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FINAL REPORT

on

'BIOPHYSICAL AND SPECTRAL MODELING for CROP IDENTIFICATION AND ASSESSMENT'

for

NASA-JOHNSON SPACE CENTER, HOUSTON

by

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1. INTRODUCTION

The key tasks to be performed under contract No. NAS9-16873 were:

(1) Given the reflectance data for a crop canopy and a canopy reflectance (CR) model which satisfactorily represents the crop (e.g. the Suits and the SAIL model for a uniform and homogenous crop canopy), determine how correctly and uniquely can one determine the canopy parameters of importance, and how sensitive is this determination to the variation in the reflectance data?

(2) Implement on a computer the inversion of a CR model and use it to determine the agronomic parameters using measured data on the reflectance of representative canopies. A comparison of the calculated parameters with the field measured parameters will then provide an assessment of the possibility of estimating agronomic parameters from the CR data via inversion of a CR model.

Work was done towards both the tasks. The reports on progress have been periodically presented to the NASA-managements and at various professional meetings. Since the detailed results have also been documented in the form of papers which have been published in the open literature, in this final technical report we will only highlight the activities carried out and the progress made and summarize results obtained to date. We refer the readers to various documents listed in Appendix A for further details. (In Appendix B, we have added copies of the first pages of the reports/papers which have been published).

2. HIGHLIGHTS OF THE ACTIVITIES

The principal investigator and his associates focused their efforts in developing a technique for inverting CR models, i.e. a technique for estimating all the canopy parameters, occuring in a CR model, from the measured canopy reflectance data. In the published report R1, we laid down the strategy for our efforts. According to it, we first chose a simple CR model - namely, the Suits' model for a one-layer, one-dimensional homogenous canopy. This model uses six canopy parameters:

Agronomic Parameters: Hd, Vd

Spectral Parameters: ρ, τ, ρ_s

Illumination Source Parameter: SKYL

Here H and V, respectively, are the projections on the horizontal and vertical planes of the average leaf area per unit volume, d is the height of the canopy, and SKYL is the diffused fraction of the incident solar radiation. ρ is the leaf reflectance, τ is the leaf transmittance and ρ_s is the soil reflectance. The dependence of reflectance on wavelength λ is implicit in the dependence on λ of ρ, τ, ρ_s, and to some extent of SKYL.

In addition to the above canopy parameters, the CR also depends upon the illumination and view directions parameters (θ_s, θ_v, ψ). Here θ_s is the solar zenith angle, θ_v is the view zenith angle, and ψ is the relative azimuth angle ($0^0 \leq \psi \leq 180^0$) between sun and view directions.

Initially for the purpose of investigating the invertibility of this simple Suits model, we used "perfect" or "error free" CR data. That is, we used the Suits' Model to calculate the CRs for a set of values of the canopy parameters. Then these reflectances were treated as measured values and used in inverting the CR model to obtain canopy parameters. The values of these parameters were compared with those used in the original forward-direction calculation.

The basic procedure for inverting a CR model is as follows. Let R_i be the CR computed for a set of canopy parameters for the solar/view direction (θ_s (i), θ_v (i), and ψ (i). Let R_i' be the measured CR for the same set of solar/view angles. We define a merit function F by

$$F = \sum_{i=1}^{n} w_i \, (R_i - R_i')^2 \qquad (1)$$

Here, the summation is over the number of solar/view angles, and the canopy parameters appear as unknowns in R_i. The w_i's are weight factors which could all be set equal to 1, or be given unequal values to reflect the relative importance and accuracy of the various observed CRs. In the absence of any other information, we set all these weight factors equal to 1. The unknown canopy parameters which best match a given set of values, R_i', of observed CRs, are those for which the function F is minimal. (Hopefully this minimum will exist and be unique.)

The basic procedure for finding the (global) minimum of F is to start with an initial guess for the unknown canopy parameters, to calculate F using the CR model, and to use some method to choose successive values for the parameters until the computed F takes on its minimum value.

Initially we used a general purpose nonlinear optimization procedure to find the minimum value of F. This procedure was designed to ensure that one will always reach the global minimum of F while iterating on the canopy parameters. Using this procedure, we showed that the agronomic parameters of the Suits' model Hd, Vd (which are related to the leaf area index by $LAI \simeq d(H^2 + V^2)^{\frac{1}{2}}$), could be estimated from the CR data in one wavelength band (preferably near-infrared band) for a few solar/view directions, provided that the other canopy parameters (ρ,τ,ρ_s and SKYL) are known (i.e. kept fixed at their values in the optimization procedure).

To assess if canopy parameters other than LAI could also be estimated from the CR data through inversion of the CR model, we also chose ρ and τ as unknown parameters. With these four parameters as unknown, we initially found that, depending upon the initial guess for the canopy parameters, one may or may not succeed in determining their values by the inversion process. That is, for certain initial guesses one obtains values which are correct, while for others one is unable to obtain correct values. Instead a so-called slow convergence problem is encountered in which unrestricted computer time is required to succeed in obtaining the correct values.

We analyzed the slow convergence phenomenon and developed a so called 'angle transform' approach which alleviated the problem somewhat. In this approach, one constructs combinations or transforms of CRs at various solar/view angles which are either sensitive or insensitive to a given agrophysical variable. Ideally, one would like to have transforms which are minimally sensitive to those variables/parameters which are prone to error in measurement and maximally sensitive to those which one wishes to estimate by the inversion technique. Then one could switch from one transform to another to estimate one set and then another set of canopy parameters. For example, we were able to define an angle transform which was very sensitive to $\rho+\tau$ and relatively insensitive to individual values of ρ or τ and other transforms which are sensitive to H/V and ρ/τ. Using these angle transforms we showed that the slow convergence problem could be avoided and we could determine all the four canopy parameters Hd, Vd, ρ, and τ, from the CR data. The results of our efforts are described in detail in published report R3.

In this report we also presented an analytical procedure for assessing the levels of errors in the estimation of canopy parameters as a function of errors in the measurement of CRs or, equivalently, as a function of accuracy with which a CR model represents the canopy reflectance. This procedure showed that if ρ and τ are kept fixed in the inversion procedure, the important agronomic variable LAI could be estimated quite accurately. However, when these two parameters are treated as unknown, the estimation of LAI could be quite erroneous. Further the level of error depends upon the solar/view angles used in the inversion process. In fact, the error analysis could be used to define optimal set of solar/view angles.

The angle transform approach, though addressed the slow convergence problem, did not satisfactorily alleviate the problem; the convergence to the optimum values for the canopy parameters still took several thousands of iterations.

Instead of using a general purpose optimizer, we then developed an optimizer especially for this problem which is much more efficient, requiring tens rather than thousands of iterations. This optimizer is described in detail in the published report R4. We showed that, with this procedure, one can, in principle, estimate all six canopy parameters appearing in the Suits model for homogenous single layer canopies, using only CR data. In other words, we showed that such a Suits model is mathematically totally invertible. We also carried out an analysis of the accuracy of the estimation of canopy parameters as a function of random errors in the CR data using the techniques developed in report R3. We investigated how this accuracy depends upon the nominal values of the canopy parameters, the number of unknown parameters, and the number of solar/view angles for which the CRs are used in the inversion process.

We then applied the techniques for CR model inversion and for analyzing the accuracy of estimation of canopy parameters to two more complex models - the SAIL (scattering by arbitarily inclined leaves) model due to W. Verhoef and N. Bunnick of the National Aerospace Laboratory of the Netherlands and the CUPID model due to J. Norman of the University of Nebraska. Suits model assumes that the leaves are either horizontally or vertically inclined while both of these models allow arbitrary leaf angle distributions (LAD). Both of these models use fraction of leaves at discrete leaf inclination angles as parameters. To minimize the number of unknown canopy parameters, we looked for a simple continuous distribution (with minimal number of parameters) which could represent the leaf angle distribution well. In published report R8, we showed that a simple beta distribution, characterized by two parameters, μ and ν, represents well not only the well-known leaf angle distributions (planophile, plagophile, erectophile, extremophile, uniform and spherical) but also measured distributions for soybean, wheat and blue grama grass canopies. With this simplification, the number of canopy parameters, for both the SAIL and the CUPID models, increased only to 7 from 6 for the Suits' model. We showed that both SAIL and CUPID models are also mathematically totally invertible. The details of the inversion and the error analysis are given in published reports R2 and R5.

The error analysis for all these models showed that when one estimates the canopy parameters using only the bidirectional CR data, for certain nominal values of the canopy paramaters, the estimated value of a parameter can change by several thousand percent when CRs are randomly changed by 1%. This analysis led us to conclude that, in general, for the expected levels of errrors in the measurement of CRs and the accuracy with which these models are likely to represent CR, one <u>can not</u> practically determine the agronomic parameters using <u>CR data alone</u>. Such a determination, in general, will require ancillary data e.g. on the reflectance and transmittance of vegetation elements and on the soil reflectance.

The activities and the results summarized above were all directed towards completing task (1) mentioned in the Introduction. Towards completing the task (2), we implemented a computer program for carrying out the inversion of a CR model. This program is general enough to be usable with any CR model. Using the SAIL model, we tested if the inversion technique can be used to estimate LAI and LAD using measured CR data. In published report R6 we showed that for a fully covered soybean canopy, one can indeed determine fairly accurately the LAI and the average leaf inclination angle (ALA) using measured CR data (collected, using ground based sensors, for about 50 view angles over a period of about 15 minutes) and easy to measure canopy parameters (leaf reflectance and transmittance, soil reflectance, and fraction of diffused skylight). The estimated LAD appears to be somewhat erroneous; it is a narrower distribution (peaked at an angle close to the correct value of ALA) than the observed one.

To determine if the inversion technique can be used to estimate LAI for an inhomogenous canopy such as that for a forest using remotely sensed bidirectional CR data and some (ground) measured ancillary data on spectral and architectural parameters of the canopy, we applied the technique for a black spruce canopy for which the CR data was collected using a C-130 aircraft, equipped with a Thematic Mapper (TM) sensor. In published report R7 we showed that in principle LAI can be estimated. However, because of the complexity and inhomogenity of the black spruce canopy, it can not be accurately determined with just 7 bidirectional CRs which were available. Ideally, one would require measurements of CRs for more solar/view angles. In addition, some improvements on the CR model (e.g. inclusion of shadow effects) so that it represents more accurately the CR of a forest canopy are needed.

We also briefly carried out an analysis of optimal solar/view angles for measuring CR for which the estimation of LAI is likely to be most accurate. The results of this analysis were presented in an oral report (P10) when specific recommendations were made for CR data collection strategy. This strategy was implemented for the field work carried out during the summer of 1984. Whether the concept of optimal solar/view angles is valid or not must await the analysis of this data.

3. FUTURE RECOMMENDED ACTIVITIES

We successfully accomplished the two tasks specified in the contract. The research on the inversion of the canopy reflectance model, which we carried out is obviously not yet complete. We recommend that the following activities, divided into three major categories, all related to the inversion of the CR models be pursued.

(1) Inversion of the One-Dimensional CR Models

The activities in this category could be simply described as the natural continuation of the work already done and summarized in the preceding section. They are essentially of two types:

(a) Additional apsects of inversion and sensitivity analysis of the existing CR models investigated so far (Suits, SAIL, and CUPID models).

(b) Modification of these models to make them more realistic and then the inversion and sensitivity analysis of modified models.

In the first type, we recommend that the following activities be carried out:

(a.1) Use of CR Data in Many Wavelengths or Spectral Bands

As the number of wavelengths or spectral bands increases, the data base for estimating LAI and LAD increases. Thus it can be argued that one could substitute wavelengths for solar/view angles and obtain these agronomic parameters with fewer bidirectional CR measurements. The advantages and disadvantages of using many wavelengths over many solar/view angles should be quantified. Here, it should be noted that as the number of wavelengths increases, the number of ancillary parameters (the spectral parameters like leaf reflectance and transmittance, soil reflectance and fraction of diffused skylight) also increases.

The approach for this quantification is straightforward. It will involve increasing the number of canopy variables and the number of R'_i in Eq. (1), where now the index i will refer to solar/view angles as well as wavelength/band. By trading off CR for various angles with CR for various wavelengths, we hope to arrive at an optimal combination for which LAI and LAD estimation is most accurate. This should then be tested by using available CR data sets on various vegetative canopies.

(a.2) Use of Linear and Non-Linear Transforms of CRs for Various Solar/View Angles and Various Spectral Bands

In the present inversion technique, the measured CRs are fitted to those calculated from a model in a least square fashion. It is not obvious that the choice of such a fit is the best. In other words, if in Eq. (1) one replaces R_i by a linear or non-linear function of several R_is, for different solar/view angles and for different spectral bands, could the sensitivity of F to LAI and LAD change so as to make their estimations more accurate? The basis for raising such a possibility is the well known linear (greenness/brightness) transform of CRs for four MSS bands or seven TM bands. Greenness is very sensitive to LAI and not to soil reflectance while brightness is very sensitive to soil reflectance and not to LAI. Another simillar reason is the concept of angle transform mentioned in the preceding section.

It is recommended that the inversion and sensitivity analysis using various linear and non-linear transforms of CRs for various solar/view angles and for various wavelength bands be carried out. In fact, sensitivity analysis could be used to search for such transforms. The goal should be to choose that form of F which has minimum sensitivity to ancillary variables/parameters (which may have some errors in their measurements) and maximum sensitivity to those (LAI and LAD) which one wishes to estimate by the inversion technique.

(a.3) <u>Inversion of Radiance Data Inside the Canopy</u>

The LAI estimation based upon CR measurements above the canopy involves the use of a model which accurately represents the interaction of downwelling radiation as well the interaction of upwelling radiation, reflected from background, with the canopy elements. On the other hand, if one could measure the radiation flux inside the canopy at various locations and relate it (through essentially "half" of the CR model) to LAI and LAD, it appears that the estimation of LAI and LAD could be simpler and more accurate. The technique for below canopy measurement of sunfleck area for estimating LAI, developed by John Norman, essentially makes use of this simplicity.

It is recommended that the fluxes inside the canopy at different heights, using the simple CR models discussed above, be calculated and then the inversion and sensitivity analysis with these fluxes as the measured variables rather than CRs be carried out. This analysis should then be used to quantify the accuracy of estimation of LAI and LAD for typical canopies and for specifying the most desirable set of measurements (incident solar direction, location of sensors in the canopy, etc.). This work should lead to a rapid method for ground measurement of LAI and LAD which are heretofore labor intensive to measure.

(a.4) <u>Optimal Solar/View Angles for LAI and LAD Estimation</u>

On the basis of sensitivity analysis, we have conjectured that there are certain solar/view angles for which LAI and LAD estimation is likely to be most accurate. The set of these angles varies somewhat with the nature of the canopy but still one could provide some guidelines for selecting these angles for all type of canopies.

We recommend that one should look into details of the interception of radiation by the canopy elements, as imbedded in the above mentioned CR models, as a function of solar/view angles. We expect that one will find that for the optimal angles the gradient of interception as a function of LAI and LAD is maximum. This enquiry, as a function of values of ancillary canopy parameters, should provide a fundamental basis for optimal selection of solar/view angles and wavelengths for the purpose of estimating agronomic variables from the CR data.

Parenthetically we note that if one could identify a small set of optimal solar/view angles for which all the canopy parameters can be determined reasonably accurately from the CR data, then these parameters can be used to calculate bidirectional reflectances for <u>all</u> solar/view angles. These reflectances can then be integerated to find the hemi-spherical reflectance and the vegetation albedo.

(a.5) <u>Angle Transforms for Filtering out Terrain Slope Effects</u>

In the analysis of remotely sensed CR data it is usually assumed that the topography of the scene is flat, i.e., all surfaces or materials are assumed to be viewed at same sensor and illumination angles. In mountainous terrain, however, the local surface normal varies and, consequently, a wide range of effective view and illumination angles are obtained, even for a single image. In these cases the interpretation of CR data could lead to erroneous agrophysical conclusions.

Several authors have tried various correction procedures to improve the results obtained. These approaches are either essentially empirical, making no assumptions concerning the physical behavior of scene elements, or utilize some assumed natural characteristics of the scene element.

It is recommended that the angle transform approach be used to develop a procedure which is minimally sensitive to local surface normal. One specific approach is to characterize the normal to the ground surface with two angles (zenith and azimuth) and calculate the CR reflectances for various illumination/view angles by using one of the above mentioned CR models. Such a calculation is straightforward and is essentially equivalent to using a different set of illumination and view angles. One can then seek transforms of CRs for these angles which are insensitive to the angles defining the normal to the surface. If such transforms can be found (preliminary calculations support such a possibility), then one would have a simple technique to filter out the effects of terrain slope.

We now discuss the recommended activities of the other type involving <u>modifications</u> of the one-dimensional models constantly referred to in the preceding description of recommended future activities. All these activities are designed to make the CR models more realistic and thus to ensure that the estimated values of agrophysical parameters, based on inversion of these models, is more accurate. The following three activities are recommended for future investigation.

(b.1) <u>Inclusion of Specular Reflectance</u>

Current CR models do not adequately account for specular reflectance, (direct mirror-like reflection from first-surface leaves), though it has shown to be quite significant for a number of vegetations and it has been known for some time that leaf reflectance is quite directional. Since the model inversion technique relies on angular variation of the CR data, more accurate representation of the angle dependence is crucial for its success with actual field data.

It is recommended that a model for specular reflectance, based on geometrical optics be developed. This approach is known from the physics literature to work for reflectance from "rough" surfaces. In this approach one will consider leaves as reflecting "facets" of a surface, distributed according to the leaf angle distribution of the canopy. The angular dependence of the specularly reflected radiation will thus be a "trignometrical convolution" of the direction of the incident radiation and LAD. The total reflectance could then be decomposed into the sum of a direct specular part (determined by geometrical optics approach) and a uniformed diffused part (determined by using one of the CR model referred above). Since electromagnetic waves combine according to the superposition principle, this is a very natural and well-justified decomposition.

The modified model should then be subjected to the inversion technique with measured CR data as the input, to determine if the new model does indeed give more accurate values of the agronomic parameters. It should be pointed out that the relative proportions of specular and diffuse components will be taken as an unknown parameter in the inversion process. Its values can then be calculated with the independent measurements of such proportions carried out by Vanderbilt and Grant at LARS using polarized light.

(b.2) <u>Inclusion of Angular Dependence of Leaf Reflectance and Transmittance</u>

In the estimation of LAI and LAD, from the measured bidirectional CR data via inversion of a CR model, the values of leaf reflectance ρ, and transmittance, τ, used are usually measured with incident radiation located in the nadir direction. Such measurements should tend to give a lower value for ρ and a higher value for τ than will be felt by the incident radiation in a typical canopy. Moreover, this differential will be dependent upon the direction of solar radiation, leading to a modification of the dependence of the canopy reflectance on the illumination direction.

It is recommended that the angular dependence of ρ and τ in the CR model be included and the modified model be investigated to determine if the estimated values of the agronomic parameters through the inversion technique improve. The specific dependences to be tried could be guided by the direct experiments on the angular dependence of ρ and τ on the incident and view angles and by various models of leaf reflectance and transmittances.

(b.3) Inclusion of Shadowing Effects

The CR, in the near infrared bands, for low density trees stands has been found to be higher than for high density tree stands rather than the other way around, as implied by the simple canopy reflectance models used so far in the inversion technique. When these models are used for low density tree stands, as to be expected, the estimated values of agronomic parameters are quite erroneously high (see published report R8). It is believed that the higher CR for low density tree stands is due to shadow effects (shadow of a tree on itself, on other trees and on ground).

It is recommended that these simple models be modified to include the shadowing effects. An approach could be geometrical, with trees assumed to be spatially distributed according to a pre-assigned distribution. The amount and nature of shadowing will be dependent on the illumination direction and the effects of shadowing on the measured CR will be dependent on the view direction.

We now describe the recommended future activities.

(2) Inclusion of Atmospheric Scattering

In all the inversions of canopy reflectance models we have neglected the effects of atmospheric scattering of reflected radiation. This simplification was not detrimental because we used CR only in the near infrared band. Also, the CR used in the inversion process were either measured on the ground and/or in very clear sky conditions. For remotely measured CRs, especially in the visible band, the atmospheric effects are obviously very important and for certain atmospheric conditions may in fact dominate. As mentioned above under the discussion of optimal solar/view angles, when atmospheric scattering is neglected high view zenith (and solar zenith) angles are more desirable than low zenith angles, to maximize the accuracy of estimation of agronomic parameters like LAI and LAD. For such angles, however, due to increased radiation path length between canopy and the sensor, the atmospheric scattering effects should tend to be maximum. Therefore, before one could develop an optimal strategy for bidirectional CR measurements one must include atmospheric scattering effects in the model to be inverted or develop methods to "filter out" these effects.

There are two basic approaches to include the effects of atmospheric scattering. One is to treat atmosphere and the vegetation canopy as a single system and solve the radiative transfer equation for complex boundary conditions. Such an approach is being pursued by Gerstl and Diner and Martonchik. The other approach is to use an atmospheric scattering model which generates parameters which can be used in the CR models to couple their outputs to the atmosphere. (Parameters needed are atmospheric transmittance 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.) Such a model then needs to be incorporated into the vegetation CR model.

The first type of approaches are obviously more rigorous, representative and elegant. However, they are still under development anu not be generally available for a few years. Also, it appears that computer time for solving the radiative transfer equation may be excessive enough to preclude it from being an attractive candidate for a CR model to be used in the inversion process (Recall that inversion techniques uses an iterative procedure and in each iteration the CR model is used to calculate CRs for various solar/view angles, for a given set of canopy parameters).

We therefore recommend that the second approach be pursued using atmospheric scattering model, such as due to Dave and/or the LOWTRANS 6 model developed at Hanscom Air Force Base in Massachusetts. These models should then be used to calculate atmospheric scattering for a few model atmospheres that range from "clear" to "murky". Aerosol distributions could be limited to continental spring, continental summer and maritime summer. For each of these distributions, one could choose say, three optical thickness, from low to high.

The incorporation of the atmospheric model with the vegetation canopy reflectance models can be done in the following two ways:

(1) Coupling an atmospheric scattering model with a CR model: One way this can be achieved is by extending a multi-layer canopy model by adding two or three layers atmospheric model at the top. One approach would describe atmospheric parameters in terms of CR model parameters (e.g., scattering cross section expressed in terms of effective LAI and LAD). Another approach simply couples existing atmospheric scattering and CR models so that the lower boundary conditions for the atmospheric model match with the upper boundary conditions for the canopy model. It should be noted that since either approach leads to a combined model whose upper boundary condition is specified by the solar energy curve, a simplification in parameter specification is achieved namely, it will not be necessary to specify fraction of incident diffused radiation.

(2) Treating atmospheric scattering and canopy reflectance models as uncoupled: Here the secondary interactions between 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 separate entities which are coupled

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.

Both of these approaches should be explored. The CR model coupled with atmospheric scattering effects included should then be subjected to the inversion and sensitivity analysis in the same fashion as we have done so far. One could also investigate the possibility of using an angle transform to "filter out" the effects of atmospheric scattering.

Finally, we now describe the recommended research activities in the third major category.

(3) Inversion of Complex Canopy Reflectance Models

Simple CR models represent fairly well only uniform vegetation canopies but are generally inaccurate for canopies with complex geometries such as for crops planted in rows, and for trees. For such canopies, one must resort to complex models.

It is recommended that the inversion and sensitivity analysis of a few such complex models be carried out. The choice of the models will be dependent upon the maturity of a model and the availability of the software implementing the model.

Suits row model is one such candidate. Not only this model is mature and a software package is available, it is simple enough that it can be modified and made more realistic in the same way as described above for the other homogenous models.

Norman and Wells three dimensional model is another potential candidate. Kimes and Kirchner model is still another possibility. (It is somewhat less developed than the Norman and Wells model).

There are other models which are actively being developed. It is quite conceivable that one of these models could be chosen over those mentioned above, depending upon the advancement of the model and the willingness of the author(s) to make the software available to other investigators.

The inversion technique, with these complex models, should then be tested using measured CRs of heterogenous canopies such as those for forests. Such data is being collected by investigators at many institutions (e.g. NASA-Goddard Space Flight Center, NASA-Johnson Space Center, Purdue University - LARS, Oak Ridge National Labs.).

APPENDIX A

REPORTING OF THE PROGRESS AND PUBLICATIONS

In this appendix we will list the reporting of the progress made throughout the tenure of this contract. The reporting was done both in the form of briefing as well as in the form of technical reports and papers by the principal investigator as well as by other personnel associated with the contract. The copies of the slides used in the briefing and reports/papers have already been provided to the Technical Monitor. It should be noted that some of the technical results were only partially supported by this contract.

(a) TECHNICAL PRESENTATIONS AND BRIEFINGS

P1:	N.S. GOEL	"Progress in Scene Analysis Research: Use of Canopy Reflectance Models to Address Critical AgRISTARS Problems" Nov. 30, 1982, AgRISTARS Semi-annual Review, NASA-JSC, Houston.
P2:	N.S. GOEL	"The Use of Vegetative Canopy Reflectance Models in Support of AgRISTARS", Dec. 1, 1982, AgRISTARS Minisymposium, NASA-JSC, Houston.
P3:	N.S. GOEL D.E. STREBEL and R.L. THOMPSON	"On the Estimation of LAI and Other Agronomic Variables Using Canopy Reflectance Model, Especially The Suits Model". March 1, 1983, Quarterly Technical Interchange Meeting, NASA-JSC, Houston.
P4:	N.S. GOEL and R.L. THOMPSON	"On the Estimation of Agronomic Variables from Bidirectional Canopy Reflectance Data", April 29, 1983, NASA-GSFC, Greenbelt.
P5:	N.S. GOEL	"Spectral Techniques for In-Situ Measurement of LAI", May 1, 1983. Biological Productivity Experiment Review, NASA-JSC, Houston.
P6:	N.S. GOEL and R.L. THOMPSON	"Estimation of Agronomic Variables Using Spectral Signatures", Sept. 12, 1983, Plenary Session. Intl. Colloq. on Spectral Signatures of Objects in Remote Sensing, Bordeaux, France.
P7:	N.S. GOEL	"Estimation of Agronomic Variables Using Canopy Reflectance Data", Oct. 19, 1983. Quarterly Technical Interchange on 'Assessing Key Vegetation Characteristics from Remote Sensing', NASA-JSC, Houston.

P8:	N.S. GOEL	"Estimation of LAI with Nadir View Spectral Reflectance Data - Some Comments", October 20, 1983, NASA-JSC, Houston.
P9:	N.S. GOEL and R.L. THOMPSON	"CUPID Model and LARS Soybean Data", Oct. 20, 1983. Workshop on 'Modeling of Crop Reflectance', NASA-JSC, Houston.
P10:	N.S. GOEL and R.L. THOMPSON	"Optimal Illumination/Viewing Geometries for Remote Sensing of Agronomic Variables", Nov. 7, 1983, NASA-GSFC, Greenbelt.
P11:	N.S. GOEL	"Agronomic Parameters from Bidirectional Canopy Reflectances", Jan. 10, 1984. Second Meeting of the NASA Fundamental Research Scene Radiation and Atmospheric Effects Characterization, Colorado State University, Fort Collins.
P12.	N.S. GOEL	"Agronomic Variables from Canopy Reflectance Data", March 9, 1984, Canadian Center for Remote Sensing, Ottawa.
P13:	N.S. GOEL	"Advanced Optical Techniques for LAI Estimation - Inversion of Models", April 24, 1984. COVER Experiment Review on 'Characterization of Vegetation with Remote Sensing' NASA-JSC, Houston.
P14:	N.S. GOEL	"Optimal Illumination/Viewing Directions to Maximize the Accuracy of Estimation of LAI and LAD", April 25, 1984. COVER Experiment Review on 'Characterization of Vegetation with Remote Sensing', NASA-JSC, Houston.
P15:	N.S. GOEL K.E. HENDERSON and D.E. PITTS	"Estimation of LAI from Bidirectional Canopy Reflectance", June 14, 1984. 10th Intl. Symp. on Machine Processing of Remotely Sensed Data, Purdue University.

(b) PUBLISHED REPORTS/PAPERS

R1:	N.S. GOEL and D.E. STREBEL	"Inversion of Vegetation Canopy Reflectance Models for Estimating Agronomic Variables I: Problem Definition and Initial Results Using Suits' Model". Remote Sensing of Environment, Vol. 13, Pages 487-507, 1983.
R2:	N.S. GOEL and R.L. THOMPSON	"Estimation of Agronomic Variables Using Spectral Signatures". Proceedings of International Colloquim on Signatures of Remotely Sensed Objects. Bordeaux, France, Sept. 12-16, 1983.

R3: N.S. GOEL, D.E. STREBEL and R.L. THOMPSON — "Inversion of Vegetation Canopy Reflectance Models for Estimating Agronomic Variables II: Use of Angle Transforms and Error Analysis as Illustrated by the Suits' Model". Remote Sensing of Environment. Vol. 14, Pages 77-111, 1984.

R4: N.S. GOEL and R.L. THOMPSON — "Inversion of Vegetation Canopy Reflectance Models for Estimating Agronomic Variables III: Estimation Using only Canopy Reflectance Data as Illustrated by the Suits' Model". Remote Sensing of Environment. Vol. 15, Pages 223-236, 1984.

R5: N.S. GOEL and R.L. THOMPSON — "Inversion of Vegetation Canopy Reflectance Models for Estimating Agronomic Variables IV: Total Inversion of the SAIL Model". Remote Sensing of Environment. Vol. 15, Pages 237-253, 1984.

R6: N.S. GOEL and R.L. THOMPSON — "Inversion of Vegetation Canopy Reflectance Models for Estimating Agronomic Variables V: Estimation of LAI and Average Leaf Angle Using Measured Canopy Reflectances". Remote Sensing of Environment. Vol. 16, Pages 69-85, 1984.

R7: N.S. GOEL, K.E. HENDERSON and D.E. PITTS — "Estimation of Leaf Area Index from Bidirectional Spectral Reflectance Data by Inverting a Canopy Reflectance Model". Proceedings 1984 International Symposium on Machine Processing of Remotely Sensed Data. Purdue University, June 12-14, Pages 339-347.

R8: N.S. GOEL and D.E. STREBEL — "Simple Beta Distribution Representation of Leaf Orientation in Vegetation Canopies". Agronomy Journal. (to appear in Sept. 1984.)

APPENDIX B

FIRST PAGES OF THE REPORTS/PAPERS WHICH HAVE BEEN PUBLISHED

In this appendix, we have attached the first pages of the various reports/papers which have been published and which were listed in the preceding appendix.

Published Paper R1

REMOTE SENSING OF ENVIRONMENT 13:457-507 (1983) 457

Inversion of Vegetation Canopy Reflectance Models for Estimating Agronomic Variables. I. Problem Definition and Initial Results Using the Suits Model

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An important but relatively uninvestigated problem in remote sensing is the inversion of vegetative canopy reflectance models to obtain agrophysical parameters, given measured reflectances. The problem is here formally defined and its solution outlined. Numerical nonlinear optimization techniques are used to implement this inversion to obtain the leaf area index using Suits' canopy reflectance model. The results for a variety of cases indicate that this can be done successfully using infrared reflectances at different views or azimuth angles or a combination thereof. The other parameters of the model must be known, although reasonable measurement errors can be tolerated without seriously degrading the accuracy of the inversion. The application of the technique to ground based remote-sensing experiments is potentially useful, but is limited to the degree to which the canopy reflectance model can accurately predict observed reflectances.

1. Introduction

When electromagnetic radiation is incident on a vegetation canopy, it is scattered and reflected, and its direction and spectral composition are altered in a complex manner by the vegetation. For the purpose of agricultural monitoring by remote sensing, part of this altered and reflected radiation is intercepted by a satellite-borne sensor. The success of this monitoring method depends upon being able to relate reflectance measurements to vegetation properties. One expects that this can be done once the nature of the alteration in the radiation by the agrophysical and environmental factors is specified.

Over the last two decades there have been fairly intensive investigations, both experimental and theoretical, attempting to understand the relationship between vegetation and environment variables and the spectral reflectance. These investigations have identified the key variables. On the theoretical side, one type of study has been the modeling of crop canopy reflectance (see Goel, 1982; Smith, 1982 for reviews of various models). Here one defines or derives a function or an algorithm which yields the reflectance given the variables specifying the canopy. These variables generally include: optical properties of the vegetation components, e.g., wavelength (λ) dependent reflectance and transmittance of leaves, stalks, heads, etc.; physical parameters defining the canopy geometry, e.g., density, angular inclination, and distribution of vegetation components; variables defining the soil, e.g., λ-dependent reflectance of soil; variables defining source of radiation (sun) and the properties of the detector, e.g., sun zenith angle, detector (observer) zenith and azimuth (with respect to the sun) angles. On the experimental side, an extensive amount of data has been col-

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0034-4257/83/$3.00

Published Paper R2

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ESTIMATION OF AGRONOMIC VARIABLES USING SPECTRAL SIGNATURES

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SUMMARY

A technique for inverting a canopy reflectance model to estimate agronomic variables, using spectral signatures in the infrared region, is described. Its use is illustrated, for a soybean canopy, using a few representative models, due to Suits, Verhoef and Bunnik, and Norman. An analysis of the sensitivity of the estimated agronomic variables, like leaf area index and leaf angle distribution, to random errors in the canopy reflectance data is presented.

(Paper to be presented at the Int. Colloq. on Spectral Signature of Objects in Remote Sensing, Bordeaux, France. Sept. 12-16, 1983.)

Published Paper R3

REMOTE SENSING OF ENVIRONMENT 14:77–111 (1984) 77

Inversion of Vegetation Canopy Reflectance Models for Estimating Agronomic Variables. II. Use of Angle Transforms and Error Analysis as Illustrated by Suits' Model

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The technique for inverting a vegetation canopy reflectance model described earlier (Goel and Strebel, 1983) is investigated further. The novel concept of an "angle transform" is introduced. This concept allows the formation of functions of reflectances at different view zenith and azimuth angles, which are either sensitive or insensitive to a certain agronomic parameter. A proper combination of these functions can allow determination of all the important agronomic and spectral parameters from measured canopy reflectance data. The technique is demonstrated using Suits' (1972) model for homogenous canopies. It is shown that leaf area index, leaf reflectance and transmittance, and average leaf angle all can be determined from the canopy reflectance at a set of selected view zenith and azimuth angles. A sensitivity analysis of the calculated values to the errors in the data is also carried out. Guidelines are formulated for the number and types of observations required to obtain the values of a particular canopy variable to within a given degree of accuracy for a given level of error in the measurement of canopy reflectance.

1. Introduction

The estimation of agronomic parameters from reflectance data is an important practical problem. In the first paper in this series (Goel and Strebel, 1983; hereafter referred to as I), we defined this problem formally and in some detail. The procedure for estimation involves inversion of a vegetative canopy reflectance model. This inversion was illustrated for two parameters, although it was noted that the use of more reflectance measurements would allow the determination of more parameters. Here we extend the method by showing how six reflectance data points, for different view directions, can be used to obtain four parameters, and how additional data can be used to improve the accuracy with which those parameters are determined when measurement errors are present.

We shall emphasize that an accurate estimation of agronomic parameters from the measured canopy reflectance data has two key ingredients:

(1) A canopy reflectance model which represents a canopy accurately.
(2) A procedure for inverting such a model.

In our initial studies, to focus our attention on developing techniques for inverting canopy reflectance models, we simulate the observed canopy reflectances That is, we choose a certain set of values for the parameters occurring in a model and use them to calculate the canopy reflectances. The parameters are then "forgotten," and the calculated reflectances are taken as the observed ones. These "error-free" reflectances are then

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Published Paper R4

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REMOTE SENSING OF ENVIRONMENT 15:223–230 (1984)

Inversion of Vegetation Canopy Reflectance Models for Estimating Agronomic Variables. III. Estimation Using Only Canopy Reflectance Data as Illustrated by the Suits Model

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The technique for estimating agronomic and spectral parameters for a vegetation canopy from the canopy reflectance (CR) data, described earlier (Goel et al., 1984), has been improved. These improvements are twofold: first, one can now, in principle, estimate various parameters using only CR data, in the infrared band, for a set of solar/view angles; second, the method is now computationally much more efficient. These improvements are illustrated via Suits' model. An analysis of the sensitivity of the calculated agronomic and spectral parameters to changes in the CR is also carried out. This analysis suggests that, in general, for expected levels of errors in the measurement of CRs and the accuracy with which the Suits model is likely to represent CR, one is unlikely to be able to estimate agronomic parameters like leaf area index (LAI) and average leaf angle (ALA) using only measured CR data. Such a determination will likely require ancillary data on the reflectance and transmittance of vegetation elements and on the soil reflectance.

1. Introduction

One of the most desirable goals of the research on the remote sensing of vegetation canopies is to be able to estimate key agronomic parameters like leaf area index (LAI) and leaf angle distribution (LAD), using only canopy reflectance (CR) measurements. LAI is perhaps the most important variable for determining growth and yield. Though LAD is not of the same importance as LAI, it is a possible indicator of plant stress level. With the goal of estimating agronomic parameters, many systematic theoretical and experimental investigations have been carried out in the last quarter of a century. These investigations have led to the clarification and quantification of the relationship between these and other parameters describing the spectral properties of vegetation elements and soil, incident solar flux, and viewing directions and the canopy reflectance in various wavelength bands (Ross, 1981; Goel, 1982).

Our investigations have focused on developing an approach for obtaining agronomic parameters by inverting a CR model which represents the relationship between canopy parameters and CR. For this purpose we have initially chosen the Suits model (Suits, 1972) for a homogeneous canopy. In the first paper in this series (Goel and Strebel, 1983; hereafter referred as I), we defined this problem formally. We showed that one could, in principle, estimate LAI and average leaf angle (ALA) using CR data, in the infrared band, for several view angles, provided one knows the other auxiliary parameters like canopy component (e.g., leaf) reflectance ρ, and transmittance τ, soil reflectance ρ_s, and fraction of diffused incident solar radiation, SKYL. In the second paper in this series (Goel et al., 1984; hereafter referred as II), we

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Published Paper R5

REMOTE SENSING OF ENVIRONMENT 15:237–253 (1984)

Inversion of Vegetation Canopy Reflectance Models for Estimating Agronomic Variables. IV. Total Inversion of the SAIL Model

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The estimability of all the canopy parameters for a vegetation canopy using only canopy reflectance (CR) data and the SAIL model is investigated, using techniques described earlier (Goel and Thompson, 1984a). It is shown that in principle such an estimation is possible, i.e., the SAIL model is mathematically totally invertible. An analysis of the sensitivity of the calculated values to changes in the CR data is presented. This analysis suggests that, given the expected accuracy of CR measurements and the accuracy of the SAIL model in representing CR in the infrared region, the agronomic parameters, leaf area index, and leaf angle distribution, can be estimated fairly accurately using ancillary data on spectral parameters.

1. Introduction

Remote sensing of vegetation relies on the spectral signatures of the vegetation, in particular, the signatures in the visible and infrared regions. During the last 25 years or so, many models (Goel, 1982; Ross, 1981) at different levels of complexity have been developed. They attempt to provide a realistic relationship between the important agronomic and spectral parameters of the vegetation canopy and its canopy reflectance (CR) signatures. The agronomic parameters are leaf area index (LAI) and leaf angle distribution (LAD). The spectral parameters include leaf reflectance ρ and transmittance τ. A desirable application of these models is the estimation of these parameters from the measured reflectances.

In this series of papers (Goel and Strebel, 1983; Goel et al., 1984; Goel and Thompson, 1984a) we have been investigating the possibility of such an estimation, using CR data in the infrared region for a set of solar/view directions. In the preceding paper of this series (Goel and Thompson, 1984a; henceforth referred to as III), we have shown that such an estimation is possible, in principle, for the Suits model (Suits, 1972) for a homogenous canopy. The parameters occurring in this model are the leaf reflectance and transmittance, leaf area index and average leaf inclination angle θ_1, soil reflectance ρ_s, and the fraction of diffused incident solar radiation (SKYL). Specifically, we showed that all of these parameters can be estimated using only CR data and the Suits model, provided that the Suits model is an accurate representation of canopy reflectance and that the reflectance measurements are accurate. In other words, the Suits model is mathematically totally invertible. We also analyzed the sensitivity of the parameters estimated by model inversion to changes in the CR data.

In this paper we apply the techniques developed in III to a more complex model —the so-called SAIL (scattering by arbitrarily inclined leaves) model due to

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Published Paper R6

REMOTE SENSING OF ENVIRONMENT 16:69-85 (1984)

Inversion of Vegetation Canopy Reflectance Models for Estimating Agronomic Variables. V. Estimation of Leaf Area Index and Average Leaf Angle Using Measured Canopy Reflectances

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The technique described earlier (Goel and Thompson, 1984b) for estimating agronomic parameters from bidirectional crop reflectance data is applied to a fully covered soybean canopy, using data measured in the field. This technique employs the inversion of a canopy reflectance model. It is shown that using the SAIL model one can estimate leaf area index (LAI) as well as average leaf angle (ALA) quite well, provided that the other canopy parameters (leaf reflectance and transmittance, soil reflectance, and fraction of diffused skylight) are known. Some suggestions are made for improving the SAIL model. This should improve the accuracy of estimation of not only LAI and ALA but should also allow the estimation of the complete leaf angle distribution.

1. Introduction

It is now very well established that the reflectances, in the visible and infrared regions, from a vegetation canopy are strongly correlated to the agronomic and spectral parameters of the canopy. The agronomic parameters include leaf area index (LAI) and leaf angle distribution (LAD). The spectral parameters include leaf reflectance ρ and transmittance τ. This correlation has been quantified by many canopy reflectance (CR) models (see Goel, 1981; Smith, 1983; Ross, 1981 for reviews of some of these models). It will be very desirable to exploit this correlation to estimate the agronomic parameters from the measured canopy reflectance data.

In this series of papers (Goel and Strebel, 1983; Goel et al., 1984; Goel and Thompson, 1984a, b) we have been investigating the possibility of such an estimation, using CR data in the infrared region for a set of solar and view directions. We have shown that such an estimation is, in principle, possible at least for a homogeneous vegetation canopy. The procedure involves the inversion of a canopy reflectance model. In the preceeding paper of this series (Goel and Thompson, 1984b) and in another paper (Goel and Thompson, 1983) we showed that one can determine all the canopy parameters occurring in the SAIL model (Verhoef and Bunnik, 1981) and in the CUPID model (Norman, 1979) using only CR data in the infrared region. The parameters occurring in these models are the leaf reflectance and transmittance, leaf area index, and leaf inclination angle distribution (LAD), soil reflectance ρ_s, and the fraction of diffused incident solar radiation, SKYL. Thus all of these parameters can be estimated using only CR data and these models, provided that these models accurately represent measured canopy reflectances.

To focus our initial attention on developing techniques for estimating canopy parameters, we have so far simulated the observed canopy reflectances in our stud-

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Published Paper R7

ESTIMATION OF LEAF AREA INDEX FROM BIDIRECTIONAL SPECTRAL REFLECTANCE DATA BY INVERTING A CANOPY REFLECTANCE MODEL

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ABSTRACT

A technique for estimating the leaf area index from bidirectional canopy reflectance (CR) data, in the infrared region, e.g., in band 4 of a Thematic Mapper (TM), is described. It involves inversion of a CR model which accurately represents the reflectance from the canopy. A method for remotely collecting this CR data using an aircraft based TM is described. The bidirectional CR's, for a black spruce (*picea mariana*) canopy, for 7 solar/view directions, as measured using this technique, are given. A very preliminary analysis of the data from a point of view of estimating LAI by inversion of a CR model is given. This analysis suggests that for an acceptably accurate estimation of LAI, one will require bidirectional CR's for many more than 7 solar/view directions.

I. INTRODUCTION

It is now very well established that the reflectance, in the visible and infrared regions, from a vegetation (crop, grassland, and forest) canopy is strongly correlated to the agronomic, architectural, and spectral parameters of the canopy. Remote sensing of vegetation relies on this correlation. The agronomic parameters include the densities and orientations of vegetation components like leaves, stems, branches, and bark. The architectural parameters include spatial distributions, both in horizontal and vertical directions, of vegetation components. The spectral parameters include reflectances and transmittances of these components. In addition, the canopy reflectance (CR) depends upon the ground (soil, moss, disintegrated vegetation etc.) reflectance and the relative fraction, SKYL, of the diffused incident solar radiation.

During the last quarter of a century, many models (see Ross, 1981; Goel, 1982; and Smith, 1983 for reviews of these models) at different levels of complexity, have been proposed to provide a realistic relationship between important canopy parameters and canopy reflectance. With these CR models one can, in principle, calculate the canopy reflectance as a function of the illumination and view directions (bidirectional CR), using the measured values of the canopy parameters, ground reflectance, and incident diffused radiation. A desirable application of these models is the estimation of important agronomic parameters like leaf area index (LAI) from the measured bidirectional CR's by carrying out such calculations in "reverse", i.e., by inverting a CR model.

One of the authors and his collaborators (Goel and Strebel, 1983; Goel, Strebel and Thompson, 1984; Goel and Thompson, 1984a,b,c) have investigated the possibility of such an estimation, using CR data in the infrared region, for a set of solar/view directions. We have shown that such an estimation is, in principle, possible, at least for a homogenous canopy. Specifically, we have shown that at least for three CR models - the Suits model (Suits, 1972), the SAIL model (Verhoef and Bunnik, 1981), and the CUPID model (Norman, 1979), there is a one to one relationship between the canopy parameters and the bidirectional CR. That is, all the canopy parameters can be estimated uniquely using only CR data, provided of course these models accurately represent the measured CR's. We also applied this canopy reflectance model inversion technique to field measured CR's for a set of view directions. We have shown (Goel and Thompson, 1984c) that one can estimate quite accurately the leaf area index (LAI) as well as the average leaf inclination angle (ALA) for a homogenous fully covered soybean canopy, using CR data for about 50 view directions, provided that the other canopy parameters like leaf reflectance and transmittance, soil reflectance and

Published Paper R8

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[1] Contribution from the Dep. of Systems Science, State Univ. of New York (SUNY), Binghamton, NY. Received 18 Nov. 1983. Published in *Agron J.* 76:000-000.

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Simple Beta Distribution Representation of Leaf Orientation in Vegetation Canopies[1]

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ABSTRACT

It is shown that a two-parameter beta distribution represents very well the leaf angle distribution for a variety of vegetation canopies. Comparison to theoretical distributions as well as field data suggests that this distribution be considered as a candidate for a "universal" leaf angle distribution. The parameters of the distribution can then be used to identify and classify intermediate canopy types and possibly to quantify canopy changes caused by environmental stress.

Additional index words: Leaf angle distribution, Crop classification, Remote sensing.

THE arrangement of leaves in a plant canopy influences the interaction of electromagnetic radiation with the plants. In particular, photosynthesis and yield are determined by the light distribution within the canopy and hence by the azimuth, inclination, and spatial distributions of leaves. These distributions also determine the radiation reflected from the canopy, thus influencing the spectral signature used for the purpose of remote sensing (Smith, 1983). It is therefore important to have a good way to describe the leaf distribution.

The distribution of leaf inclination and azimuth angles vary from crop to crop and may also be dependent on the growth stage of the crop (Ross, 1981) or even the time of the day (Kimes and Kirchner, 1983). One may expect changes also to be correlated with stress and hence changes in these distributions could be used to quantify the stress. For species with no preferred azimuth direction, de Wit (1965) and others (Ross, 1981; Smith, 1982) have developed several special distributions to characterize the leaf angle distribution (LAD) which distinguish major kinds of plant canopies. These types are: (1) planophile—horizontal leaves most frequent (2) erectophile—vertical leaves most frequent, (3) plagiophile—oblique leaves most frequent, (4) extremophile—oblique leaves least frequent, (5) uniform—same proportion of leaves at any angle, and (6) spherical—leaf angle frequency same as for surface elements of a sphere. This case by case approach, though is somewhat limited in analyzing intermediate canopy types or the range of variation within a canopy type.

In this note we propose that the well-known two parameters beta distribution (Hastings, 1975) ...