or correction of stress situations could be assisted by the analysis of remote crop reflectance data (e.g. detection of disease, pests, water stress, or nutrient deficiencies).

The discriminant analysis employed in the crop type and disease classification incorporated spectral reflectance data from 182 separate plot measurements acquired during the flowered growth stage (GS6-8). The analysis was based on eight discriminant functions which incorporated wavelength band ratios one, and three through eleven (Table 4) as the discriminant variables (Table 9). The overall accuracy of classification for specific crop types (Table 10a) was only 56.04%. However, the specific classifications for rapeseed, fababean and soybean were 75%, 92%, and 100% accurate, respectively. The low overall classifier accuracy was therefore due to classification results obtained for specific diseased and healthy cereal plots. When the group structure of the classification was condensed to show healthy vs. diseased cereals (Table 10b), the accuracy of classification was 71.7% and 67.9% respectively for these groups. The overall accuracy for the "grouped" cases was increased to 75.27%. Further revision of the group structure to show cereals vs. specific broadleaves (Table 10c) increased the classification accuracy of cereals to 91.8% and the overall accuracy to 90.7%. The 9.3% error in this case represents 17 plots which were incorrectly classified.

Historically, the ability to distinguish wheat, oats, or barley by

TABLE 9. Standardized Discriminant Function Coefficients: Crop Type and Disease Classification.

	Function 1	Function 2	Function 3	Function 4	Function 5	Function 6	Function 7	Function 8
RAT 01	-2.39987	0.54408	0.09437	0.09511	0.78545	1.41942	-0.80656	-2.20654
RAT 03	0.24670	-3.34669	-0.08752	3.17879	-4.06215	-4.56803	0.85563	1.09469
RAT 04	-0.37946	-0.68021	-0.89096	5.48595	-3.33285	-1.86697	-2.55634	-0.81550
RAT 05	0.97661	-2.32000	-2.28602	0.07094	-0.89614	-9.40297	-1.20313	5.59093
RAT 06	-0.76768	4.04231	2.87507	-0.30253	0.87751	9.46094	-0.27584	-2.37950
RAT 07	0.91695	-1.83708	-1.09035	-0.37999	-0.96062	-0.86793	1.89390	-1.73007
RAT 08	-0.51212	2.37047	-1.05993	-1.42261	4.48607	0.52394	-5.02145	-1.57344
RAT 09	-0.31218	-2.54735	1.86277	1.90491	-7.57379	-0.84083	7.18635	1.79231
RAT 10	-0.02432	3.82488	0.02386	-7.00490	8.35351	3.68250	-3.41903	0.91574
RAT 11	0.01905	0.29735	0.22761	0.28915	0.23108	-0.56436	0.24224	-0.74647

Table 10 a Prediction Results: Crop Identification

Actual Group	No. of Cases	Predicted Group Membership (No. and % of Cases) W	O	B	R	F	S	W*	O*	B
Wheat	63	27 (42.9%)	8 (12.7%)	8 (12.7%)	4 (6.7%)	2 (3.2%)	0	7 (11.1%)	2 (3.2%)	5 (7.9%)
Oats	21	5 (23.8%)	14 (66.7%)	0	0	1 (4.8%)	0	0	1 (4.8%)	0
Barley	22	5 (22.7%)	1 (4.5%)	8 (36.4%)	2 (9.1%)	0	0	4 (18.2%)	0	2 (9.1%)
Rapeseed	16	2 (12.5%)	0	1 (6.3%)	12 (75.0%)	1 (6.3%)	0	0	0	0
Fababean	25	1 (4.0%)	1 (4.0%)	0	0	23 (92.0%)	0	0	0	0
Soyabean	7	0	0	0	0	0	7 (100.0%)	0	0	0
Wheat*	8	2 (25.0%)	0	0	0	0	0	2 (25.0%)	2 (25.0%)	2 (25.0%)
Oats*	10	1 (10.0%)	2 (20.0%)	1 (10.0%)	0	0	0	1 (10.0%)	4 (40.0%)	1 (10.0%)
Barley*	10	0	0	1 (10.0%)	1 (10.0%)	1 (10.0%)	0	2 (20.0%)	0	5 (50.0%)

Percent of "Grouped" cases correctly classified: 56.04%
* diseased

Table 10 b Prediction Results: Crop Identification

Actual Group	No. of Cases	Predicted Group Membership (No. and % of Cases)				
		Cereals	R	F	S	Cereals*
Cereals	106	76 (71.7%)	6 (5.7%)	3 (2.8%)	0	21(19.8%)
Rapeseed	16	3 (18.8%)	12 (75.0%)	1 (6.3%)	0	0
Fababean	25	2 (8.0%)	0	23 (92.0%)	0	0
Soybean	7	0	0	0	7 (100.0%)	0
Cereals*	28	7 (25.0%)	1 (3.6%)	1 (3.6%)	0	19(67.9%)

Percent of "Grouped" cases correctly classified: 75.27%

Table 10c. Prediction Results: Crop Identification

Actual Group	No. of Cases	Predicted Group Membership (No. and % of Cases) Cereals	R	F	S
Cereals	134	123 (91.8%)	7 (5.2%)	3 (2.2%)	0
Rapeseed	16	3 (18.8%)	12 (75.0%)	1 (6.3%)	0
Fababean	25	2 (8.0%)	0	23 (92.0%)	0
Soybean	7	0	0	0	7 (100.0%)

Percent of "Grouped" cases correctly classified: 90.7%

the analysis of remote reflectance data has been low (Mack and Bowren, 1974; Mack et al., 1975; Mack and Bowren, 1975; Macdonald, 1976; NASA-NOAA-USDA, 1976). Due to similarity in morphology, pigmentation, and growth and development, the reflectance of these crops tended to be quite similar throughout the growing season (Table 10a). Also, the test plot area exhibited a manganese deficiency (tissue analysis: Fe:Mn, 5.77:1; Normal healthy Fe:Mn values approx. 2:1), and a high incidence of natural disease infection, which seemed to have the greatest effect on cereal growth. The reflectance spectra of these crops therefore tended to be quite similar throughout the growing season, and were difficult to discriminate. Conclusions as to the ability to discriminate between cereal crops by spectral analysis could not be made. The results of the diseased vs. healthy cereal classification (Table 10b), when considered in terms of the confounding effects of disease and nutrient status, were felt to be a positive indication of a phenomenon which might be more discernable under different crop conditions.

Broadleaf plots were distinct in vegetative and flowering growth, leaf type, and vegetative and floral pigmentation. The spectra of these plots were therefore quite distinct, and were accurately classified into their respective groups, (Table 10a). Also, due to the similarities of the cereal plots and the discernability of the broadleaf plots, the ability to distinguish cereals as a group from specific broadleaf plots was high (Table 10c).

The results of the crop type and disease classification were not totally conclusive. However, the classification of general crop types (cereals vs. broadleaves) and specific broadleaf crops by the analysis of crop reflectance was highly accurate. These results support the general conclusions obtained from the classification of crop spectra from Landsat data during the period from 1973 to 1975. It was shown that major crop groups and land use areas (fallow, cereals, rapeseed, forage) are classified with high accuracy and that cereals are classified less accurately (50 to 100%) probably due to variation in relative stage of development (Mack and Bowren, 1975; Mack et al., 1975).

GENERAL CONCLUSIONS

It has been shown that it is possible to discern land use categories, general crop maturity, and specific or general crop types from the analysis of remotely acquired reflectance data. The results of the classifications of specific crop maturity stages, cereal types, or disease status were not conclusive. The parameters successfully classified could be incorporated into a functional crop reporting system. It would, however, be advisable to carry out further testing at different locations in order to substantiate the results presented in this paper. As stated previously, further testing under optimum conditions could lead to an accurate classification of crop disease status. Also, an increased number of measurements during the earlier stages of plant growth could result in a more extensive range of discernable growth stages. Due to the inherent similarities of cereals, it was felt that an increase in the net resolution by the incorporation of greater environmental monitoring and correction might aid in their identification. All of these recommendations were incorporated into field tests which were carried out during subsequent growing seasons.

GENERAL DISCUSSION

Current hypotheses of the interaction of radiation with single leaves and canopies describe the factors which affect the radiation regime within, and the radiance from vegetation canopies. The net radiance of a canopy, subsequent to absolute correction for the conditions of measurement, would be due to the combined effect of canopy factors such as single leaf and non-leaf component optics, and the frequency and orientation of these components in the canopy. The optics of single leaves and non-leaf components depend on their pigmentation, water content, and internal and external morphology. The orientation and frequency of the canopy components are determined by the canopy type, stage of development, physiological status, and, in the case of some crops, by prevailing cultural practices. It has been proposed that a number of canopy parameters such as crop type, stage of development, and disease status may be determined from remote reflectance measurements. The success of such determinations would depend on the level of correction and the analytical methods employed, and the existance of discernable reflectance "signatures" which may be related to the parameter of interest.

This study has shown that it was possible to discern a number of crop parameters by the discriminant analysis of corrected canopy reflectance data. The accuracy of classification was felt to be related to the apparent similarities or differences that exist between the canopies studied. The classification of subtle canopy differences by discriminant analsysis of canopy reflectance data would depend on the levels of data correction employed, and on the existance of discernable canopy reflectance "signatures".

SUMMARY AND CONCLUSIONS

1. The classification of sod, soil, and crop plots, which are somewhat analogous to the LACIE pasture, fallow, and crop classes, was 88.9, 100, and 95.6% accurate, respectively. The overall classification accuracy was 95.2% for this analysis. Errors of commission and omission occurred only between the sod and crop classifications and were felt to be due to the similarity of these plots at an early growth stage.

2. Crop maturity was accurately classified (93.3% overall accuracy) when the classification groups were condensed to consist of vegetative and flowered growth stages. Maximal discriminability was felt to exist between these groups because of marked differences in canopy reflectance due to changes in canopy morphology, pigment content, moisture content, and the degree of tissue senescence. It was felt that this classification could aid in the estimation of crop yields since the two critical periods affecting crop yields were delineated.

3. Broadleaf crops were accurately discriminated from each other (rapeseed, 75.0%; fababean, 92.0%; soybean, 100% accurate classification), and from cereal crops (broadleaves vs. cereals: 90.7% classification accuracy). The classification of healthy and diseased cereals were 71.7 and 67.9% accurate, respectively. Due to prevailing nutrient and disease conditions, it was felt that confounding of an otherwise

discernable parameter (disease infection) may have occurred. Specific cereal types were not discernable by the methods employed.

CONTRIBUTIONS TO KNOWLEDGE

Further research should be carried out to determine the discriminability of crop parameters, and to test the methods developed by this and subsequent studies over a number of years and locations. Although certain useful crop parameters were discriminated, modification of the experimental design and environmental monitoring and correction techniques may further enhance the detectability of crop parameters by remote canopy reflectance measurements.

1) The number of test plot replicates should be increased to obtain a better estimate of the variability in crop growth and canopy reflectance.
2) Plot dimensions should be increased to decrease the interaction of plots with neighboring plots and with the environment. The observed canopy reflectance would then be a better approximation of that observed from a large field canopy.
3) The number of crop types studied should be decreased so that the probability of measuring the reflectance of all plots at a given stage of development is increased.
4) The cycle of measurements carried out should be more closely synchronized to the development of the crops studied. In this way, discernable changes in the canopy reflectance may be more easily related to actual changes within the canopy.

5) A more extensive program of biological measurements, including leaf area and angle estimations, pigment measurements, tissue moisture measurements, elemental tissue analyses, and canopy productivity measurements, should be incorporated in subsequent studies to aid in the identification of discernable canopy parameters.

6) The incident sky and solar spectral radiance and the micro-climate within the canopy should be monitored simultaneously with crop spectral reflectance measurements. Such monitoring would increase the accuracy of corrections carried out on the crop spectral data and, thus, improve the discrimination of canopy parameters.

7) The effects of the angular conditions of measurement on the observed canopy reflectance, the normalized canopy reflectance, and the discrimination of canopy parameters should be studied to determine the efficiency of the angular corrections employed, and the optimum conditions for discrimination.

8) The study of small plot (flats) reflectance under controlled growing conditions could supply preliminary data on the discrimination of certain crop parameters. This preliminary information could aid in the estimation of these parameters under field conditions.

The incorporation of these recommendations in subsequent studies should aid in the discrimination of crop parameters by remote reflectance measurements.

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APPENDIX

IMPROVEMENTS IN SPECTRAL REFELECTANCE MEASUREMENTS OF FIELD CROPS[1]

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Received 24 January 1977

Brach, E.J., R.W. Tinker, and **G.T. St. Amour.** 1977 Improvements in spectral reflectance measurements of field crops. Can. Agric. Eng. 19: 78-83.

A mobile field spectrometer is described that measures the optical properties of the visible and near infrared spectrum and the fluorescent infilling of the solar absorption lines for the study of remote sensing techniques applied to crops. The partially preprogrammed spectrometer sequentially scans a pre-selected bandwidth and also records irradiance calibration bands, other reference information and weather data. An arc-shaped arrangement of the field test plots provided a constant path-distance for the radiance from the plots to the telescopic detector system to simplify normalization of the data and calibration of the system.

INTRODUCTION

A mobile field spectroradio laboratory to measure spectral characteristics of plants by remote sensing techniques and study (a) crop yield potential in breeding research, (b) early disease detection, and (c) field-crop yield estimates was previously reported (Brach 1974; Brach et al. 1977). The purpose here is to report improvements made to the instrumentation and to the arrangement of the field plots. Infrared spectrum and laser fluorescence detection were added which coupled with improved data recording of the total radiant energy and the energies in the blue and red spectral regions increased the potential applications of the system as a research tool.

FIELD LAYOUT

To arrange the plots for the study within the horizotal azimuth range of the telescope, plot width was restricted to accommodate the viewing angle of the telescope (Brach et al. 1977). The rectangular arrangement of the plots used in the 1975 and the new circular arrangement used in 1976 are compared (Fig. 1). In 1975 the radiance path distance to the telescope was different for each plot because of the rectangular layout. This also introduced difference in viewing angle and viewing area at each plot. To compare data from the plots it must be corrected on the following basis:

$$E_r = \frac{N}{d^2} \cos \alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where E_r = the reflected energy from the plants;
N = the irradiance to the plant;
d = distance between the mirror (M) and the plot; and
α = viewing angle.

Since E is inversely proportional to d^2 and directly proportional to $\cos\alpha$, the reflected energy changed by a factor of 9 between the nearest and farthest plot (about 25 m).

In 1976, to reduce the problem of correcting for distance, the plots were arranged as arcs (72°) of two concentric circles with radii 24.4 and 30.5 m with the spectrometer telescope located at the center. Thus, the radiance distance for all plots within one circular arc was constant. The reduction in reflected energy over the longer distance to the outer circular arc is partially compensated for by the larger viewing area of the telescope which increases with distance, proportional to the ratio of the radii (r_2/r_1). The difference in viewing angle between the plots in the two circular arcs is small (α = 1.19° so that $\Delta\cos\alpha$ = 0.002). The theoretical error was thus <1%, which was ignored. The spectrometer was located with the telescope pointing north (1976, Fig. 1B).

TEST PLOTS

Control

The control plots used in 1976 were clipped sod and bare soil located adjacent to each replicate crop to facilitate studying the sun-angle effects (Fig. 1B). Lawn grass sod containing a mixture by weight of 70% Kentucky bluegrass cv. Merion and 30% common Kentucky bluegrass and creeping red fescue was established early in 1976 and clipped to an approximate height of 7.5 cm twice weekly during the experiment. The bare soil control plots were kept free of vegetation.

Field Crops

Wheat,oats, rapeseed, soybean and faba beans were seeded on 27 May (D_1) and again on 23 June (D_2) to provide a range of plant morphology and growth stages (Table 1). Additional plots of wheat cv. Marquis, oats cv. Garry and barley cv. Conquest were inoculated with stem-rust (*Puccinia graminis* f.s.p. *trictici), crown rust (Puccinia coronata* cda) and leaf blotch (*Cochliobolus sativus* (Ito and Kurib)), respectively, at the 3rd-leaf growth stage. To prevent infection from spreading, each inoculated plot was located adjacent to non-susceptible crops

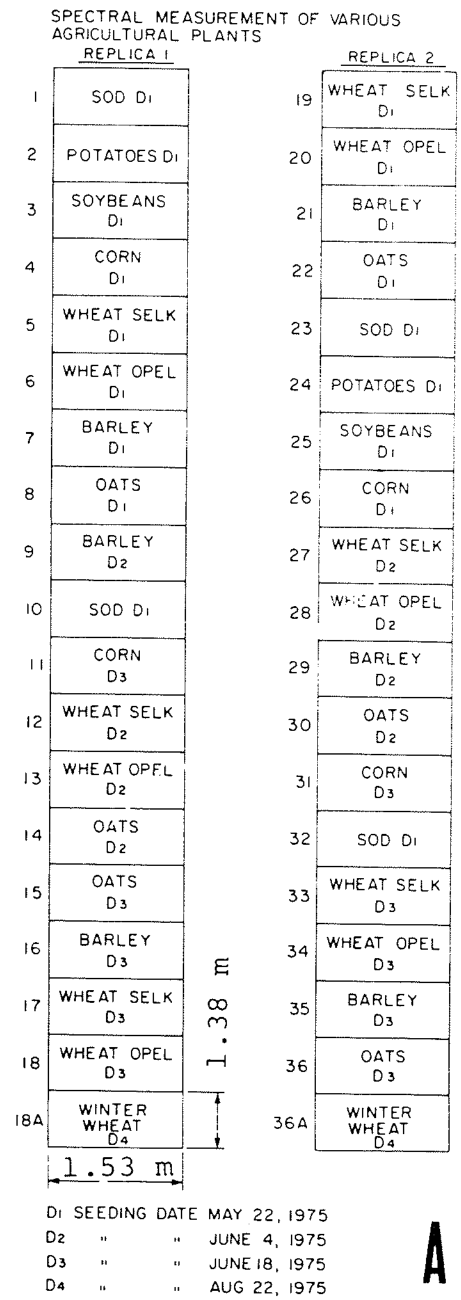

Figure 1A. Field layout for 1975 experiment.

[1]Contribution no. 661 from Engineering Research Service.

(e.g. wheat inoculated with stem rust, adjacent to barley or oats). All rows were seeded perpendicular to the viewing angle axis of the spectrometer. Normal rates of seeding were used (wheat, 101 kg/ha; oats, 79 kg/ha; barley, 94 kg/ha; rapeseed, 5.6 kg/ha; faba bean, 157 kg/ha; and soybean, 157 kg/ha).

INSTRUMENTATION IMPROVEMENTS

A radiant energy pyroheliometer provided a reference for changing atmospheric interference to the incoming energy to the plots. It was placed on the mobile laboratory roof to reduce interference from nearby objects. A photometer, placed with the pyroheliometer, was used to measure the relative variation between the blue (475 nm) and the red (675 nm) incoming radiation in a 25 nm half-bandwidth. This information, together with the ambient temperature, was printed on a teletype and punched on a paper tape before each spectral scan of a plot. The operation of the spectral measuring system was hardware programmed through the teletype. After the date was manually punched in, measurement was initiated to automatically record the following: (a) time (h and min) from a digital clock, (b) plot number as previously entered by a thumb-wheel switch, (c) the incoming radiant energy (Watts cm^{-2}), (d) the ambient temperature (C), (e) the blue and red component of the incoming radiant energy (m Watt), and (f) finally the wavelength and corresponding spectral output reflected from the plot were printed in sequence to obtain a spectral scan between preset wavelength limits.

A spectral system for measuring from 800 to 6,000 nm in the infrared region was developed to extend the facilities' spectral range (Fig. 2). This included a 220 X 155-mm folding mirror (M), a 12.7-cm Cassegrain Schmidt telescope, telecompressor (Tc), 0.25-m focal length monochromator in an Ebert optical configuration, a lead sulphide (PbS) detector (D), a lock-in amplifier and a data processing system, and a recorder. To improve the signal to noise ratio, the radiant energy was chopped by a 100-Hz chopper (Ch) before it entered the monochromator. The synchronous signal to the lock-in amplifier from the chopper was provided by a silicon photodetector (Ds).

In 1976 the mobile spectral laboratory was equipped with Nitrogen (337.1 nm) and Helium Cadmium (410 nm) lasers for fluorescence detection (Fig. 3) as described

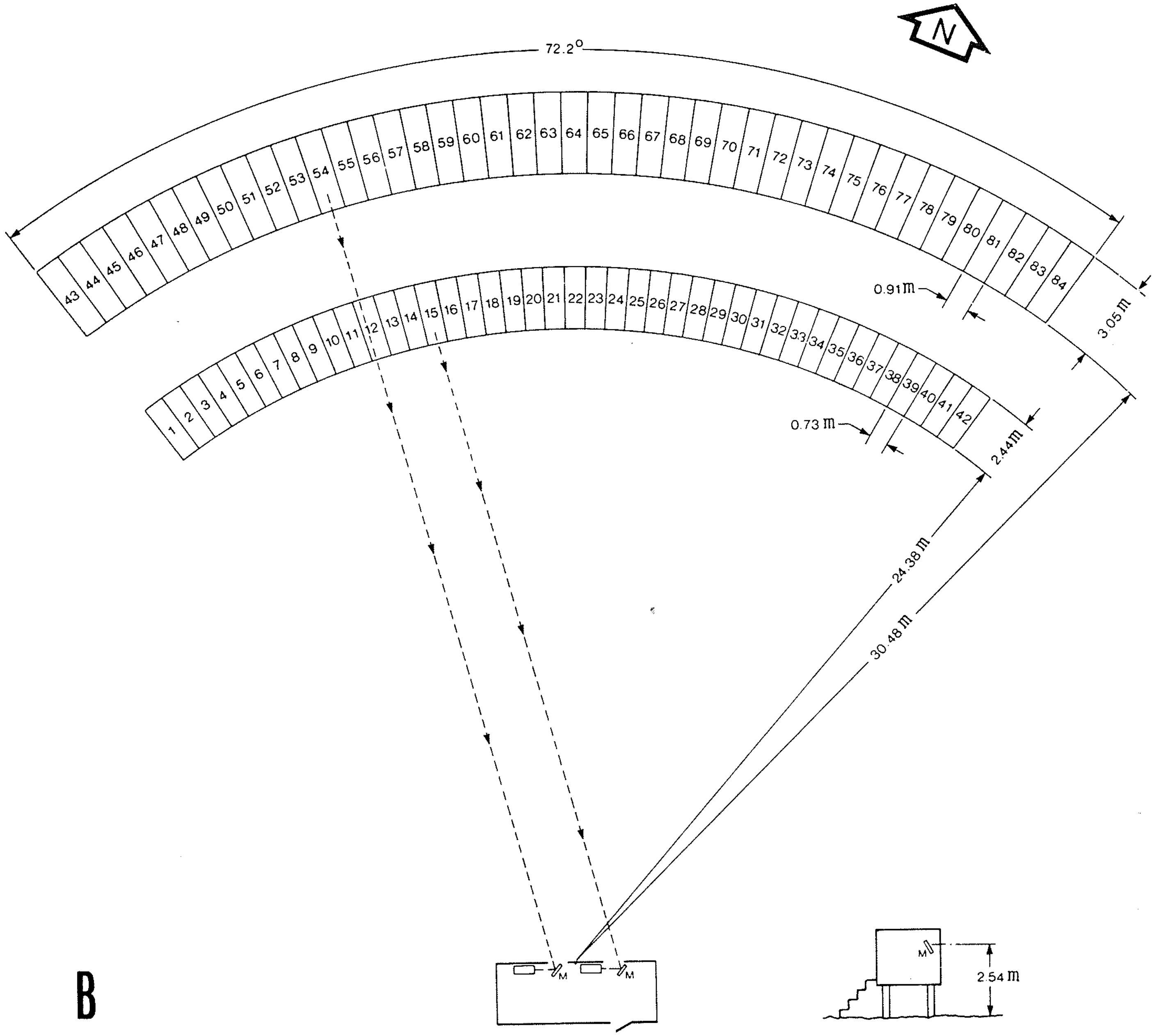

Figure 1B. Field layout for 1976 experiment.

previously (Brach and Molnar 1977; Brach et al. 1977).

RESULTS

The relative spectral output (350-750 nm) of the sun, soil and oat crop uncorrected for sun angle and for environmental and atmospheric conditions (Fig. 4) indicate the resolution of the system where the sun absorption lines (Fraunhofer) are clearly visible. Table II indicates the wavelength where the absorption lines occur and their bandwidth. The sun spectra show a greater number of lines than the soil or oats. The lines in the UV region of the soil spectra have greater intensity than the oat spectra. The prominent lines in the crop spectra are those of hydrogen (a, F, G). Also, some of the iron (L, N) and calcium (e, M, k) lines are distinct. There are also many lines shown on the crop spectral curves which are not known to relate to specific elements.

Fraunhofer line infilling techniques for luminescence and fluorescence studies of natural materials that discriminate among various materials have been reported (Watson et al. 1973; Hercules 1966; Hemphill 1968; Harrison and Kendall 1974) and the results obtained with crops and soil suggest that there is a potential for agricultural applications. The sodium line D_1 is a good example for the Fraunhofer line infilling technique. The intensity of the irradiance of the sky is measured by turning the mirror towards the sky. The ratio E of the energy at 589.6 nm (E_f) and the energy of the adjacent shoulder of the spectra (E_s) is:

$$\frac{E_f}{E_s} = E \qquad (2)$$

The ratio e of the reflected energy from the crop target at the sodium line (D_1) (e_f) and the adjacent shoulder of the reflection spectra of the target (e_s) is:

$$\frac{e_f}{e_s} = e \qquad (3)$$

and if e is greater than E, fluorescence and fluorescence infilling is indicated. Such a sun absorption infilling technique is under consideration for crop discrimination and disease detection.

Figure 5A shows the relative spectral output of three varieties of wheat from the infrared spectrometer. The spectra were corrected for sun angle and atmospheric and environmental conditions. The varieties were seeded on the same date (D_1) and their spectra taken on 31 Aug. 1976 in a 30-min period showing varietal differences between Neepawa, Macoun and Sinton. Sinton showed a greater reflectance throughout the 750- to 1,850-nm bandwidth than Macoun or Neepawa, and Macoun indicated greater absorbance at the 1,150- and 1,200-nm wavelengths than Sinton or Neepawa. Figure 5B shows spectra of legume and brassica crops (soybean, rapeseed and faba bean) seeded on the same date (D_2) taken 28 Sept. 1976. The highest reflectance was for soybean and the lowest for faba bean and this pattern held throughout the growing season.

TABLE I RANDOMIZATION ARRANGEMENT OF CROPS, INOCULATED VARIETIES AND DATES OF SEEDING

Replicate I			Replicate II		
Plot no.	Crop type	Seeding date†	Plot no.	Crop type	Seeding date†
1	Sod		43	Barley; Conquest	D_2
2	Wheat; Hercules	D_1	44	Barley; Herta	D_1
3	Wheat; Sinton	D_1	45	Soil	
4	Oats; Garry	D_1	46	Wheat; Marquis SR6	D_2
5	Barley; Fergus	D_1	47	Oats; Garry	D_2, diseased
6	Barley; Herta	D_1	48	Barley; Conquest	D_2, diseased
7	Soil		49	Sod	
8	Oats; Hudson	D_1	50	Soybean	D_2
9	Wheat; Neepawa	D_2	51	Barley; Conquest	D_1
10	Wheat; Napayo	D_1	52	Barley; Peguis	D_1
11	Rapeseed; Tower	D_1	53	Rapeseed; Tower	D_1
12	Oats; Garry	D_1, diseased	54	Wheat; Glenlea	D_2
13	Wheat, Marquis	D_1, diseased	55	Rapeseed; Torch	D_2
14	Faba bean; Diana	D_2	56	Wheat; Marquis	D_1, diseased
15	Barley; Centennial	D_1	57	Faba bean; Diana	D_2
16	Wheat; Glenlea	D_2	58	Barley; Herta	D_2
17	Wheat; Macoun	D_1	59	Wheat; Marquis SR6	D_1
18	Barley; Conquest	D_2	60	Wheat; Macoun	D_1
19	Wheat; Marquis	D_1	61	Wheat; Sinton	D_1
20	Oats; Garry	D_2, diseased	62	Oats; Garry	D_1
21	Sod		63	Oats; Terra	D_1
22	Wheat; Hercules	D_2	64	Wheat; Hercules	D_1
23	Rapeseed; Tower	D_2	65	Barley; Fergus	D_1
24	Barley; Peguis	D_1	66	Oats; Hudson	D_1
25	Faba bean; Herz Freya	D_2	67	Wheat; Neepawa	D_1
26	Wheat; Neepawa	D_1	68	Faba bean; Herz Freya	D_2
27	Wheat; Marquis SR6	D_2	69	Barley; Conquest	D_1, diseased
28	Barley; Conquest	D_2	70	Rapeseed; Tower	D_2
29	Rapeseed; Torch	D_2	71	Wheat; Napayo	D_1
30	Wheat, Glenlea	D_1	72	Wheat; Glenlea	D_1
31	Soybean	D_2	73	Oats; Harmon	D_1
32	Wheat; Marquis	D_2, diseased	74	Oats; Garry	D_2
33	Barley; Conquest	D_1, diseased	75	Barley; Bonanza	D_1
34	Faba bean; Diana	D_1	76	Wheat; Marquis	D_1
35	Oats; Terra	D_1	77	Wheat; Neepawa	D_2
36	Oats; Garry	D_2	78	Barley; Centennial	D_1
37	Barley; Herta	D_2	79	Soil	
38	Oats; Harmon	D_1	80	Wheat; Marquis	D_2, diseased
39	Wheat; Marquis SR6	D_1	81	Oats; Garry	D_1, diseased
40	Barley, Bonanza	D_1	82	Faba bean; Diana	D_1
41	Barley; Conquest	D_1	83	Wheat; Hercules	D_2
42	Soil		84	Sod	

†D_1 — 27 May 1976; D_2 — 23 June 1976.

Figure 6 shows the reflectance curve of oats (Garry) seeded at the same time (D_2) in four different plots, two of which (plots 20 and 47) were inoculated with crown rust (*Puccinia coronata* cda). This indicates that the reflectance of the diseased crops was greater than the non-diseased crop over the whole spectrum of 750-1,880 nm and had a greater absorption at 940-, 1,130- and 1,390-nm wavelengths. These data also demonstrate the reproducibility of spectra from the replicate plots (non-diseased 36, 74 and diseased plots 20, 47). Figure 7 indicates extremes of reflectance data from two control plots, lawn grass sod and bare soil. The lawn grass data are used to measure the effect of the sun angle on the spectral reflectance reading. The bare soil data are a useful additional reference for incoming radiant energy and for soil condition.

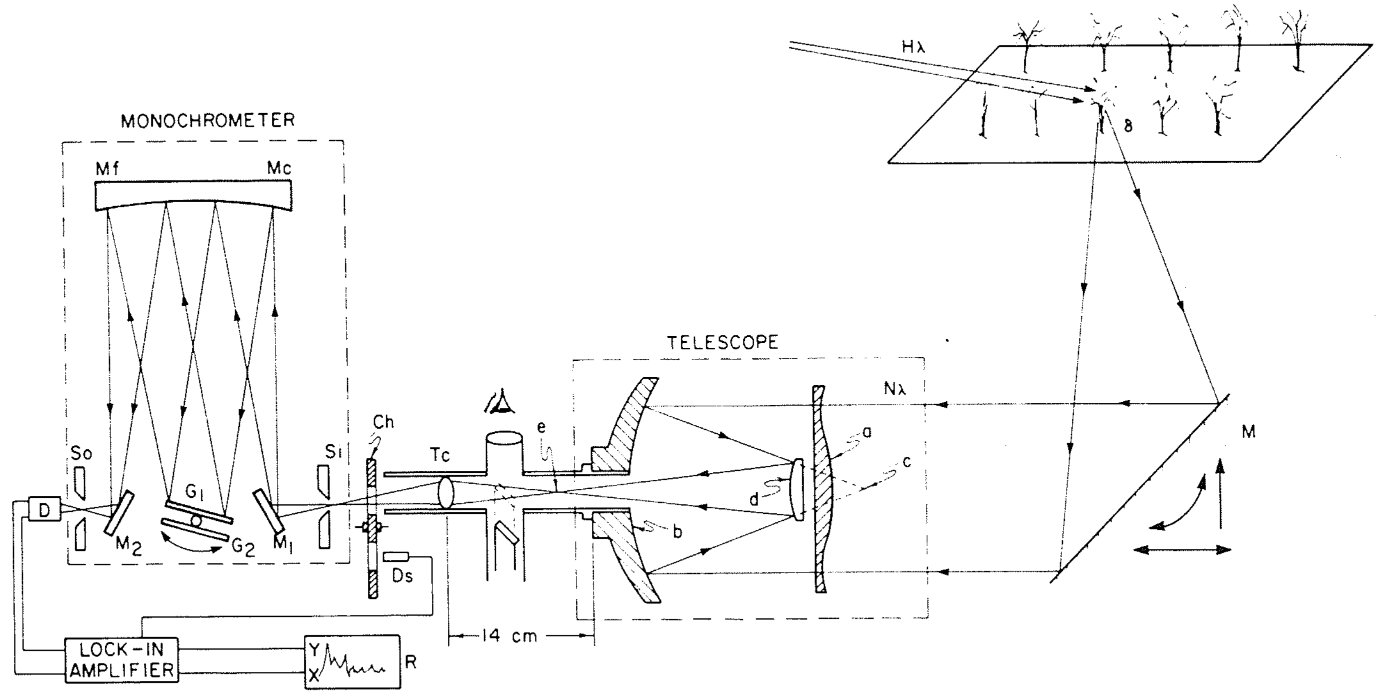

Figure 2. Schematic of the infrared spectral system.

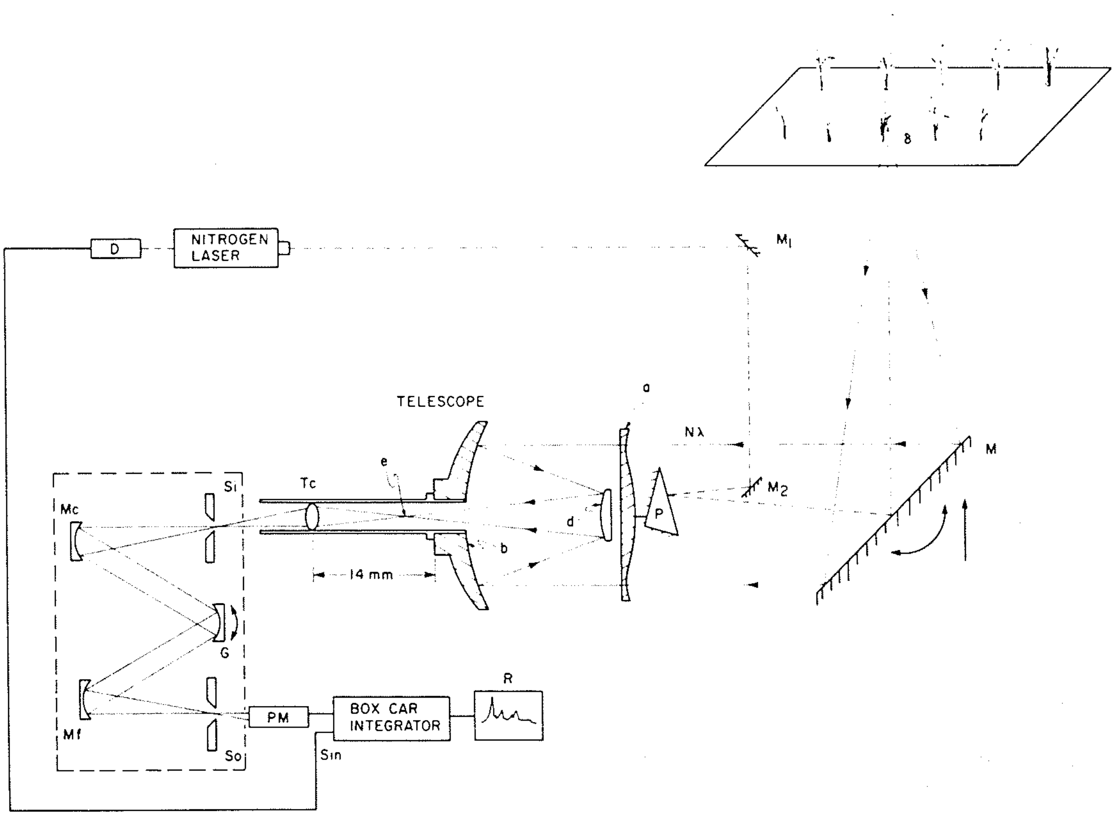

Figure 3. Schematic of the laser fluorometry system.

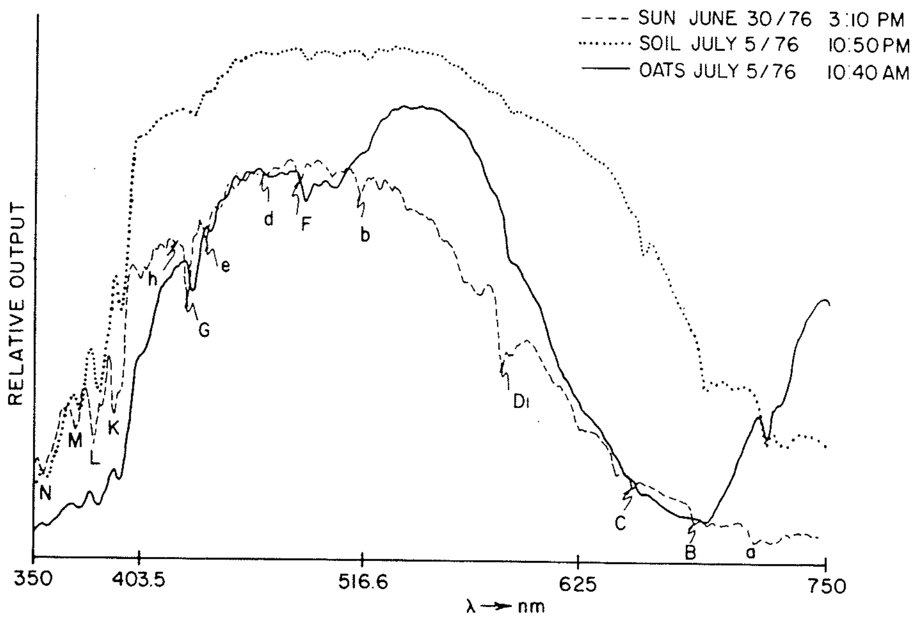

Figure 4. Spectral curves showing Fraunhofer lines of sun, soil and oats. The lines are identified by letters that are explained in Table II.

TABLE II SOME OF THE FRAUNHOFER LINES DETECTABLE WITH THE SPECTROPHOTOMETERS IN THE MOBILE LABORATORY SHOWN ON FIG. 4

Designation	(λ) Wavelength nm	Atom †	Source†	(λ HBW) nm Equivalent width
A	758.4	0_2	Oxygen in atmosphere	
a	719.7		Water vapor in atmosphere	
B	686.7	0_2	Oxygen in atmosphere	0.41
C, Hα	656.2808	H	Hydrogen Sun	0.41
D_1	589.5923	Na	Sodium Sun	0.057
D_2	588.9953	Na	Sodium Sun	0.077
E	527.0	Fe	Iron Sun	
E_2	526.9541	Ca	Calcium Sun	
b_1	518.3618	Mg	Magnesium Sun	0.16
b_2	517.2699	Mg	Magnesium Sun	0.13
b_3	516.8901	Fe	Iron Sun	
b_4	516.7491	Fe	Iron Sun	0.09
b_4	516.7343	Mg	Magnesium Sun	0.09
	500.0			
c	495.7	Fe	Iron Sun	
F, Hβ	486.1342	H	Hydrogen Sun	0.42
d	466.8140	Fe	Iron Sun	0.11
	447.0			
	441.6	Fe	Iron Sun	
e	438.3547	Fe	Iron Sun	
G, Hγ	434.0465	H	Hydrogen Sun	0.35
G	430.7906	Fe	Iron Sun	
G	430.7741	Ca	Calcium Sun	
g	422.6728	Ca	Calcium Sun	0.15
	417.7			
h, Hδ	410.1748	H	Hydrogen Sun	
	404.5	Fe		
H	396.8492	Ca	Calcium Sun	1.44
K	393.366	Ca	Calcium Sun	1.92
L	382.0436	Fe	Iron Sun	0.18
M	373.4874	Fe	Iron Sun	0.31
	361.0			
N	358.1209	Fe	Iron Sun	0.22

†Data taken from American Institute of Physics Handbook 1957, Mauro 1966; Rudaux and DeVaucouleurs 1959.

SUMMARY

Improvements were made on the instrumentation and methods of remote spectral measurement in crop variety and maturity identification and disease studies through the development of an infrared detection system, blue and red spectral references and a programmed measuring and recording operation. A phenomenon, the Fraunhofer (sun absorption) line infilling technique in field studies was introduced. The spectral data, along with the environmental data are stored on paper tape and processed by computer. The preliminary results indicate that the diseased crops may be discriminated from healthy ones at an early growth stage. Different crops as well as varieties within one crop can be identified; however, identification of varieties at an early growth stage is not yet established.

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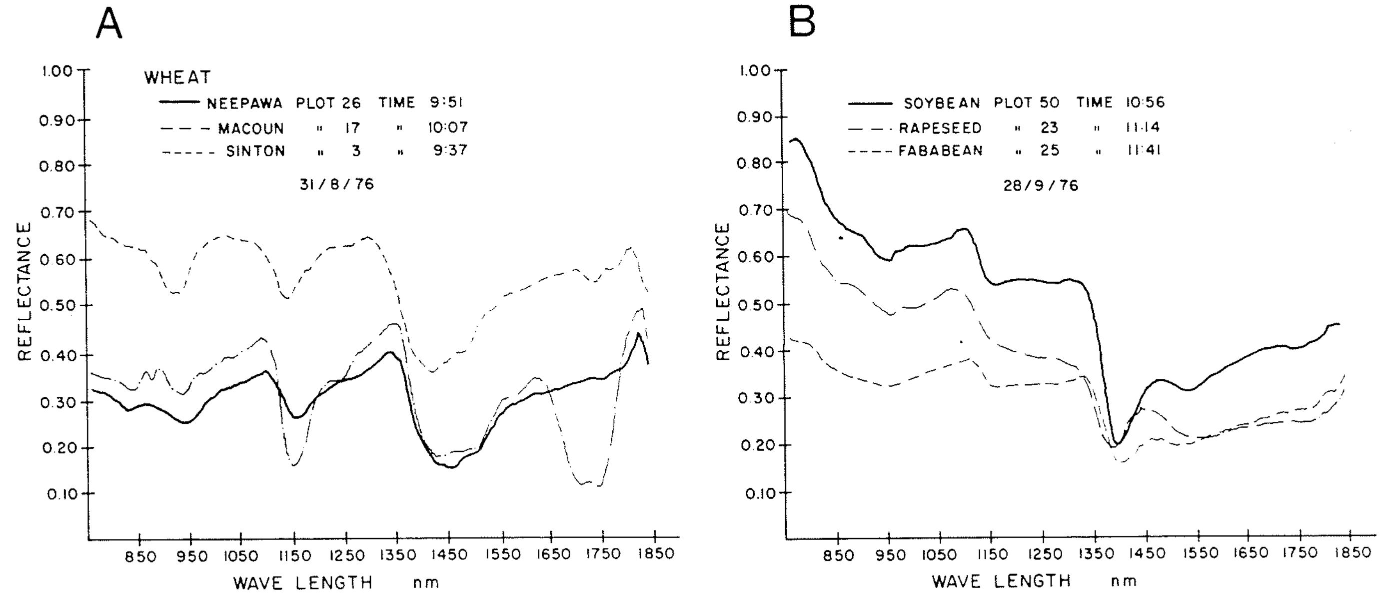

Figure 5. Spectral curves indicate variety identification. A. for Sinton, Mac nd Neepawa wheat varieties; B. for legume products: soybean, rapeseed and faba beans.

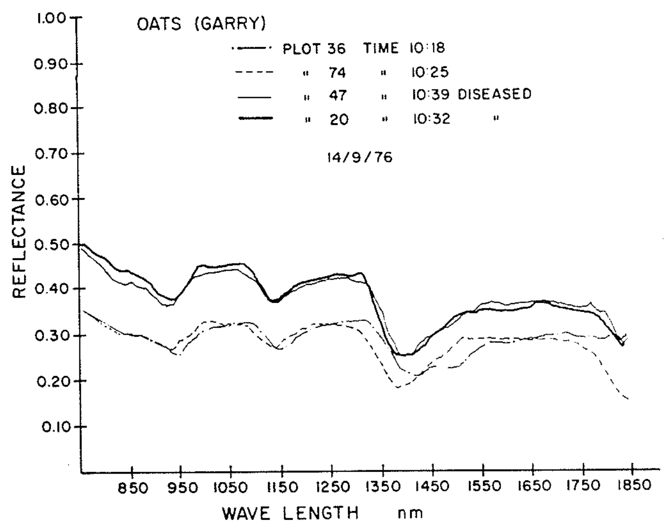

Figure 6. Spectral curves of healthy and diseased oat (Garry) crops in replicates.

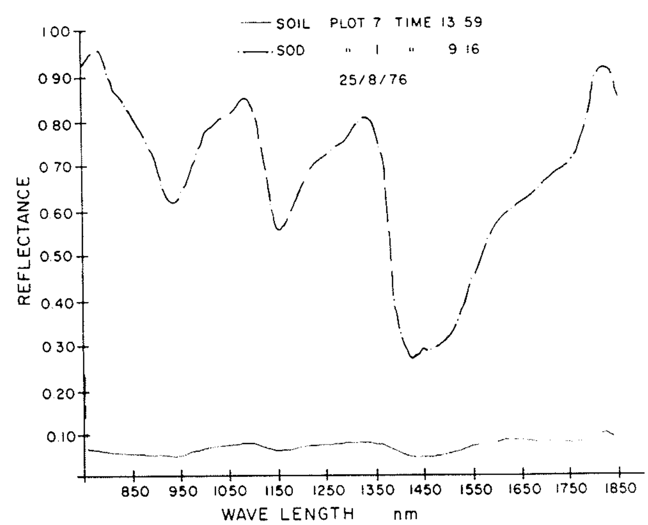

Figure 7. Spectral curves of bare soil and lawn grass sod.