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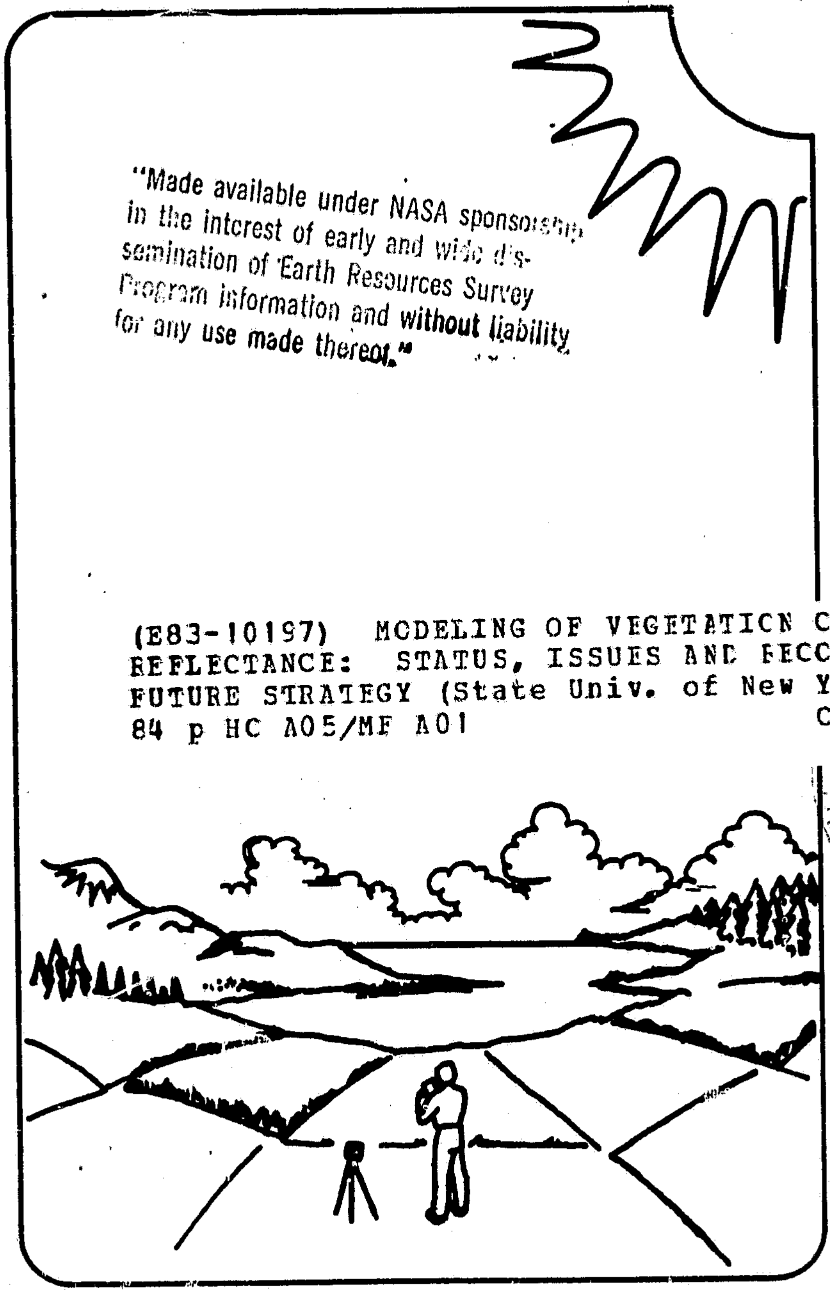

Modeling of Vegetation Canopy Reflectance

Status, issues, and recommended future strategy

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MODELING OF VEGETATION CANOPY REFLECTANCE:

STATUS, ISSUES AND RECOMMENDED FUTURE STRATEGY

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with
Technical contributions from
all the participants of the
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Reflectance' held on July 12-27
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PREFACE

The NASA Supporting Research (SR) Program, sponsored under AGRISTARS, has as its objective, the mapping of vegetative type, condition and stage of maturity, utilizing satellite remote sensing data. Over the years, a number of issues has been raised related to this objective. To address some of these issues a program of Fundamental Research in Scene Radiation and Atmospheric Effects Characterization (SRAEC) has been initiated. The objective of this program is to develop and test canopy reflectance models which quantify the relationship between canopy biophysical and radiative properties.

To meet the overall objective of the SR program, it appears that there may be a need for more applied effort. This effort is needed to utilize the existing biological and physical understanding of plant growth and canopy radiative properties, as well as the output from the Fundamental Research program to identify spectral features, analysis approaches and mathematical techniques for identifying vegetative type, condition and stage of development.

In the summer of 1982, NASA convened, for 12 days, a group of researchers in AGRISTARS, as well as other physicists, biologists, plant physiologists, agronomists, computer and system scientists, and mathematicians, at the Pingree Park campus of the Colorado State University. Remote sensing specialists represented by the participants included canopy reflectance modeling, field measurements, temporal profile modeling, crop condition modeling, atmospheric physics, and ecological modeling. The charter of the group was to clearly formulate the current research issues in the remote sensing of vegetation, to recommend possible approaches to addressing these issues, and to define key problems which must be overcome to achieve the recommended approaches.

This report describes the results of this intensive study, including the group's recommendations.

Another unpublished report*, consisting of the presentations made by various participants, provides more technical depth and basis of various issues discussed in this report.

* This report entitled "Minutes of the Workshop on Modeling of Crop Reflectance" is in the custody of NASA-Johnson Space Center, Supporting Research Project.

ABSTRACT

Various technical issues related to mapping of vegetative type, condition and stage of maturity, utilizing remotely sensed spectral data are reviewed, and, where possible, formulated more clearly. The existing knowledge base of models, especially of radiative properties of the vegetation canopy and atmosphere, is reviewed to establish the state of the art for addressing the problem of vegetation mapping. Activities to advance the state of the art are recommended. They include working on canopy reflectance and atmospheric scattering models, and field measurements of canopy reflectance as well as of canopy components.

Leaf area index (LAI) and solar radiation interception (SRI) have been identified as the two most important vegetation variables requiring further investigation. It is recommended that activities related to sensing them or understanding their relationships with measurable variables, should be encouraged and supported.

It is recommended that a Scene Analysis Group be formed to serve as a bridge between NASA Fundemental Research and Applied Research Program with its major objective as evaluation, utilization, and adoption and adaptation of relevant models.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

The application of remote sensing to agricultural monitoring holds the greatest promise if reflective measurements or their transforms can be directly related to crop agrophysical or environmental factors. Research in agriculture has identified numerous agrophysical factors that are important if one is to predict agricultural production. For example, crop growth models rely on the well established relationships between light interception and photosynthetic productivity for the prediction of dry matter accumulation and yield. SRI also is closely related to crop evapotranspiration, which is an essential component for assessing the potential for water stress. These same models require some knowledge of the stage of development to partition the photosynthetic production among various components (leaves, flowers, fruits, roots). Another, and perhaps, the single most important agrophysical factor in crop growth modeling is leaf area index (LAI). Prediction of dry matter production or water use, relies on LAI. The crop yield also depends on vegetative stresses on parameters like concentration of CO_2 and H_2O, temperature, light level, and factors like diseases, insects, etc.

Thus the key quantities for estimation of vegetative condition are:

- Leaf area index.
- Solar radiation interception.
- Evapotranspiration.
- Vegetative Stress.

When electromagentic radiation is incident on a vegetation (crop) canopy, it is scattered and reflected, and its direction and spectral composition are altered in a complex manner by the vegetation. Part of this altered spectrum radiation can be remotely sensed by a satellite borne sensor. One will expect that this alteration in the radiation will be dependent on the agrophysical and environmental factors mentioned above.

The AGRISTARS Supporting Research (SR) program, sponsored by NASA, has its objective, the mapping of vegetative type, condition and stage of maturity, utilizing satellite remotely sensed data. This effort investigates the use of visible, near infrared, middle infrared, thermal infrared and microwave spectral regions available on the Landsat MSS, TM and future satellite sensors.

The SR program has been investigating this problem since 1980 and has raised a number of significant technical issues* relevant to the best set of spectral features for identifying vegetation type, condition and stage. These issues can only be resolved by a more complete understanding of the relationships between agronomic, biophysical and geometric properties of the canopy and its observed radiative properties in the various wavelength bands.

The present report is the result of a study carried out by a group of researchers, over a 12 day period (see Preface). The purpose of this study was to:

- review technical issues, defined by the SR project, in vegetative mapping, and where possible, formulate these issues more clearly.
- review existing knowledge base of models, especially of radiative properties of the vegetation canopy and atmosphere, to establish the state of the art for addressing vegetation mapping.
- recommend activities for using existing knowledge data bases to address vegetation mapping issues. These activities should concentrate on canopy reflectance models, atmospheric scattering models, and field measurement on reflectance as well as on canopy components.

* NASA Report on 'Description of Research Issues - Scene Radiation and Atmospheric Effects Characterization', July, 1980.

. identify the relation of these activities to other NASA programs, particularly the Fundamental Research Program.

Sections 2 through 4 are devoted to the clear formulation of various technical issues, the review of the existing knowledge base, and for recommendations to fill the holes in the base. Section 5 is devoted to recommendations for technical activities as well as for the infra-structure for implementing these activities.

In Section 2, we describe the basic problem of the remote sensing of vegetation, including the description of the total system which includes radiation source, atmosphere, canopy, ground and satellite borne sensors. We define the remote sensing problem, - the direct problem, of calculating sensed reflectance given the parameters defining the system, and the feature identification problem - the inverse problem, of calculating agronomic variables from the reflectance data. We delineate various roles for modeling.

In Section 3, we discuss the various aspects of the direct problem, including a review of vegetation canopy reflectance models, the problem of verification and adoption of the existing canopy reflectance models and the transfer of models from the authors to the users, models of atmospheric scattering, and crop reflectance in mid-IR, microwave, and thermal infra-red regions. For each case, we provide a brief introduction, point out the key issues, and make recommendations for future activities.

Section 4, is devoted to the inverse problem - perhaps the more important one from the application point of view. We discuss the temporal profile modeling, the problem of inversion of canopy reflectance model, and the potential use of equivalent models which are invertible and have been used in other applications.

Section 5 contains our strategic recommendations - both of a technical nature, and for implementation. We recommend initial focus on understanding issues related to the estimation of the leaf area index and solar radiation interception, and the formation of a scene analysis group to serve as a bridge between the NASA Fundamental Research and the Applied Research Programs.

2. BASIC PROBLEM AND MODELING

The total system involved in remote sensing of reflectance from vegetation has three regions defined by three boundaries. (Fig. 1); atmosphere, vegetation canopy and

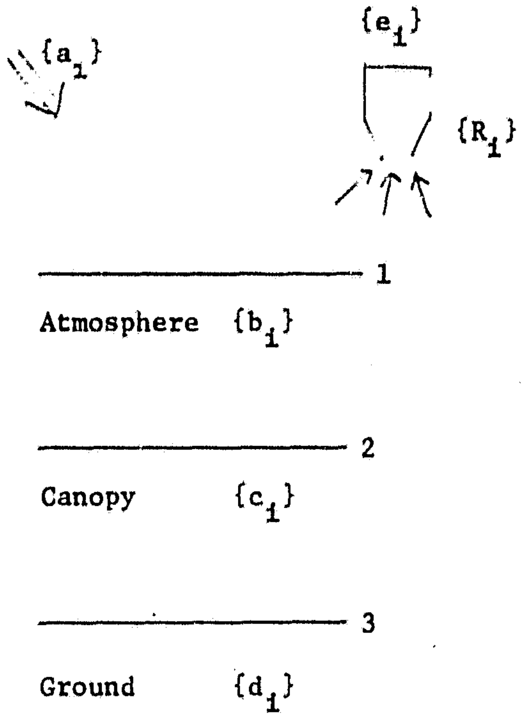

Fig. 1. Schematics of the total remote sensing system

ground or soil, each defined by a set of properties/parameters. They are denoted by {b_i}, {c_i}, and {d_i} respectively, for the three regions.

With the exception of remote sensing with microwaves, the solar radiation, defined by a set of properties {a_i}, is incident at the top of the atmosphere. This radiation passes through the three regions and the scattered/reflected radiation is detected by a detection system, in a satellite, characterized by the properties {e_i}. The set {R_i} of observables detected are dependent on wavelength λ, time t, and the spatial details introduced by the three regions.

In the microwave regime, the source of incident radiation is a microwave transmitter and the detector is also located near the transmitter (i.e. only back scattering is detected).

The <u>remote sensing problem</u> can be stated as

$$\{R_i\} = f(a_i, b_i, c_i, d_i, e_i) \tag{1}$$

where the function f invokes the radiative transfer processes which produce the set $\{R_i\}$ of attributes of the radiation received by the satellite. In other words, the problem is that given the system characteristics $\{a_i, b_i, c_i, d_i, e_i\}$ define or derive the function or algorithm which will give the set $\{R_i\}$ observed by the detector. This problem will be referred to as the <u>direct problem</u>.

The <u>feature identification problem</u> can be stated as

$$\{c_i\} = g\{R_i, a_i, b_i, d_i, e_i\} \tag{2}$$

where the function g represents a convolution of the radiative transfer processes and the remotely sensed properties $\{R_i\}$. In other words, the problem is that given the observed spectral response of the detector, and parameters characterizing the atmosphere and ground, define or derive a function g which will give the set $\{c_i\}$ of parameters which characterize the canopy. This problem will be referred to as the <u>inverse problem</u>.

Evidence collected during the last 5 years or so suggest that the chore of obtaining g can be made easier if one uses certain linear transforms of the observables $\{R_i\}$ i.e.

$$G_i(\lambda, \vec{r}, t) = \sum_j \alpha_{ij} R_j(\lambda, \vec{r}, t) \tag{3}$$

where α_{ij} are constants, mostly dependent on the characteristics of the detector. Two well known transforms are greenness and brightness introduced by Kauth and

Thomas (1978). Then

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$$\{c_i\} = \bar{g}\ \{G_i;\ a_i,\ b_i,\ d_i,\ e_i\} \tag{4}$$

represents a potentially more useful statement of the feature identification problem.

Theoretical and experimental studies of the last two decades or so have identified the following variables which will characterize the various components of the system, i.e. interaction of electromagnetic radiation with the system.

Solar	$\{a_i\}$	: Spectral intensity $I(\lambda)$, location of the sun $(\theta,\ \phi)$
Atmosphere	$\{b_i\}$	: Density of air and aerosol particles, relative humidity and temperature and their spatial and temporal dependence
Canopy	$\{c_i\}$	: Reflectance ρ, absorptance α, transmittance τ, and geometrical shape, and position of components; layer structure and planting structure; environmental parameters like temperature, R.H., wind speed, precipitation. λ, $(\theta,\ \phi)$, and t dependences of these parameters.
Ground	$\{d_i\}$	: ρ and α; surface roughness; slope; texture and bulk density profiles; water absorption profile; λ, (θ,ϕ) and t dependences of these parameters.
Detector	$\{e\}$:	Spectral sensitivity, position $\vec{r}$ vs t, view angles, calibration, normalization and transmittance details.

It should be noted that the parameters c_i, which are the ones one can hope to obtain from solving the inverse problem, may not be sufficient for crop identification and yield assessment. Instead one may need another set of more biophysical variables $\{x_i\}$. If this indeed is the case, one has an auxiliary direct problem to solve, namely, to define/derive a function h where

$$\{c_i\} = h\ \{x_i\} \tag{5}$$

Corresponding to this is the auxiliary inverse problem of finding the function ℓ, where

$$\{x_i\} = \ell \{c_i\} = h^{-1} \{c_i\} \qquad (6)$$

Some desirable biophysical variables $\{x_i\}$ are leaf area index (LAI), leaf angle distribution (LAD), solar radiance intercepted (SRI), dry biomass (DM) and degree of stress or health of the plant.

2;1 Roles for Modeling

Once the system has been described in terms of its various basic parameters, the purpose of modeling is to explicitly define the functions f, g, $\bar{g}$, h, and ℓ. Models for the direct problem describe the radiative interaction processes like absorption, reflection, transmission, emission, flourescence, etc. and derive equations or algorithms for calculating the function f and h, relating measured spectral properties to the parameters of the system. In models for the inverse problem, given some system description and observable $\{R_i\}$, one determines if the functions g, $\bar{g}$, and ℓ exist and are they unique, again via a set of equations or algorithms. As in other similiar situations, usually. a pre-requisite for solving the inverse problem is the understanding of the direct problem.

There are at least the following five general areas of application for canopy reflectance models.

(1) Explanation of phenomena observed empirically in remote sensing, e.g. the maximum greenness of soybeans is observed to be greater than the maximum greenness of corn, even though the maximum leaf area indices of the two crops are roughly equal.

(2) Sensitivity Studies, e.g. of greenness to atmospheric haze, crop row direction, etc.

(3) Prediction e.g. the combination of spectral bands which is best for observing solar radiation intercepted.

(4) Simulation e.g. of reflectance as a function of LAI, soil backgrounds etc. and testing of algorithms, e.g. for estimating LAI and their sensitivity to background effects.

(5) Biophysical Parameter Estimation by algorithms which use models in a forward predictive manner or in the inversion mode.

The last application, is of course, of more direct relevance to an applied program like Supporting Research.

In Section 3, we will discuss various aspects of the direct problem or remote sensing problem. We will give the status of various models, point out the relevant issues and recommend future activities. Section 4 will be devoted to the inverse or feature identification problem. Here, we only point out that the state of the art for modeling of the direct problem is much more advanced than that for the inverse problem. The inverse problem is more diff-difficult to solve, but obviously, has more practical relevance to an applied research program.

3. REMOTE SENSING OR DIRECT PROBLEM

In this section we will discuss various aspects of modeling the problem of remote sensing, i.e. of calculation of spectral response of a vegetation canopy given the parameters which characterize it.

In subsection 3.1 we summarize the state of the art of modeling of vegetation canopy reflectance in the visible and IR region and make recommendations for future emphasis. We recommend the continued development of three types of models, (1) a simplified, approximate, and comprehensible one, based on the Suits model, (2) a comprehensive, more exact and numerical one, and (3) another one in between, e.g. based on the Norman and Welles model. We also recommend combining a canopy reflectance model, preferably a simple one like the Suits model, with a vegetation growth model. The combined model will allow calculation of temporal profiles for crop reflectance.

Most of the models, with the exception of a few, which are simpler to comprehend, have been tested mostly by their authors using limited experimental data bases. In Subsection 3.2 we discuss the problem of verification and adaptation of the existing canopy reflectance models and transfer of models from the authors to the users. The verification involves use of a common data base, which has been identified, to be coordinated by a centralized Modeling Technology Transfer Group. This group will also be responsible for transfer and implementation of the models.

To use the information collected by satellite borne sensors, one has to account for atmospheric scattering. We recommend that the existing models are adequate and the emphasis should be on incorporating the atmospheric model with the vegetation canopy reflectance models. We propose a specific strategy for doing so.

The remaining subsections are devoted to the sensing of vegetation in other regions of electromagnetic spectrum. Subsection 3.4 is devoted to the mid-IR region (1.55 - 1.75 μm) a region insensitive to atmospheric water. However, it appears that in this region the leaf optical properties are sensitive to changes in leaf water content due to stress and vary more with the crop type than in other regions. Therefore, observations in the mid-IR region may significantly improve discrimination between crops through the growing season. The recommended activities are to use existing crop reflectance models and atmospheric scattering models for predicting the reflectance in the mid-IR region and to better analyze the existing data. These activities can then provide an improved basis for deciding how much should one emphasize the mid-IR region.

In subsection 3.5 the microwave sensing of vegetation is discussed. In this wavelength band, the data collection is, in general, not hampered by the weather. Further, the wavelength is comparable to the size of the vegetative scatterer. This band has the potential for measuring soil mositure and plant moisture (in addition to LAI) and also for discriminating small grains (using measurements with different planes of polarization of the incident radiations). The major recommendation is to develop a physical vegetation scattering model which takes into account the effects of soil, stalks and leaves.

Finally, in subsection 3.6 we discuss the modeling of reflectance in the thermal infrared band (3 - 20 μm). This reflectance has the potentials of allowing the estimation of vegetation and soil surface temperatures, which can be used to infer the water status of the vegetation and soil. These in turn, can be used in optimal scheduling of water irrigation and also crop yield calculations. We recommend that the existing model, which mostly has been applied to tree canopies, should be tested for crops before developing alternate models.

3.1 Vegetation Canopy Reflectance Models

Introduction:

Over the last fifteen years or so, several canopy reflectance models have been developed (See Goel, 1982b; Smith, 1982; Smith and Ranson, 1979, for reviews of various models). These models represent either an approximate or a numerical attempt to solve a radiative transfer equation, which is a macroscopic manifestation of the interaction of radiant energy with matter, for complicated and heterogenous canopies. The basic radiative transfer equation is

$$\frac{d I(\tau, \hat{s})}{d\tau} = -I(\tau, \hat{s}) + \frac{1}{4\pi} \int p(\hat{s}, \hat{s}') I(\tau, \hat{s}') d\hat{s}' + \varepsilon(\vec{r}, \hat{s}) / \sigma \rho \qquad (1)$$

Here I is the specific intensity (also called radiance or brightness, is the average power flux density within a unit frequency band centered at frequency ν within a unit solid angle), which is in general a function of position and direction $\hat{s}$ in a three dimensional space. ρ is the number of particles per unit volume with which the incident radiation interacts and σ is the total of scattering and absorption cross sections of particles (i.e. each particle absorbs/scatters the power σ I). τ is the optical distance defined by

$$\tau = \int \rho ds \qquad (2)$$

$p(\hat{s}, \hat{s}')$ is the so called phase function which is the probability that radiance $\hat{s}'$, will be scattered into a solid angle, about $\hat{s}$. ε is the the emission from within a vegetation canopy.

Eq. (1) is the basic integro-differential equation which needs to be solved for I for a vegetation canopy which can then be used to determine spectral response of the vegetation canopy. The solution of this equation involves two major steps:

(1) Calculation or specification of the phase function in terms of the properties of the scattering medium - the vegetation canopy. This is a rather difficult task for any scattering medium (e.g. atmosphere, earth and ocean surfaces) and is even more difficult for the canopy because vegetation is extremely heterogenous and complex and the canopy cannot be treated either as a regular or completely random medium.

(2) Solution of the radiative transfer equation for a given phase function and boundary condition. For vegetation, the upper surface of the canopy is exposed both to the direct specular radiation and the diffuse flux of the scattered radiation from the sky leading to a somewhat difficult boundary condition. For solving the integro-differential equation, one of the procedures is to substitute an initial guess for I in the right hand side of Eq. (1), integrate the equation, subject to the boundary conditions on I, to get a new I, which is then used in the right hand side of Eq. (1) to get a new solution. This iterative procedure is continued until the value of I does not change (within a desired accuracy). For a vegetation canopy, the optical thickness is substantially higher (8-10) than that for the atmosphere (0.2 - 0.6), leading to a slower convergence of the iterative procedure.

Various models of crop reflectance represent a solution of the simpler problem obtained by imposing abstractions on the shape or boundary of the canopy and on the form of the phase function. One of the simplifications made in the majority of models is to approximate the canopy with a parallel-plane infinitely extended medium. That is, one in which the medium can be split up into distinct layers (one or more) in which the optical and structural properties are constant. In this case, the specific intensity is only a function of one dimension z perpendicular to the layer and angles θ and ϕ defining the direction of the incident beam. Even for this simple geometry, no closed form solution has been found for a general arbitrary phase function and one has to resort to computer based numerical solutions. Various canopy reflectance models either make some further approximations or find numerical solutions.

The modeling of the temporal dependence of the reflectance of a growing crop canopy can be done using one of two basic approaches.

The first approach requires measurements at time intervals over a vegetative season, use these measurements to calculate the parameters of a reflectance model,and then use the model to calculate the reflectance for each of these time intervals. The advantage of this approach is that it is conceptually simple and straight forward to implement from the model point of view. However, it requires laborious time consuming measurements, may not be valid for crop plots other than those for which the data were taken and can not be easily extrapolated to differing crop growth conditions.

In the second approach, one couples a reflectance model with a crop growth model such as the Ritchie model for wheat and the Arkin model for corn. Such an approach, if successful could allow calculation of temporal profiles of vegetation in differing conditions.

To date only the first approach has been attempted and even that on a rather limited basis.

Status of Modeling, Issues and Recommendations

There are about a dozen models of crop reflectance (see Goel, 1982b). Most of these models, with the exception of a few like those based on the Kubelka-Munk theory, and the Suits model, have been tested against only very limited experimental data, and even that mostly by the author's themselves. Their general agreement with the experiments suggest that the radiative transfer theory is applicable to crop canopy reflectance. Thus, it should continue to play its pivotal role in crop canopy reflectance modeling.

To objectively assess the limitations and capabilities of various models and thus to assess the status of crop reflectance modeling, it is necessary that they all be tested against the same data base. The details of this recommended testing are given in the next subsection.

Even without this testing, it appears that none of the models will work for all crops and for all conditions. Therefore, parallel to testing, the development of crop reflectance models should continue. Here, though in principle, it is desirable to develop as many models as possible, in practice one may have to choose only a few. The best strategy, therefore, is to concentrate efforts on two or three types of models.

One model should be simple, analytical (or at least semi-analytical), easily comprehensible and able to be used with limited computing power and time, to calculate reflectance from known canopy properties for a fairly large set of crops and canopy geometries. A model adapted from the Suits model seems to be a good candidate. This modified model should allow inclusion of unequal optical properties of a vegetation element on its two sides, various leaf angle distribution functions, and row effects. These inclusions have already been done separately, but not in one encompassing and tested model.

Another model should be a comprehensive one, and be capable of incorporating detailed properties of the canopy, without making any significant approximations in the process. This model should be characterized not by its simplicity and comprehensibility, but by its accuracy in calculating the crop reflectance from canopy parameters. Such a model will, of necessity, require numerical solution of the radiative transfer equation, and hence may not be very kind to computer storage and time requirements. The more difficult part of the development effort of this model will be the characterization of the scattering phase function in terms of canopy variables, not the procedure to iterative numerical solution of the radiative transfer equation. The latter technology has been fairly well developed in many other applications of the radiative transfer equation.

The third model, may be somewhere in between the two models with respect to comprehensibility and rigor. The model currently being developed by J. Norman and his associates at the University of Nebraska seems to be a promising candidate.

Since the simpler model is an adaptation of several existing models, it could become available in a comparatively short time (1-2 years). The comprehensive model involves some original development and may require a longer term effort. Therefore, the second and third types of models should be developed under the aegis of the Fundamental Research Program, in collaboration and cooperation with the Applied Research Program.

As mentioned earlier, all the canopy reflectance models proposed to date have a major deficiency. They do not include time as an implicit variable. That is, if one wants to calculate crop reflectance at different times (stages of development), one has to input into the model the canopy variables for each time value. Getting information for this input is rather time consuming. Therefore, it is recommended that a reasonable level of effort be made to combine a canopy reflectance model (preferably a simple one like the Suits model), with a vegetation growth model. Such a model, will then provide a natural link to the temporal profile models which have been used for automatic crop classification and crop emergence date and growth stage determinations (see subsection 4.1).

3.2 Verification and Adaptation of the Existing Canopy Reflectance Models and Transfer of Models from the Authors to the Users.

Introduction:

As noted in subsection 3.1, various reflectance models represent either an approximate or a numerical attempt to solve radiative transfer equation (which is a macroscopic manifestation of the interaction of radiant energy with matter) for complicated and heterogeneous canopies. With the exception of a few more comprehensible models (e.g. Suits model for homogeneous canopies), most of the other models are accessible to only a few users. There are a few models which are not available to any of the users. In fact, these more complex and numerical models (which are intended for modeling more realistically the canopy reflection for a larger variety of vegetation and canopy geometrics) and their intricacies are hard to grasp even by those who have developed competitive models.

To maximize the effectiveness of the development effort for various models, it will be desirable to facilitate the maximum use of the models by the users. These users include experimentalists as well as other modelers. The latter category includes those who will use a canopy reflectance model as a submodel in a more complex higher level model (e.g. one which includes a model of the atmosphere, see subsection 3.3), and for estimating the agronomic variables from the reflectance measurements (inverse problem, see subsection 4.2).

The transfer from the authors of the model to the user involves a few issues discussed below.

Issues and Problems:

There are issues and problems from both the user's and author's viewpoints. From the user's point of view some of the problems, encountered in applying the models are:

. There are a large number of models available for use, but there is very little information concerning their range of validity and which model is most appropriate for a given application.

. For some of the models, it is not always clear what inputs are required for the model or what outputs can be expected from the model.

. In implementing a model there is the time-consuming and error-prone task of adapting software from one machine to another and in verifying that the implementation of the model is as intended by the author.

. The above problems are compounded due to usual continual improvement and updating of models by the authors as well as by other investigators.

From a model author's point of view, some of the problems encountered are:

. Because of a lack of understanding on the part of the user, models are sometimes used in an inappropriate manner.

. Documentation of a model to the point where the user has the information he needs for implementing it can be very time consuming and unproductive for the model developer.

. Providing assistance and consultation to users of the models can be very time consuming.

The above issues and problems need to be overcome before one can exploit fully the potentials of crop reflectance models.

Strategic Recommendation:

A recommended solution is the creation of a small Modeling Technology Transfer Group (MTTG) to act as an interface between the model developers and the model users. Some of the functions of this group will be:

- Coordination of the comparative testing and verification of various models using a standard data test (a benchmark test). (More details of this testing and verification procedure are given later in this subsection).
- Central receiving facility for accepting the model from its author, in whatever form an author feels appropriate (software, algorithms, procedures, etc.), along with results from the above verification tests.
- Implementation of the models in a standard format so that they will be available to potential users.
- Verification of the model implementation using test results supplied by the author.
- Documentation of the models in terms of input requirements, output products, algorithms used, and the range of applicability for the models.
- Evaluation and comparison studies on the models available as more data becomes available.
- Consultation and assistance to model users in selecting models for particular applications and in the proper use of the models.
- Providing feedback to the model developers concerning the applications of the models (provided by the users) and any problems encountered in their use.

The initial and major effort required is for comparative testing and verification of and for acquiring various models.

Specific Recommendation for Verification and Acquisition of Various Models

. A single data test, including nadir and bidirectional measurements with the necessary inputs of incident direct and diffuse radiations and soil and canopy properties be sent to the authors of various models for verification of their models.

. In return, the authors should present the results of verifications and enough pertinent information to characterize the properties and performance of their models. They should also be urged to supply their models in whatever form they feel appropriate to the Modeling Technology Transfer Group.

Models developed by the following authors have been identified as potential candidates for the testing. These are in various stages of development, varying from the embryonic to nearly completed.

. N.J.J. Bunnik and W. Verhoef, National Aerospace Lab., Amsterdam, Netherlands (B).

. K. Cooper et al. Colorado State University (A).

. D. Deering and J. Park, NASA Goddard Space Flight Center (C).

. D.D. Egbert, University of Kansas.

. S.A.W. Gerstl, Los Alamos National Laboratory (A).

. R. Jackson et al, USDA Phoenix.

. D.S. Kimes, NASA Goddard Space Flight Center (A).

. J.M. Norman and J.M. Welles, University of Nebraska (A).

. A.J. Richardson et al, USDA, Weslaco.

. J. Ross and T.A. Nilson, Estonian Academy of Sciences.

. J. Smith and R.E. Oliver, Colorado State University (A).

. G. Strahler and X. Li, Hunter College.

. G. Suits, ERIM, Ann Arbor (B).

. J.A. Weitman and P.J. Guetter, University of Wisconsin (C).

(The letter A denotes that the model is applicable for bidirectional and nadir reflectance, B denotes its applicability for directional and nadir reflectance, and C denotes only for nadir reflectance).

Each author, in addition to reporting the results of testing should be asked to provide useful information about the performance of each model, including:

. benchmark of the run time and computer storage requirements (for the author's specific computer).

. assumptions made in running the test data base.

. relative validity of the model as a function of input parameters, especially wavelength, type of vegetation, and development stage of the crop.

. sensitivity to the errors in the input parameters.

. any comments concerning the mutual appropriateness of the model with the test data set.

. need for additional data for better validation of the model.

Though various models use different input and output parameters, it appears that the data base with the following input and output parameters should for the most part be adequate for testing most of the existing models. The input parameters are:

. wavelength dependence of the reflectance (ρ_λ) and transmittance (τ_λ) of the vegetation components (leaves, stalks, etc.).

. wavelength dependence of the soil reflectance (ρ_s).

. leaf angle distribution.

. leaf area by layer; leaf area index.

. thickness of each layer - canopy profile.

. row spacings and directions.

. type of crop and its development stage.

. solar angles θ, ϕ .

. view angle θ , ϕ .

. atmospheric parameters specifying a limited but pronounced range of atmospheric conditions; incident direct and diffuse flux.

The output parameter is the (narrow band) wavelength dependence of the canopy reflectance. It will be very desirable if a description of the measurement technique, including the sensors used, and the errors bars in the data are included.

It should be added that the following information if available, could be used to get soil surface water content, relevant to some models.

. surface roughness, texture profile, bulk density profile, temperature, initial soil water content profile and reflectance vs. water content all of soil.

. air temperature and humidity, wind speed, precipitation level.

Potential data sets for comparative testing of various models have been acquired by LARS at Purdue University for soybean canopies during the 1980 growing season. These data include:

. "turntable" experiments which include canopy reflectance as a function of solar angles θ and ϕ, and nadir viewing made at 3 development stages with 3 backgrounds (black, white and soil). Supporting data include canopy profile, LAI, and vertical photographs of canopy made with each reflection measurement.

. "sunangle - view angle" experiments which include canopy reflectance measured as a function of solar angles θ and ϕ and view angles θ and ϕ made at three development stages. Supporting data include canopy profile, LAI, leaf angle distribution, soil reflectance, vertical photographs, and leaf reflectance and transmittance.

It is recommended that any gaps in the data be eliminated by using additional sources of information (e.g. for leaf and soil spectral properties from Gausman or Breece and Holmes and LARS Soil Reflectance Atlas).

We conclude this subsection by making a few additional comments.

. The data set used for comparative testing and the results of such testing will become a benchmark by which new vegetation reflectance models can be tested.

. As data sets becomes available for other crops, the models should be tested further for other vegetations. Such data sets include the one similiar to soybean or corn, being collected in 1982 growing season at LARS/Purdue and on winter wheat and corn or soybean being planned for collection of of Spring-Summer, 1983. Other data sets should include ones on small grains (to assist the crop discrimination for mixed pixels), and any other fairly complete set.

3.3 Modeling of Atmospheric Scattering

Introduction:

Atmospheric scattering of electromagnetic radiation is manifest by diffuse irradiance, modified optical depth, and sky color or optical phenomena. The air molecules are primary contributors to the diffuse irradiance, sunrise/set colors, polarization of the diffuse irradiance, and enhancement of the direct solar irradiance. Water vapor modifies the optical depth in a few absorption bands in the solar spectrum. Aerosols contribute to all these effects, and have variable density in space and time. These modifications in optical depth form severe restrictions on the validity of comparisons of vegetative reflectance between areas or between times of observation for satellite data.

At the canopy level the incident radiation from above consists of direct solar radiation and scattered radiation (diffuse). The latter consists of radiation scattered in the atmosphere and radiation from the canopy backscattered by the atmosphere. The exitance at the canopy consists of radiation reflected from the top of the canopy and radiation which has been reflected or scattered inside the canopy and is directed upward. Except for the thermal regime, there are no radiation sources in the canopy.

In the context of relation between the vegetation canopy properties and the spectral reflectance measurement by satellite borne sensors, atmospheric models should generate parameters which can be used in the canopy models to couple their outputs to the stimulated atmospheres. Parameters needed are atmospheric transmittence from nadir, path radiance and the direct and diffuse components of solar flux incident on the earth's surface as a function of wavelengths and solar zenith angle. The wavelength interval should at least be in 50 nm increments from 400 to 2500 nm. The solar zenith and surface element view angles should be in 10^0 increments from 0^0 (zenith) to 80^0.

In the thermal band pass region, from 3,000 nm to 14,000 nm, the atmospheric transmittance and path radiance as functions of wavelength, solar zenith angle and surface element view angle are needed. The increments in wavelength and angle should be as for the optical region.

Issues:

The atmospheric scattering depends upon the density of air and aerosol, water vapor concentration and temperature, and their spatial and temporal distributions. These parameters change significantly and, in any case, are hard to measure. Therefore, it is reasonable to limit the goal of atmospheric scattering model to a few - say 9, model atmospheres that range from "clear" to "murky". Aerosol distributions can be limited to continental spring, continental summer and maritime summer. For each of these distributions, three concentrations, ranging from low to high optical thickness are needed (a fixed seasonal average water vapor amount is sufficient for each distribution). For the thermal regime, the 9 atmospheric cases should assume average (constant) aerosol amounts while varying the water amount (e.g. 1 gm, 3gm, and 5gm) for each of the three atmospheric types.

Recommendations:

It appears that Dave (1980) model meets all the criteria needed for parameter generation. Therefore, development of new models is not a high recommended priority in the context of mission oriented research. Instead, the emphasis should be on incorporating this atmospheric model with the vegetation canopy reflectance models. This incorporation can be done by:

(1) Coupling an atmospheric model with a canopy reflectance model. The solution of the coupled problem deals fully with interaction between the atmosphere and the canopy by simply using the same method to treat scattering in the atmosphere as in the vegetation canopy.

(2) Treating atmospheric scattering and canopy reflectance models as uncoupled. Here the secondary interactions between the various components of the total remote sensing system (canopy, atmosphere, sunlight) are essentially ignored and the approach is therefore considerably simpler. The atmosphere and the canopy are treated as seperate entities which are related only in that flux from the canopy passes through the atmosphere. The scattering of flux back from the atmosphere to the canopy is treated only in a simplistic way without considering detailed interactions. Likewise, the atmosphere contributes to the canopy only in that it scatters incident sunlight to provide diffuse radiance on the canopy.

Coupling of Atmospheric model with Canopy Model

A twofold approach should be followed in combining atmospheric models with canopy models as follows:

(1) Multi-layer atmospheric models should be altered to allow lower layers to represent vegetation canopy properties. It is necessary to parametrize these properties (leaf orientation, reflectance, transmittance, LAI, etc.) in terms of effective coefficients or other atmospheric model parameters. The lower boundary conditions may be specified from soil properties (e.g. reflectance). Most multi-layer atmospheric models are rather sophisticated and expressing canopy properties in terms of model parameters may be quite tricky. Sigfried Gerstl's 31 level model, requiring numerical solution of radiative transfer equation which is being developed under the Fundamental Research Program, offers great promise in this area.

(2) Incorporating a simplistic treatment of the atmosphere as an extension to current multi-level canopy models by coupling a two or three layer atmospheric

model at the top should be a relatively easy task. One approach would describe atmospheric parameters in terms of model inputs (e.g. scattering cross section is expressed in terms of effective LAI and leaf geometry). Another approach simply couples existing models so that the lower atmospheric boundary conditions match the canopy models upper boundary conditions. Since either approach leads to a combined model whose upper boundary condition is specified by the solar energy curve, a simplification in model parameter specification is achieved over the current canopy modeling situation (i.e. it is unnecessary to specify diffuse and direct irradiance components). Initial candidate for a coupled model is Suits canopy model in conjunction with the Dave atmospheric parameterization.

Uncoupled Analysis

The following recommendations are intended to promote an understanding of the effect of the atmosphere on the spectro radiometric properties of the ground as observed from space and to quantify these effects in terms of impact on discriminability and condition assessment.

(1) The range of atmospheric conditions of interest in remote sensing applications in terms of aerosol and H_2O vapor distributions should be established. The data sets assembled for testing sensitivity of reflective and thermal models (9 atmospheres set for each of these regimes) provide a useful first cut.

(2) The impact of variations (spatial and temporal) in aerosol and water, on transported spectra of key crops (corn, soybean, wheat and barley), at representative growth stages should be determined. Existing measurements should be surveyed with the objective of determining relative aerosol variations. Atmospheric measurements should be incorporated into existing field measurement programs. Measurement of direct beam and downward diffuse component are needed. Irradiance may be measured with instruments such as Volty sun photometers and Epply pyranometers. Even measurements as subjective as estimated visibility are useful.

Once a basis for the scale of atmospheric variation is established, system sensitivity studies, in terms of NE$\Delta\rho$ (noise equivalent change in reflectance) at the observing platform, should be conducted through atmospheric simulation. Results should be analyzed in terms of impact on classification accuracy. The tradeoffs of atmospheric sensitivity against vegetation response as a function of spectral region should be determined. Spectral transforms which minimize atmospheric effect should be determined.

(3) There is a need to investigate effects of varying look angles in anticipation of future sensor systems. A group with expertise in optical properties of atmosphere and canopy, and a familiarity with proposed sensor systems should be asked to look into this matter further.

(4) Simulation techniques and assertions regarding impact of atmospheric effects may be validated through simultaneously acquired satellite, aircraft and surface measurements. Some of the data collected over AGRISTARS Intensive Study Sites may be used in constructing the needed data sets.

3.4 Crop Reflectance in Mid-Infrared Region

Introduction

Studies of leaf properties show that the reflectance and transmittance of corn leaves are lower than those of soybean in the mid-IR atmospheric windows (1.55 - 1.75μm and 2.08 - 2.35μm). In the near-infrared spectral region, they are essentially identical. The difference in the behavior in these two spectral regions has been attributed to the impact of corn C_4 monocot structure as compared to soybean C_3 dicot structure on leaf water content relative to structure reflectance property. Also, it appears that the variations in leaf water content due to stress will also alter mid-IR optical properties. These observations suggest that mid-IR observations of vegetation reflectance should provide additional information about vegetation type and condition when compared with visible and near-IR measurements. This coupled with the insensitivity of this region to atmospheric water, makes it attractive to investigate.

Initial studies by Ungar and Goward (1982) show that mid-IR observations significantly improve discrimination between soybean and corn through the growing season, when this can not be done uniquely with any other single band.

Issues

There are two major issues which need to be resolved: (1) Does the additional information provided by mid-IR lead to discrimination or condition assessment capabilities not obtainable through information contained in the combination of the other bands?, and (2) Why does mid-IR sometimes track near-IR response and at other times red band response?

To address these two issues and to further quantify the uniqueness of mid-IR region for crop identification and assessment, we recommend the following activities:

Recommendations

The recommended activities are on modeling as well as on statistical analysis of the data (used in initial studies). For modeling, they are

- Determine mid-IR soil background response.
- Run Webster County soybean/corn data through Suits model and compare with the observations, pending availability of more agronomically complete data set.
- Apply atmospheric corruption base on Dave data (See Section 3.3).
- Simulate thematic mapper response.
- Carry out multi-variate temporal separability analysis with and without mid-IR.
- Investigate spectral transforms (like greenness and brightness), using mid-IR, which are insensitive to soil and atmosphere variation, but sensitive to canopy parameters (e.g. LAI, SRI).

For data analysis, the recommendations are:

- Perform multi-dimensional corn/soybean separability analysis (e.g. Kalman distance) with and without mid-IR for each acquisition in the 1979 and 1980 Webster County FSS data sets.
- Extend the above analysis to multi-temporal data using assorted combinations of acquisitions (e.g. use all possible pairs of acquisitions from early through mid-season).
- Insert effects of atmosphere into the above analysis
- Analyze Cass County small grains data in a similiar manner.
- Investigate mid-IR response for a variety of soil types, wetness and debris to better quantify the fundamental advantages of mid-IR observations over those in other bands.
- Examine between and within-field variances.

3.5 Microwave Sensing of Vegetation

Introduction:

In the microwave region, it has been observed (Ulaby, 1975) that under an appropriate choice of sensing parameters (polarization, frequency, incidence angle), the measured scattering coefficient, σ^0, has a strong correlation to surface soil moisture, plant moisture, and the leaf area index (for some crops). These observations have not yet been verified and/or explained by a scattering model based on known physical principles. Such a model when developed could also provide additional information on experiment design or better choice of the sensing parameters. This is because (1) gaps in the data can be filled using such a model, (2) self-consistent variation of σ^0 versus any given model parameter can be generated, and (3) sensitivity studies can be carried out to identify canopy attributes.

A limited number of studies on crop classification (e.g. Shanmugam et al, 1981 and the references therein) using the microwave data have also been reported. These studies, while showing promise, are far from complete. The best choice of sensing parameters and their combinations has not been completely determined. Crop classification is relatively simple when the temporal profile of a crop is available over most of the growth period. A key question is whether crop classification can be performed at a reasonably early stage of the growth period. Here it should be added that the microwave frequency band is particularly suited for acquiring time profiles since the data collection is, in general, not hampered by weather.

There are three important issues related to microwave sensing of the vegetation in the context of modeling.

Issues:

(1) What are the appropriate (and why?) sensing parameters (polarization, frequency, incidence angle) for estimation of surface soil moisture, plant

moisture and LAI?

(2) What is the appropriate choice of sensing parameters for crop discrimination and identification using the scattering coefficient measurements?

(3) Can one estimate the growth status and/or stages of a given crop?

Recommendations:

To address the above issues, the following activities are recommended.

To determine appropriate sensing parameters, one should develop and use a physical vegetation scattering model which must take into account the effects of soil, stalks and leaves. More specifically it should consist of two parts. One part should model the interaction of the electro-magnetic radiation in terms of the permittivities and the geometric properties of soil and vegetation. The other part relates the permittivities and the geometric properties to time, temperature, moisture, leaf distribution and other relevant measurable parameters. As with any other model, this model needs to be validated and its useful range of validity needs to be established using a set of σ^0 measurements for different crops (covering different frequencies, incidence angles, polarization and time periods), with adequate ground truth (sufficient information to estimate the permittivities and the geometric parameters in the scattering model). Through sensitivity and/or parameter studies, the validated model could be used to establish the optimum choice of the sensing parameters and the significance of the choice.

To address the second issue, standard classification techniques may be used to explore for the best combination of the sensing parameters - frequency, like cross polarizations, incident angle, and time.

To further enhance the discrimination and identification capability, it is desirable to search for special crop attributes and incorporate them in the classification scheme. For example, the LAI of wheat can increase to its maximum value (around 5) and drop back within 45 days; while the LAI of corn takes about the same time period to increase to its maximum value (about 4.5). Thus the difference in the rates of change of LAI can possibly be used for discrimination. In short, the time profiles of different crops should be examined to improve existing classification capability.

It is conceivable that the growth status of a crop can be estimated from the time profiles of its scattering coefficient, its moisture content, LAI, and the surface soil moisture. While these quantities can be sensed, no serious study has been done to access the growth status of crops. When enough data are available, an average growth rate (as indicated by LAI, for example) and/or an average growth period can be obtained and used as a standard for comparison to decide whether the crop is in its normal state or under stress. Thus the recommended initial emphasis for addressing the third issue is the collection of data on growth status and the simultaneous microwave measurement.

3.6 Thermal Infra-red Exitance Modeling

Introduction

Many investigators have studied the possibilities of utilizing the thermal infra-red region (3 - 20 μm) to make inferences about vegetation canopy characteristics. There have been a number of studies concerning the use of vegetation surface temperatures along with other variables to infer the water status of the vegetation canopies. In addition, there has been some work using soil surface temperature to predict the water status of bare soil. Both temperature and moisture of the canopy components (leaves and soil) are of primary importance in determining crop yields. The information on vegetation and soil temperatures during the early stages of growth (before the vegetation completely covers the ground) could be useful in predicting the maximum potential yield of a crop via prediction of maximum LAI. Canopy temperatures early in the growing season would also be useful in scheduling the first few irrigations in arid lands. Because of these potential advantages, the thermal band has been incorporated in the TM sensors on board the most recently launched Landsat satellite.

Status of Modeling and Issues:

The basic relationship between radiant exitance, M, into the hemisphere above a source of unit area, at absolute temperature, is very simple. It is

$$M = \varepsilon \sigma T^4 \tag{7}$$

where σ is the Stefan-Boltzmann constant, and ε is the emissivity of the surface. However, its application in the context is complicated for reasons described below.

(1) Eq. (7) is valid only if the radiant exitance is measured over the entire wavelength range 0 to ∞ . The finite wavelength range is usually handled through a change in the power dependence of T.

(2) For accurate estimation of T from Eq. (7), the emissivity ε must be known very accurately. This sensitivity can be minimized by using the ratio of radiant exitance in two wavelength bands.

(3) For a canopy, one has a wide distribution of temperatures as well as emissivities throughout the canopy. The temperature distributions are a result of a number of simultaneous energy transfers, including transpiration, soil and foliage evaporation and solar absorption, thermal infrared emission and absorption for soil and foliage, soil conduction, and soil and foliage convection. These energy transfers depend on the characteristics of the canopy.

In spite of these complications, Kimes and his collaborators (Kimes, 1981; Kimes, Smith & Link, 1981; Smith et al, 1981 and the references cited therein) have been able to develop models relating the canopy's properties to the sensor response in the thermal IR range. In their models, the canopy is abstracted into a number (m) of horizontally infinite layers (including ground).

They derive a relationship between thermal IR radiance $L(\theta , \phi)$ of a canopy, in the viewing direction defined by (θ , ϕ), as a function of the mean emissivity, ε_i , and the mean temperature, T_i , of the i^{th} layer and geometrical parameters, defining canopy. These parameters are similiar to those used for modeling of crop reflectance in other wavelength regions (See subsection 3.1).

The above relationship has been used in two basically different forms, leading to direct and an inverse model.

(A) In one case (Kimes, Smith and Link, 1981), T_i is determined by energy transfers between various components of the canopy. Here, though the flow of energy is time-dependent, a steady state condition, in which elements of the canopy are neither gaining nor losing a net amount of energy, is assumed. Also, the energy loss due to photosynthesis, energy gain by respiration and heat exchange by conduction are considered negligible. These assumptions are good for vegetation elements of small dimensions (not good for large branches and trunks). Other assumptions made are: spectral effects in the thermal region are insignificant, reflection of thermal flux within the canopy is negligible and individual canopy elements limit thermal radiation in an isotropic manner.

The model successfully predicts the average canopy element temperatures for a lodgepole pine canopy to within 2 ^{0}C, and the angular variations in thermal radiance over a diurnal cycle. It shows that though the total global irradiance absorbed by the canopy is relatively constant with solar zenith angle, the proportion absorbed by individual canopy layers varies as a function of solar zenith angle. It also shows that for certain canopy elements inclination distribution, LAI, and environmental conditions, the sensor inclination angle will greatly affect the sensor response. This should be taken into account in selecting the optimum view angle.

The model has been reexpressed and simplified by Smith et al (1981) to make it more usable and computationally easier. Its predictions agree, to within 2 to 3 ^{0}C, with the observations on coniferous (Douglas-fir) and deciduous (Oak-hickory) canopies for clear weather as well as hazy or foggy conditions.

(B) In the other case (Kimes, 1981), no detailed modeling is done for the energy transfer. Instead, *a priori* information of vegetation geometry and the measurements on a series of *off-nadir* sensor view angles are used to determine the temperature profile. This model has been evaluated on data from several wheat canopies at different stages of development. It is found to most applicable for the separation of vegetation and soil temperatures. It infers mean vegetation surface temperature accurately (within 1.8^{0}) for intermediate and dense canopies, but relatively poorly for sparse canopies.

The status of modeling for the reflectance in the thermal infrared region seems to be quite good, keeping in mind the complications of the thermal energy transfer. However, the models have been applied mostly to the tree canopies.

Recommendations:

It is recommended that most of the effort in this area should be on applying the existing models to crop canopies like corn, soybean, wheat, oats, etc. and determining the range of validity and shortcomings of these models. The application should use the ground data as well as TM data for thermal exitance.

4. FEATURES INDENTIFICATION OR INVERSE PROBLEM

In this section we will discuss various aspects of features identification from the crop reflectance data or the inverse problem.

One of the most widely used approaches for crop identification is through the multi-variate statistical analysis of the satellite data using ground truth data to train the classifier. This approach emphasized the data collected at a single time. Since various crops undergo differing developmental sequences, these should manifest themselves in reflection changes over time and thus could be used for better crop identification. This has been successfully captured by the temporal profile modeling discussed in subsection 4.1. In the model, time dependent reflectance data is fitted to a temporal profile. The parameters so derived are characteristics of the crop and its phenological stage of growth. The future recommended activities emphasize providing a better physical/ biological basis for the profile and its parameters.

In subsection 4.2, we discuss the problem of inverting the canopy reflectance models. Like any other inversion problem, the key questions are: For given data, how unique will the solution (parameters) be? How sensitive is the solution to the errors in the data? What are the relationships of these parameters to biophysical parameters? And can these parameters discriminate between various crops, stages of development and quality of crop?, etc. We recommend that the problem of inversion should be looked into to get a better assessment of these important questions.

It is possible that the present canopy reflectance models, especially the more complex ones, may not be attractive from the inversion point of view. It is therefore desirable to look into some reflectance models which are invertible, but have not yet been tried in the context of crop canopies. One such model is the so called multi-thin layer model which has been used in designing optical system which modifies spectral composition of an incident radiation in a given manner. It is described in subsection 4.3 together with the anticipated problem in adapting this model to the canopy reflectance model and the recommended strategy for determining its applicability to the crop identification problem.

4.1 TEMPORAL PROFILE MODELING

Introduction:

It is also known that various biological systems undergo differing developmental sequences, and consequently have different growing seasons and season lengths. These developmental differences manifest themselves in reflectance changes over time. These changes over time or temporal profile have proved to be useful for the separation and unique identification of several crops. Potentially, the method could prove useful in the identification of all cultivated crops.

The temporal profile model is basically an aid in parameterizing the time dependence of the spectral data for a crop during its growing cycle. It greatly enhances the ability to extract features from the time dependence. In order for such a model to be useful, it should qualitatively describe the temporal behavior of the spectral data to the model should be related derived from fitting the remotely sensed data to the model should be related to some biophysical characteristics of the crop. In addition, the model should be simple in nature so that there are a minimum number of parameters which need to be estimated from fitting the model to the relatively limited, remotely sensed, available data.

Current Temporal Profile Model

The growth cycle for a cultivated crop has five identifiable stages: (a) a lag phase when the seed is getting ready to grow into a plant; (b) an exponential growth rate; (c) a retardation stage; (d) a steady state; and (e) a senesence state. The "growth rate" of a plant thus exhibits a sigmoidal shape. Work done by Kauth-Thomas (1976) has shown that a linear transformation of the Landsat spectral date, called Greenness G, was highly correlated to green component development of the plant population. The time profile of greenness has been observed from Landsat data to be bell shaped in form. A model of this temporal profile can be derived from an ecological type model (Badhwar, 1982).

$$\frac{dG}{dt} = k\,(t)G\;(1-G/G_m\;) \qquad (1)$$

where k(t) is a time dependent parameter and G_m is the maximum greenness. Such a model can reproduce the observed temporal profile under a wide variety of observational conditions and for a variety of crops. At present, k(t) has been interpreted as a net difference of rate of new leaf development minus the rate of old leaf die off.

The parameters derived from fitting the model to the data have some interesting properties. For example, maximum greenness and width, σ, of the temporal profile between two inflection points, t_1 and t_2 (one point corresponds to the rising part of the bell shaped curve and the other for falling), have provided good accuracy in separating crops. They have also been shown to be constant over a wide range of conditions. The parameters t_1 and t_2 also seem to correspond to unique phenological stages of corn, soybeans, and spring wheat.

Issues Concerning the Current Model

Most of the research issues with respect to this type of model are to essentially provide a better physical/biological basis for the various parameters, observations on the relative values of these parameters for various crops and for the basic form of the bell-shaped curve. Some of these specific issues are:

(1) What is greenness measuring in a plant canopy? This is perhaps the most fundamental question.

(2) Can the model, including k(t), be derived from first physical and/or biological principles or is this model only heuristic in nature?

(3) How does one test the validity of this model, and test its limitations? (fertilization, plant population and water treatment experiments?).

(4) Why is C_m (soybean) > G_m (corn)? Under what conditions does it hold and can it be derived from leaf characteristics?

(5) Why are t_1 and t_2 related to the phenological stage of a crop and can this relation be derived?

(6) Why is the fractional area under the profile linearly related to phenological stage for corn. For other crops, can one derive the functional form of this relationship?

The other issues are: the extendability of the model to provide additional agronomic information (e.g. on planting density), developmental stage estimation and prediction without knowing the full temporal profile development, assessment of similiar models in other wave length bands (thermal, microwave), and use of spectral measures or vegetation-specific indices other than greenness (e.g. brightness, band ratio, etc.).

Recommendations:

The recommendations are that various approaches to address the various issues should be pursued. Specific approaches to address some of the issues, are as follows:

(A) Understanding Greenness

The key to many issues related to greenness temporal profiles is the fundamental understanding of the relationship between greenness and plant growth variable(s), that is, what precisely in the crop canopy greenness measures.

A good initial guess, supported by some experimental evidence, is that greenness may be responding, at least in part, to LAI and/or biomass (total or leaf). An approach to test this is to use a crop reflectance model like the Suits model and vary LAI (within some bounds), keeping all other parameters constant (at measured value), and relate LAI to greenness. A similiar study can relate biomass (calculated through the vegetation component densities n_h and n_v of the Suits model) to greenness. These calculations need to be repeated for various development stages of a crop and then compared with the experimental data on spectral reflectance of crop with known agronomic variables. (Here it may be noted that there are 15 ground observations on wheat made throughout the growing season). This study can also aid in determining LAI, SRI (solar radiation intercepted) and biomass from the spectral data. (See subsection 5.4).

In addition, it will be very desirable to combine a crop reflectance model (e.g. Suits model) with plant growth models (e.g. Ritchie wheat model, Arkin corn model) and use it to relate the reflectance and greenness as a function of plant growth variables. This dynamic reflectance model can be used to generate temporal profile that can be compared to the observed profile to understand the relationship between spectral and (time dependent) agronomic variables (See subsection 3.1).

(B) Form of k(t)

To semi-empirically obtain the form of k(t) one could use the temporal reflectance data, e.g. of Ray Jackson of USDA, Pheonix, measured virtually every day, convert it into greenness vs t data and then fit the data to Eq. (1). Details of agreement and lack of it may give insight into the behavior of k(t) under various crop cultural practices. This activity should be supplemented with a vegetation growth literature survey to determine if forms of k(t) already exist and if the conjecture, that k(t) is the net of birth rate and death rate of leaves, is plausible.

(C) Relationship of G_m to Crop Type

An initial activity to understand the relationship of maximum greenness G_m to crop type, is to understand why G_m (soybean)>G_m (corn). The time, t_p at which this maximum is attained for both of these crops is such that the LAI is about the same; thus differences other than LAI will have to be invoked to explain this feature. There are three likely causes for this observation.

(1) Soybean is a dicot (dorsirentral mesophyll) compared to corn, a monocot

(compact mesophyll). Gausmann showd that in IR dicots reflect more than monocot. In addition the forward and backward scattering patterns of soybeans are quite different from those of corn.

(2) Corn tassels occur around the time of peak greeness. These will reduce the corn greenness. This does not happen in the case of soybean.

(3) At t_m, the soybean canopy is fully closed unlike the corn canopy where soil is visible, resulting in lower G_m for corn.

The extensive data on the spectral reflectance of soybean collected in 1981 at LARS/Purdue and of corn being collected in 1982 (see subsection 3.2), together with a crop reflectance model such as the Suits model should be sufficient to determine if the above causes (except for differences in mesophyll structure) are indeed responsible for the inequality between G_m or corn and soybean.

(D) Brightness Versus Time

It has been observed in Landsat data and in the field measurement data on wheat, by Ray Jackson at USDA, Pheonix, that the brightness profile of wheat, barley, oats,and corn have a characteristic slope change a few days after the 'peak' greenness is achieved. This behavior is not observed for hay, pasture, soybean, trees, sunflowers, etc. What is this slope change related to? The most attractive suggestion is that it is related to appearance of heads. If it can be proved that this is indeed the case it would help considerably in separating small grains from confusion crops and in identifying their phenological stage. It would also aid in separating corn from all other crops. There are two suggested approaches to verify this hypothesis. The first in experimental; take spectral data of two identical wheat plots as a function of time, up to the time heads are formed,then on one of them cut the heads and continue to take spectral data and compare their brightness temporal profile. The second approach is using the data collected by Chance and LeMaster (1980) on wheat and use Suits model to generate brightness temporal profile with and without heads in the first layer, and comparing the two brightness profiles.

(E) <u>Alternative Spectral Transforms Versus Time</u>:

The individual spectral bands measure different spectral characteristics of a crop canopy that are more easily interpretable than greenness and brightness. However, they are sensitive to soil variations, shadow effects, and,to a limited degree,atmospheric effects, whereas greenness is not.

Greenness and Brightness emphasize particular characteristics of a canopy, but in the process de-emphasize other characteristics. In order to extract all of the information, it is desirable to develop parameterization of time profiles of each of the MSS and Thematic Mapper bands. The starting point for this would be the excellent body of data collected by Ray Jackson (USDA) on wheat, Cliff Harlan (S. Dakota) on wheat, barley, and oats, and Bauer et al on corn, soybeans, and wheat.

In analogy with the greenness transform, band ratios or other non-linear transformations that can be correlated to biophysical parameters need to be developed and their time behavior parameterized. The sensitivity of these model forms to atmospheric effects and cultural management practices would need to be studied.

In these studies a crop reflectance model like Suits model can be used to study the sensitivity of various transforms to agronomic variables.

(E) <u>Alternative Formulation of the Basic Model - Ecological Models:</u>

The current temporal profile model is based on a differential equation for the net rate of production of green leaves. Models which explicitly incorporate stage dependent dynamics of leaf and fruit production will be necessary if a deep understanding of the effects of abnormal growth (due to stress) on the temporal profile is to be achieved. The development of models for biophysical characteristics of the canopy from ecological first principles would also provide a basis for experimental determination of the parameters, as well as suggest additional temporal features which might be currently unrecognized in the MSS data.

One such model of this sort would be a set of coupled differential equations describing the temporal change in "green" and "non-green" (fruit) matter in the canopy. One would start with the PAR absorbed by the plant, subtract the energy used in respiration, and then partition the rest of the energy into the production of "green" and "non-green" biomass. Approaches similar to this have been formulated by T. Woolford of LEMSCO and D. Strebel of SUNY-Binghamton.

These approaches should be pursued to see if they can be used to produce reasonable profile forms which might have a better theoretical basis. An advantage of such ecological models is that they can be verified by field measurements. These measurements can also establish the normal range of the model parameters for comparison with estimates found in remote sensing situations.

(F) <u>Alternative Estimation Approaches</u>:

The possible use of temporal models to predict future developments needs to be explored in a mathematical sense. The general objective is to use early season data to predict later values, and then to refine these predictions as more data becomes available. An analysis of the error in fitting the parameters and the confidence in the predictions is required to make this useful.

In the broadest sense, the prediction problem can be addressed by adapting the model to new data as it becomes available. This could be done through the technique of adaptive filtering used in the field of business forecasting (Wheelwright and Makridakis 1979), adjusting the weight given to old data as new data is obtained. Another possibility is a hierarchy of models - replacing early season models with few parameters by more detailed models as data permits.

The parameter estimation problem is implicit in all of these schemes. Since the models are non-linear, a non-linear optimization technique must be used. The multiple initial conditions technique (Milstein, 1981) should be explored, since it can be used for error analysis as well as non-linear optimization. This technique has been developed specifically to allow the solution of dynamical systems for which very few data points are available. It has been very successful on difficult non-linear problems in biochemical kinetics, and would seem appropriate for remote sensing problems in which few data points are obtained during an entire season.

(G) Temporal Profiles in Microwave Region - Identification of small grains

Small grains such as wheat, barley, and oats belong to the same family and thus have relatively few physical and geometric distinctions from each other. Reports by agronomists have indicated that identifiable distinctions are:

(1) Barley heads and wheat heads are like corn on the cob, while oat heads are solid objects connected by slender stems to the central stalk.

(2) Barley heads are on the average thicker and longer than wheat heads (up to 3 times). Oat heads are 3 to 4 times larger than barley but are shaped differently as noted in (1),

(3) Barley heads lie more horizontally than wheat, and

(4) The orientations of leaves over the growing season for these grains may vary in different ways.

It has been noted that the optical and IR reflectance curves obtained from these grains over the growing season do not have enough distinguishability to permit crop classification. This is possibly due to the fact that optical wavelengths are small compared to the typical dimensions of the leaves and heads. Hence, there is very little sensitivity of the observed spectral reflectance to differences in both the size of the heads and the orientation of the heads or leaves.

What are the possible choices of sensing parameters to identify the small grains?

Since distinctions between the small grains exist only in size and possible orientation, it is necessary to capture these differences for crop identification. For example, the heads of wheat are more nearly vertical than those of barley. This indicates that polarization ratio (VV/HH) is a possible parameter to separate these crops because wheat will have a larger ratio than barley. On the other hand, oat heads are random collections of particles, small compared with certain microwave wavelengths. Hence, under the condition where heads are dominant scatterers, the principle of volume scattering from Rayleigh scatterers may be used to separate oats from wheat or barley using a two-frequency approach or a multi-frequency approach.

During the early season (before heading) only the difference in leaf orientations (or perhaps sizes) is available for separating these crops. If a significant difference exists, it implies that the backscattering versus incidence angle curves for different grains have local maxima in different angular ranges. At present complete information on leaf angle distributions is not yet available. Hence, further investigations are needed to decide what is the best strategy.

4.2 Agronomic Variables from the Reflectance Data - Inversion of Crop Reflectance Models.

Introduction:

To date, most of the crop reflectance models have been used as a research tool and for understanding, i.e. for defining the proper instrumentations (e.g. spectral bands of sensors), in interpreting data, for assisting in the identification of appropriate transform of reflectance in various wavelengths which may be insensitive to some canopy parameters, and for identifying potential causes of abnormal observations. They also have the potentials for 'forecasting' reflectance for hitherto untried sets of canopy parameters.

However, in light of the overall goal of crop identification, and crop growth stage, and quality determination from the reflectance data, it is imperative that various crop reflectance models be investigated to assess their capabilities for correctly and uniquely determining the canopy parameters of importance like LAI, solar radiation interception, etc. from the reflectance data. In other words, they should be tested for their invertability.

One of the commonly used procedures is to define a merit function, F, say by

$$F = \sum_i w_i (R_i - R_i')^2$$

where R_i and R_i' are the reflectances calculated from the model and as observed, respectively. The summation is over all observed with the w_i representing the weight given to each term. The canopy parameters are then determined by minimizing the function F by either a non-linear optimization procedure or a numerical inversion using an exhaustive search technique.

Issues

The key issues are: given the reflectance data for a crop, and a model which satisfactorily represents this crop (e.g. Suits model for uniform and homogenous crop), how correctly and uniquely can one determine canopy parameters of importance and how sensitive is the determination to the variation in the reflectance data. Can the canopy parameters so determined discriminate various crops, stages of development, and quality of various crops? The inversion of the temporal profile model seems to be successful. Whether this is so also for very high resolution ($\sim 1 \mathring{A}$) spectroscopic observations and many view angles is an important issue.

Recommendations

It is recommended that the model inversion be first tried on simpler semi-analytical models like those of Park-Deering and Suits. Here, the initial effort should be to use data with no error or noise, i.e. choose a certain set of parameters for a model, calculate reflectance and use it as data. If the range of the solutions obtained is unacceptable, modify the merit function/use of model by using more parameters, more observations, different combinations of parameters, linear combination of reflectance for many wavelength bands (e.g. Kauth- Thomas greenness) and reflectances at different times. This last effort should include noise in the data. If the noise in the data leads to large errors in the solution, (i.e. it is a ill-posed problem) either a different model or another approximation (possibly with more parameters) should be used; for a given model, standard methods to address such a problem should be investigated. These include use of different computational methods and prior knowledge of properties of the admissible solutions (regularization theory). The latter knowledge is incorporated by putting global bounds on the solutions, using statistical properties of the solutions, and imposing smoothness of solution conditions, positivity of solution constraints and inequalities.

Partial use of the experimental data on the parameters to estimate other hard to obtain parameters is a worthwhile goal even if the general problem can not be solved. For example, LAI, conventionally a very labor intensive measurement, may be easily estimable using information on the identity of crop, height of the canopy, and optical properties of the canopy components.

A successful inversion of the simpler models using data with no errors, of course, should be followed by inversion with experimental data, and inversion of more complex models involving numerical integration of the radiative transfer equation.

In addition to the inversion of the known crop reflectance model, other simpler models which are invertible should be investigated for adoption in the context of crop reflectance. One such model is described in the next subsection.

4.3 Multi-layered System Model for Crop Identification

Introduction:

In many industrial applications, it is desirable to design a thin film coating which modifies the spectral composition of an incident radiation in a given manner. Such application ranges from coating on sunglasses, for every day use, to surfaces in sophiscated instrumentation. During the last decade significant progress has been made in developing the design techniques and mathematical apparatus (See e.g. Dobrowolski, 1981). In one technique, the optical system is considered a set of thin film layers system. The main physical properties that can be modified by such a system are transmittance, reflectance, absorption, and polarization. The system is designed to meet a required performance for one or more of these optical properties at a selected wavelength or in a certain wave length region. That is, the method can be used to determine the construction parameters of a thin film device, namely, refractive index n, absorption coefficient k, and thickness d. The method has been demonstrated to be a practical one for most coating systems.

It has been proposed (Goel, 1982a) that this design method may be of some value in crop identification. According to the proposal, for a given reflectance $R(\lambda, \theta, \phi)$ which depends on wave length λ, and view direction (θ, ϕ), one will use the method to calculate the parameters $n(\lambda)$, $k(\lambda)$ and $d(\lambda)$. One hopes that the values of these parameters will be sufficiently different for different crops to allow crop identification. It is conceivable that one may need to use R at different times and/or a multilayer system with a set of parameters n, k, and d which vary continously as a function of distance perpendicular to the thin layer.

Issues:

There is an important difference between the thin film devices for which the method has been developed and the canopy system. This may lead one to question its validity. A canopy structure causes an incident radiation to scatter in all possible directions instead of being reflected in the specular direction as for a thin film system. Ignoring this difference one may still go ahead and obtain an equivalent multilayer system which can generate for a given incident radiation the specified amount of scattered radiation in a given direction. For a different view angle, another set of parameters for the equivalent system may be obtained. The main issue is that at this time it is not clear whether the two sets of parameters will turn out to be within the computational tolerance of this technique.

Should the parameters fall within the tolerance, there is a high probability that as long as two crops have two different spectral characteristics, two different equivalent systems may be generated to tell them apart (a successful crop identification technique). The weakness of the equivalent system, of course, is that the parameters obtained do not necessarily correspond to the true physical system, since they are equivalent parameters. On the other hand, the success of the technique should mean that a clearer distinction exists in the equivalent sets of parameters than the original given spectra.

On the other hand, if the parameters fall outside the tolerance, i.e. the scattering characteristics can not be equivalently replaced, the thin film technique may have to be generalized, perhaps using perturbation methods, to include the effect of scattering and then tested.

While canopy scattering occurs in both the optical and the microwave regimes, it is known that the albedo of scattering is much smaller in the microwave regime. Hence the thin film system technique should have a much higher probability of success there than in the optical regime without further generalization. However, microwave measurements are largely incoherent because normally only the backscattered signal (as opposed to the forward) is measured. Thus the required testing stated in the previous paragraphs applies even for the microwave region.

Recommendations:

Since the problem of automatic crop classification is an important one, in spite of the reservations stated above, the technique should be investigated for its applicability.

The recommended specific strategy for testing the validity and potentials of the approach is as follows:

(1) For the data for $R(\lambda, \theta, \phi)$, initially use the "theoretical" value, as opposed to observed values, obtained by one layer Suits model and using parameters of the Suits model for a crop (e.g. parameters used by Chance and LeMaster, 1977) for about 15 wavelengths and 30 to 40 sets of observation angles (θ, ϕ). For a given λ, use all of these values for $R(\theta, \phi)$ to calculate n, k, and d and investigate the uniqueness of the solution. If the solution is rather unique, the number of data points should be reduced (fewer θ, ϕ). If the solution is not 'sufficiently' unique more (θ, ϕ) data points need be added. The calculations should be repeated for about 15 wavelengths.

(2) Repeat (1) except use data for all λ and assume wavelength dependence of $n(\lambda)$ and $k(\lambda)$. This dependence may initially be chosen to be the one obtained by Allen, Gausman, Richardson, and Thomas, (1969).

(3) Repeat (1) and (2) for say 3 more crops (wheat, soybean, cotton, corn, etc.). Determine if the resulting values for $n(\lambda)$, $k(\lambda)$ and d are crop dependent.

(4) If the results are not encouraging, use a spectral transform like Greenness $G(\theta, \phi)$ as data. Also include time as another variable, i.e. use $R(\lambda, \theta, \phi, t)$ or $G(\theta, \phi, t)$ as data and calculate $n(\lambda, t)$, $k(\lambda, t)$ and $d(t)$. The resulting parameters may have enough discriminatory power. This will be a crucial decision point for assessing the applicability of the model <u>as it is</u> to crop identification problem. If it is not applicable modify the technique to include scattering in the basic method.

(5) If the results are encouraging one can, of course, still add time as a variable. In addition, one has many directions to pursue. Some of them are:

(a) Determine the sensitivity of the discriminating power of the model as a function of the error in the data. This should be done by introducing 10 to 20 percent error (randomly) in the data. Other similiar testing of the model, e.g. as a function of the objective function, weight factor etc. should be carried out. In other words, optimize and fine tune the model.

(b) Use the same model on a single leaf level using the data base for single leaves. It is suspected that the model may be able to discriminate leaves with various structures. (It is doubted that it will have the power to discriminate the leaf crop).

(c) Relate n, and k to agronomic variables of interest (as specified by experimentalists) and to parameters of the Suits model. This will be a slow process requiring creative thinking and biophysical/geometro-optical modeling. If one is successful, it obviously will be an extremely useful tool for experimentalists.

(d) By using appropriate weight functions, determine if the changes in the data could be used to detect stresses. Also, in the model since the absorptance of leaves vary as a function of days in the growing season, it is conceivable that $n(\lambda, t)$ and $k(\lambda, t)$ could be used to determine the development stage.

5. CONCLUDING REMARKS AND STRATEGIC RECOMMENDATIONS

In the preceding sections we have attempted to review various models related to the vegetation estimation from spectral reflectance data. This review contains most of the relevant topics with the following exceptions. The reviews of

- crop yield models
- spectral reflectance of mixed pixels
- crop growth models
- models of spectral reflectance of vegetative components and of soil

were not explicitly carried out; only relevant parts were implicitly reviewed with the explicit reviews of other topics. We chose not to carry out the detailed review of the first two topics to limit the scope of this study to pure pixels and to parameters which are input to crop yield models. The area of crop growth models is well developed and texts and major reviews by plant physiologists are available. On the last topic, very limited work has been done and most of the models of crop reflectance take spectral properties of the vegetative components and soil as input parameters. It is quite obvious that to better understand the relationship between vegetative stress and crop reflectance, the modeling at the canopy component level,coupled with reflectance measurements versus stress will be extremely fruitful.

For other topics we have already discussed the major issues and the recommended strategy for future activities. These activities were presented for advancing the state of art of the direct as well as the inverse problem. We will now sort out the most desirable activities required for vegetation estimation from the crop reflectance data. The format we will use is as follows.

We first identify the variables of interest and at what level of accuracy one needs to know its variable. This level is, in part, determined by the sensitivity of the variable to the purpose it is eventually used for e.g. for predicting crop yield.

For each of these variables we review the status of measurements on ground (using direct measurements and using reflectance measurements), and with satellite borne sensors. On the basis of this status we identify desirable strategic activities in terms of what model should be studied, what technique should be developed. We also enumerate a list of specific issues and questions which if understood or answered, should advance the accuracy of estimation of the variable from the spectral measurements.

5.1 Vegetation Type Identification

Of particular interest to the AGRISTARS Research programs are the identification of small grains as a class, separation of various small grains (e.g. wheat, barley, oats) within that class, and separation of corn from soybeans in early season (corn/soybeans at harvest is further along, although issues may still exist for some foreign locations).

Desirable accuracy is an error in identification of < 10% , preferably no more than 5%.

On the ground determination of vegetation type is done by human beings. It is not clear if the vegetation type can be determined by a set of measurements for all vegetation types.

Determination, by spectral reflectance measurement, has been shown to be feasible only for a few crops using temporal data. Small grains is a stress case for temporal profile modeling.

The recommended activities are:

. Field and literature studies to establish agronomic and biophysical differences between the various vegetation types of interest so that one could use them to classify crops on ground, in an automatic fashion, without human intervention. Empirical characterization of these canopies using field measurements, for a range of values of these parameters, including in mid-IR and microwave regions and as a function of time. Comparison of these data with those predicted by the reflectance models as well as quantification of error in reflectance prediction as a function of various ranges of parameters.

- Modeling studies in mid-IR region (P. 30) and microwave region (P. 32 and 47) and temporal profile modeling (P. 43).
- Studies on inversion of crop reflectance model (P. 49), and on multi-layered system model (P. 52).
- Studies on crop development stage as discussed later in the section.

Some specific questions for which information is currently unavailable are as follows.

For small grains/pasture separability:

What pasture (native and cultural grasses) classes are spectrally confused with small grains in greenness - time domain? What agro-biophysical differences exist between these classes and small grains which are distinct and may be spectrally observable? How can these differences be observed and manifest in canopy reflectances? What are the major pasture classes which grow in important small grains regions?

For these pasture classes, is the Kauth-Thomas Brightness (KTB) versus time profiles different for small grains than for pasture? On what background features does brightness depend? For natural variations in background factors (soil brightness, row direction) is the variance of brightness within small grains and pasture classes smaller than the variation between small grains and pasture (i.e. is separability achieved)? How can KTB background effects be stabilized? greenness/brightness ratio ?

Is there a dip in brightness at small grains heading which is not observed in pasture? Is this dip unique to small grains? What is the cause of this dip? How can this dip be used to identify small grains?

Is there additional separability information for small grains at TM frequencies?

For wheat, barley and oats:

What are the significant agro-biophysical differences between wheat, barley, oats and other small grains?; growth rates, planting dates, harvest?; leaf slope distribution, leaf reflectance?; reflectance and orientation of heads?; canopy morphology and LAI(t)?; 'nodding' of barley for separating it from wheat? How do these differences depend on growth (ontogenetic) stage? How are these differences manifest in terms of reflectance, in the visible-near IR, mid-IR and microwave regions, as a function of t. How can these differences be used to separate and identify wheat, barley and oats?

How do mixed pixels affect the temporal profile approaches to crop identification?

5.2 Vegetation Maturity or Development Stage

This is required for crop identification as well as for yield prediction. The desirable accuracy is ± 3 days.

On ground determination of maturity stage is done by human beings and there are several scales to quantify maturity stages for various crops.

Progress towards the determination of maturity stage from the spectral reflectance data has been extremely limited. Temporal profile modeling has been shown to be capable of estimating the development stage to ± 5-7 days for corn only. The estimation is done by calculating the fractional area under the greenness vs t curve and thus one needs the greenness profile for the total development time. This data requirement makes the maturity stage determination somewhat academic. Recent results which show some relationship between inflection points of greenness vs time curve and key maturity stages for corn, soybean, and small grains are encouraging.

The recommended activities are:

- Literature and field studies to identify important changes in canopy geometry and optical changes in its components as a function of the development stage for corn, soybean, and small grains. Measurements to quantify contributions/effects of canopy components, specifying the development stage (e.g. corn tassels) to the canopy reflectance. Simulation of canopy growth and the development stage in terms of parameters to which the canopy reflectance responds.

- Use of canopy reflectance models to simulate observed reflectance vs development stage using observed changes in canopy geometry and optical changes in its components.
- Combination of a canopy reflectance model with a vegetation growth model to simulate observed reflectance vs development stage (P. 16).
- Investigation of adaptive filtering and other alternate parameter estimation techniques in temporal profile modeling (P46).
- Investigation of reflectance in microwave region (P. 32 and 47).

Some of the specific questions which should be addressed are:

What physical mechanism explains the relationship between the fractional area under the Greenness-time profile and the development stage? How does this relation depend on vegetation type?

What are the major spectral changes in individual leaves as a function of maturity stage for corn, soybeans and small grains?

What is the physical basis for correspondence in the inflection points of greenness vs. t curve and key maturity stages for corn, soybeans and small grains?

How does 'brightness' depend on the maturity stage? Are other transformations of MSS and TM data more sensitive to the maturity stage than Kauth-Thomas channels? Are microwave bands, polarizations and look angles sensitive to the maturity stage?

Given a detailed knowledge of the canopy biophysical parameters to which greenness-brightness responds, can canopy growth be modeled in terms of those parameters?

5.3 Vegetative Stress Condition and Evapotranspiration

Here, stress condition is referred to disease or nutrient (including water) deficiency. Both of these variables are required for accurate prediction of crop yield. Evapotranspiration can be used for optimally scheduling irrigations in arid lands.

The desirable accuracy for evapotranspiration is ± 10%. For stress, it is difficult to specify the desirable accuracy because it is rather difficult to even qualitatively define stress. Its measurement, even on the ground, is only indirect through reduced yields. It would be desirable to define it directly and more precisely.

Progress towards the determination of these parameters, from the spectral reflectance data has been very limited; extreme stresses like corn blight or extreme drought can be detected from such a data in visible-IR and thermal-IR regions.

The recommended activities are:

. Development of situation specific definitions for stress and the development of a quantitative stress scale.

. Measurements on optical properties of the components of a canopy of the cultural vegetation type (corn, soybeans, small grains) versus various stress conditions (moisture stress, freeze damage, nutrient stress, disease, insects). Incorporation of these measurements in a canopy reflectance model to allow calculation of correlations bwtween reflectance and various stresses.

• Investigation of a technique for the development stage estimation to assess stress condition. Here, it should be noted that the time period for a plant to make a transition from one development stage to another depends upon the stress condition.

• Investigation of thermal exitance models (P.37) for cultural vegetation and their use for temperature estimation and eventual evapotranspiration, using results in microwave region to determine surface soil and plant moisture (P. 32).

5.4 Leaf Area Index (LAI) and Solar Radiation Intercepted (SRI)

Perhaps the most important agronomic variable is LAI. Growth and the duration of green LAI determines the proportion of solar radiation intercepted (SRI) by the canopy and thereby it influences canopy photosynthetesis, evapotranspiration and grain yield. There are a number of crop growth and yield models which require LAI as an input variable to predict dry matter production and water use. SRI is directly related to the final grain yield.

Because of the importance of LAI, it is desirable to measure it to within ± 5% accuracy. For SRI, a ± 20% or better estimate seems to be acceptable at this time.

It is not possible to manually measure LAI except for a limited number of research plots. Even then, measurement is very labor intensive. The present accuracy even for these plots is only about ± 20%. More recently a geometric shadowing technique which relates to the sunfleck distribution and density to LAI has been developed by John Norman at the University of Nebraska, to estimate LAI without labor intensive measurements of leaf areas and inclinations.

SRI is estimated indirectly by using a semi-empirical relationship between SRI and LAI or by direct measurements.

Results from several empirical studies of canopy reflectance and LAI indicate that reflectance, particularly the near infrared is sensitive to variation in LAI. There are empirical relationships between greenness as a function of LAI which depend upon the vegetation, leaf angle distributions, row spacings, and sun angles. Thus, in principle, there is a possibility of using spectral measurements to estimate LAI and SRI.

The recommended activities are:

<u>For ground measurements of LAI</u>

. Improve the accuracy of current LAI measurements from the present, about $\pm$ 20% to $\pm$ 5%. (it will be desirable if all experiments include explicit indications of precision). The first priority should be to develop the geometrical shadowing technique for general use, and testing it against high accuracy hand measurements. A later option is to develop double sampling techniques in which high cost accurate measurements are combined with larger scale lower cost measurements to get good values for larger areas.

. Use of a suitable reflectance model to develop a semi-quantititive relationship between greenness or other spectral transforms, and LAI. Testing of this relationship to study sensitivity and error in estimation.

. Inversion of reflectance models to directly estimate LAI from the reflectance data. Here it may be assumed, if necessary, that crop type is known (P. 49).

. Adapt current canopy reflectance model to specific LAI and SRI estimation. The adaptation includes inclusion of crop growth model and the calculation of transmittance of light (to calculate SRI).

. Investigate microwave scattering measurements together with an appropriate model for a feasibility of LAI estimation (P. 31).

. Develop methods for studying non-green LAI, stalks, etc. both before and after heading. In particular determine wavelength bands which respond to dead, dried, and senesced (chlorotic) foliage.

For Satellite Measurements of LAI

. Couple existing atmospheric models with canopy reflectance models to give a complete calculation of reflectance at the satellite borne sensor (P. 26).

. Couple sensor models like the Ungar model or Johnson-SC Scene Simulation Model or Goddard-SFC model with reflectance models to evaluate the effects of signal to noise ratio, aperture function and integration over wavelengths to generate channel bands.

. Use these models in the same form as the one for ground measurements of LAI discussed above.

Some of the specific questions which should be addressed are:

How accurately can LAI be measured using greenness? What are the major sources of error? How does the error in estimating LAI depend upon the magnitude of LAI? How sensitive is the greenness - LAI relationship to vegetation type, atmospheric effects, soil background variation, row direction, percent canopy cover, crop development stage, leaf angle distribution, and solar illumination angles?

Are there transformations of MSS and TM data that are most sensitive to LAI and SRI than greenness, yet equally or less sensitive to other background effects such as soil background, atmosphere, planting density, etc.?

Are other radiometric measurements, e.g. near infrared - mid infrared bands, more suited for estimation of LAI? Are off nadir angles better for LAI estimation? Which combinations of microwave frequencies, polarizations and view angles are most sensitive to LAI?

What is the relationship between LAI and SRI? How is this relationship affected by variation in the variables listed in the first set of questions. In particular, how does SRI depend on leaf angle distribution and solar illumination angle, planting density and soil reflectance in early season? What is the optimal planting density to maximize SRI for a given crop, e.g. for soybeans. How can the observations of SRI at Landsat overpass be extrapolated diurnally? How do crop stresses, such as moisture deficits, affect SRI through alterations in canopy morphology?

Because of the pivotal role of LAI and SRI, it is recommended that in the near term the investigation of these variables should be emphasized. Projects involving some aspect of sensing them directly or indirectly, or understanding its relationship with measured variables should be given higher priorities.

Implicit in the activities for the above 4 vegetation variables are the activities on testing and selection of existing canopy reflectance models, inversion of models, adoption of models for canopy reflectance and for atmosphere and use of existing sensor models. For completeness, we explicitly point out the recommended activities in these areas.

5.5 Recommended Activities for Modeling

(A) Testing and Selection of Existing Canopy Reflectance Models (P.17)

Current reflectance models should be tested to evaluate their range of validity and performance characteristics using a uniform data base. Models selected for the test should be reasonably well developed, be capable of operating in a useful domain, and have measurable input and output parameters. Testing should include as many models as possible, but at least the following: Suits model with and without row effects, Bunnik and Verhoef model with angular distribution of leaves and row effects, and Norman's CUPID model. Subject to the availability of data, models in microwave and thermal-IR should also be tested. Sensitivity of models to individual canopy components, e.g. leaf reflectance should be evaluated.

(B) Inversion of Models (P. 49)

Inversion of models should be done in parallel with the forward testing phase (See (A) above).

Under the keyword 'inversion' are included both mathematical inversions of simple transforms and numerical inversions of complex reflectance models.

Techniques necessary will include optimization and/or exhaustive enumeration in conjunction with an appropriate merit function. Error analysis should also be included.

Basic models to invert should include - Suits and its variants, CUPID, temporal profile, and a model in microwave.

Inversion should emphasize the calculation of LAI and other 3 vegetation variables.

(C) Modification of Crop Reflectance Models

The existing models and those under development need to be adapted to make them more applicable for estimating vegetation variables as follows:

Suits model should be adapted to include leaf angle distribution, and row effects. It should also be combined with a vegetation growth model to allow calculation of time dependent reflectance as a function of biophysical parameters.

Norman's General Array Model, the Cooper et. al. Adding Method and models based upon the specification of the phase function and numerical solution of the radiative transfer equation should be developed under the aegis of the Fundamental Research program. After they are fairly well developed, they should be adapted for applied research.

All the crop reflectance models should be adapted to allow calculation of transmittance (and thus SRI) and various spectral transforms like greenness and brightness for MSS and TM bands (and thus the relationship between canopy biophysical parameters and spectral variables).

Temporal profile models, e.g. Badhwar, ecological and developmental models should aim at relating temporal LAI functions into greenness (or other) reflectance values.

Multi-thin layer system model should be adapted for use in the area of crop reflectance (P. 52).

(D) Modification of Atmospheric Models (P.24)

Existing atmospheric models should be coupled with canopy reflectance models to allow a complete calculation of reflectance at the satellite sensor.

In the short term, the Dave Model should be used for this purpose.

Work on numerical models being carried out by S. Gerstl and funded by the Fundamental Research Program should be coordinated with applied research work.

Suits type atmospheric models should be investigated.

The combined atmosphere/canopy reflectance model should be used to determine if the relationship at the ground, e.g. greenness vs LAI still holds at the orbital height.

(E) Use of Existing Sensor Models

Sensor Models should also be coupled with reflectance models to evaluate the effects of signal to noise ratio, aperture function, and integration over wavelengths to general channel bands.

Models for consideration should include: Ungar model, Johnson Space Center Scene Simulation Model, Goddard Space Flight Center Model.

We conclude the section by making a few organizational recommendations.

5.6 Organizational Recommendations

The success of any strategy depends, in some cases rather strongly, on the infrastructure used to implement it. To this end, it is recommended that a scene analysis group be formed in AGRISTARS to serve as a bridge between the NASA fundamental research and the applied research program. The objectives of this group would be:

(1) To review and assist in the formulation of technical issues resulting from the vegetation mapping research effort in AGRISTARS.

(2) To evaluate various relevant models, especially of canopy reflectance , and their limitations, to address the SR issues, to provide feedback to the modelers about the utility and performance of their models, and to identify and recommend model improvements.

(3) To utilize existing models of biological and physiological growth, canopy reflectance and atmosphere, as well as output from the Fundamental Research program to address the issues of vegetation mapping.

(4) To provide general physical, mathematical and biological analysis, and modeling support to various elements of AGRISTARS.

Also, it will be very desirable if the philosphy of Research and Development has the following elements.

- It is systematic.
- It focusses on specific issues.
- Concentrated efforts are put on these issues.
- Continuity and longevity of efforts is encouraged.
- It allows ample cross-fertilization.
- It encourages more substantive and pragmatic results.

Here, by pointing out these elements, we are not implying, explicitly or implicitly, that current philosphy does not already have these elements. These elements have been noted to stress their importance in the success of any applied research program.

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WORKSHOP
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MODELING OF CROP REFLECTANCE

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WORKSHOP
ON
"MODELING OF CROP REFLECTANCE"

SCHEDULE/AGENDA

<u>Tuesday, July 13, 1982</u>

3:00 p.m.			Arrival by participants* at Rockwell Hall, Colorado State University, Colorado.
3:00 p.m.	-	5:00 p.m.	Transportation by van to Pingree Park Campus and Registration.
5:30 p.m.	-	6:30 p.m.	Dinner
7:00 p.m.	-	9:00 p.m.	Mixer

<u>Wednesday, July 14, 1982</u>

8:15 a.m.	-	8:30 a.m.	Welcoming Remarks (Barbara Brown)**
8:30 a.m.	-	9:45 a.m.	General Introduction (Goel)
9:45 a.m.	-	11:30 a.m.	Vegetation Type, Condition and Stage Mapping: Issues Relevant to Scene Modeling (Hall)
11:30 a.m.	-	12:00 noon	Discussion
12:00 noon	-	1:00 p.m.	Lunch
1:00 p.m.	-	2:45 p.m.	Profile Modeling for Crop Identification (Badhwar)
2:45 p.m.	-	3:00 p.m.	Discussion
3:00 p.m.	-	5:00 p.m.	Two Dimensional Radiative Transfer through Realistic Atmospheres with Non-Uniform Ground Reflectance (Gerstl)
5:00 p.m.	-	5:30 p.m.	Discussion
5:30 p.m.	-	6:30 p.m.	Dinner
7:30 p.m.	-	9:00 p.m.	Data Collection and Access (Badhwar/Bauer/Hall)

* Only those requiring transportation to Pingree Park.

** Coordinator, Pingree Park

Thursday, July 15, 1982

8:15 a.m.	- 10:15 a.m.	Spectral Agronomic Relationships of Corn, Soybean, and Wheat Canopies (Bauer)
10:15 a.m.	- 10:30 a.m.	Coffee Break
10:30 a.m.	- 12:15 p.m.	Spectral Properties of Plant Leaves and Canopies (Gausman)
12:15 p.m.	- 1:00 p.m.	Lunch
1:00 p.m.	- 3:00 p.m.	Determination of Agronomic Variables from Reflectance Data - Inverse Problem (Goel)
3:00 p.m.	- 3:15 p.m.	Coffee Break
3:15 p.m.	- 5:30 p.m.	Working Group Meetings
5:30 p.m.	- 6:30 p.m.	Dinner
7:00 p.m.	- 9:00 p.m.	Review of Canopy Reflectance Models and Issues (Smith)

Friday, July 16, 1982

8:30 a.m.	- 10:15 a.m.	A Review of Work Done by the Remote Sensing Group at Pan American University (Chance)
10:15 a.m.	- 10:30 a.m.	Coffee Break
10:30 a.m.	- 11:30 a.m.	Reflectance of a Vegetation Canopy using the Adding Method (Cooper)
11:30 a.m.	- 12:15 p.m.	Estimating Parameters of Inverse Problem (Milstein)
12:15 p.m.	- 1:00 p.m.	Lunch
1:00 p.m.	- 5:30 p.m.	Working Groups Meetings
5:30 p.m.	- 6:30 p.m.	Dinner
7:00 p.m.	- 9:30 p.m.	Working Groups Meetings

Saturday, July 17, 1982

8:30 a.m.	- 10:15 a.m.	Radar Measurements for Crop Classification and Estimation of Some Agronomic Parameters (Fung)
10:15 a.m.	- 10:30 a.m.	Coffee Break
10:30 a.m.	- 12:15 p.m.	Possible Use of Optical Multilayer Design Method to Crop Identification from Spectral Measurements (Ho)

12:15 p.m. -	1:00 p.m.	Lunch
1:00 p.m. -	5:30 p.m.	Working Groups Meetings
5:30 p.m. -	6:30 p.m.	Dinner
7:00 p.m. -	10:00 p.m.	Presentations of the Working Plans of Various Groups (Badhwar, Gerstl, Goel)

Sunday, July 18, 1982

8:15 a.m. -	12:00 noon	Open
12:00 noon -	1:00 p.m.	Lunch
1:00 p.m. -	5:00 p.m.	Working Groups Meetings
5:00 p.m. -	9:00 p.m.	Cookout and Working Groups Meetings

Monday, July 19, 1982

8:30 a.m. -	10:15 a.m.	Crop Discrimination Using Measurements in the Mid infrared (1.55 - 1.75μm) (Ungar)
10:15 a.m. -	10:30 a.m.	Coffee Break
10:30 a.m. -	12:15 p.m.	A Three dimensional Canopy Radiative Transfer Model (Norman)
12:15 p.m. -	1:00 p.m.	Lunch
1:00 p.m. -	5:30 p.m.	Working Groups Meetings
5:30 p.m. -	6:30 p.m.	Dinner
7:00 p.m. -	8:00 p.m.	Optical Phenomena in the Atmosphere (halos, rainbows, glory,...) (Winder)
8:00 p.m. -	9:30 p.m.	Working Groups Meetings

Tuesday, July 20, 1982

8:30 a.m. -	10:15 a.m.	Possible uses of Ecological Models in Analyzing Temporal Profiles (Strebel)
10:15 a.m. -	10:30 a.m.	Coffee Break
10:30 a.m. -	12:15 p.m.	On Inversion of Suits and Other Models of Crop Reflectance (Kaplan/Masalawala)
12:15 p.m. -	1:00 p.m.	Lunch
1:00 p.m. -	5:30 p.m.	Working Groups Meetings
5:30 p.m. -	6:30 p.m.	Dinner
6:30 p.m. -	9:30 p.m.	Working Gropus Meetings

Wednesday, July 21, 1982

8:15 a.m. - 10:15 a.m.	Progress Report, Working Group I: Strategy for temporal profile modeling; adaptive models; development stage, stress condition, LAI, etc. assessement; use of ecological models; mixed pixels, needs for data, etc.
10:15 a.m. - 10:30 a.m.	Coffee Break
10:30 a.m. - 12:15 p.m.	Progress Report, Working Group II: Strategy for Crop Canopy Reflectance Models Development; inclusion of time without requiring remeasurements, stress conditions vs. canopy reflectance, mixed pixels, reflectance models for stages when Greenness goes down with time, reflectance in thermal regime, needs for new models and for data, etc.
12:15 p.m. - 1:00 p.m.	Lunch
1:00 p.m. - 2:15 p.m.	Progress Report, Working Group III; Strategy for Modeling of Atmospheric and incorporation into reflectance models, application of techniques of atmospheric modeling fron crop canopies reflectance models, instrumentation requirements, etc.
2:15 p.m. - 2:30 p.m.	Coffee Break
2:30 p.m. - 4:30 p.m.	Progress Report, Working Group IV; Strategy for estimation of agronomic parameters from reflectance measurements; synergy between various types of models, etc.
4:30 p.m. - 5:30 p.m.	Discussion
5:30 p.m. - 6:30 p.m.	Dinner
7:00 p.m. - 9:30 p.m.	Working Groups Meetings

Thursday, July 22, 1982

8:30 a.m. - 10:00 a.m.	Spectral and Agronomic Characteristics of Small Grains (Harlan)
10:00 a.m. - 10:15 a.m.	Coffee Break
10:15 a.m. - 11:00 a.m.	Brief Overview of Crop Yield Models for Large Area Production Estimates (Kanemasu)