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FEASIBILITY OF USING LANDSAT IMAGES OF VEGETATION COVER TO ESTIMATE EFFECTIVE HYDRAULIC PROPERTIES OF SOILS

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by

Peter S. Eagleson

Edmund K. Turner Professor of Civil Engineering

Massachusetts Institute of Technology

Cambridge, Massachusetts 02139

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INTRODUCTION

This report summarizes research activities conducted from February 1, 1985 to July 31, 1985 and preliminary conclusions regarding research objectives. The overall objective is to determine the feasibility of using Landsat data to estimate effective hydraulic properties of soils. The general approach is to apply Eagleson's "climatic-climax" hypothesis (Eagleson, 1982) to natural water-limited vegetation systems using canopy cover estimated from Landsat data.

Natural water-limited systems typically consist of inhomogeneous vegetation canopies interspersed with bare soils. The ground resolution associated with one pixel from Landsat MSS (or TM) data is generally greater than the scale of the plant canopy or canopy clusters. Thus a method for resolving percent canopy cover at a subpixel level must first be established before the Eagleson hypothesis is tested.

Specific project objectives are thus,

1. Evaluate the existing capability of defining vegetation canopy density from Landsat data with a resolution and accuracy sufficient for use in testing the climatic-climax hypothesis of climate-soil-vegetation equilibrium.

2. Design the research needed to create the necessary capability if it is found (under Objective 1) to be deficient.

3. Design the series of experiments necessary to test the climatic-climax hypothesis.

One major conclusion of the work to date is that current methods for resolving mixed pixels, which have been developed primarily for agricultural lands, have not been adequately tested on natural landscapes.

Methods which require the identification of training samples can not be easily applied to naturally vegetated systems due to the inhomogeneity of the cover.

Two formulations are proposed which extend existing methods of analyzing mixed pixels to naturally vegetated landscapes. The first method involves use of the normalized vegetation index. The second approach is a physical model based on radiative transfer principles. Both methods will be analyzed for their feasibility on selected sites during the second half of this research project.

RESEARCH ACTIVITIES

The reporting period covers the initiation of work on this topic. Accordingly, research activities have included a visit to the Goddard Space Flight Center, Greenbelt, Maryland, comprehensive literature review, the preliminary formulation of algorithms to determine percent canopy cover at a subpixel scale of resolution, and the search for several representative watersheds in which to conduct the research. Details of each of these activities are described below.

Visit to Goddard Space Flight Center, Beltsville, Maryland

Research commenced with a visit by the principal investigator, Professor Peter S. Eagleson, and his assistant, Michael F. Jasinski, to the Earth Resources and Hydrological Sciences Branches, Goddard Space Flight Center (GSFC) on January 31, 1985. The purpose of the visit was to familiarize the MIT researchers with ongoing activities at GSFC and to discuss research goals with key GSFC personnel. Meetings were held with Dr. Vincent V. Salomonson, Dr. Robert Gurney, and Dr. Thomas J. Schmugge, among others. Image analysis of MSS data was demonstrated by James

Ormsby. During the afternoon, Professor Eagleson presented a seminar on water-limited equilibrium of savanna vegetation systems, work supported under a prior NASA research grant.

Literature Review

Ongoing literature review has concentrated on assessing the current capability of estimating percent canopy cover using Landsat data. Current techniques for classifying agricultural lands including those over mixed-crop types have been reviewed. The reflectance properties of vegatation canopies and soils in the visible and near infrared range have been investigated. This has required a review of the theoretical principles of radiative transfer through leaves, the atmosphere, and other media.

Vegetation Canopy and Soil Reflectance.

The reflectance of the visible and near infra-red range is well documented. Canopy reflectances are typically much less than those measured for individual leaves (Dickinson, 1983) due to the scattering properties of plant architecture and soil background. Colwell (1975) discussed the important parameters which influence canopy reflectance, including leaf hemispherical transmittance, leaf area and orientation, plant structure components, soil reflectance, solar zenith angle, look angle, and azimuth angle. Tucker et al. (1977) found that the effect of underlying soil decreases as vegetation biomass increases. The results of numerous studies of plant and canopy reflectance are summarized in Rosenberg et al. (1983), Smith (1983) and Myers (1983).

Radiative transfer formulas for homogeneous canopies have been developed in terms of the physical and optical properties of the plant and background soil reflectance (Suits, 1972; for summary of other formulas see

Smith, 1983). Typically, homogeneous canopies have been modeled as a diffusing medium with absorbing and scattering properties. Dickinson (1983) applied the two-stream approximation for radiation transfer in the atmosphere (Meador et al., 1980) to plant canopies employing the Leaf Area Index (LAI) as a measure of the optical depth.

The reflectivity of plant canopies is highly wavelength dependent. It is typically low in the visible spectrum (<30%) and high in the near infrared range (>50%). Kondratyev (1969) and Iqbal (1983) provide summaries of reflectances of various natural vegetation covers.

The spectral characteristics of bare soils have also been extensively investigated, as summarized by Meyers (1983). Soil reflectance is a function of color, mineral content, organic matter, particle size, texture, moisture content, and wavelength. Soil reflectance is generally less than 30% and increases linearly with wavelength over the range 0.4 - 1.0 μm. Wet soils exhibit lower reflectance than dry soils but generally maintain a similar linear behavior in reflectance over that range (Tucker et al., (1977).

<u>Reflectance from Natural Landscapes</u>

The reflectance from natural landscapes results from the complex interaction of light with the vegetation canopy and soil types. The canopy alone often consists of a mixture of various plant species of different sizes and architectures. Soil types can also vary over a short distance. The radiance observed by a Landsat satellite is a composite of those canopy and soil components which are subsequently scattered and attenuated by the atmosphere.

The identification of landscapes which consist of several cover types is a common problem encountered by image analysts. Both empirical classification schemes as well as more physically-based models have been developed, although empirical methods are the most widely used and by far the most successful (Estes et al., 1983). Classification methods have been used in conjunction with temporal analysis to take full advantage of seasonal vegetation changes (Robinove, 1981, Amis et al., 1981; for summary see Estes et al., 1983).

Classification of cropland has relied on various statistical clustering algorithms, such as those used in the Large Area Crop Inventory Experiment (LACIE) (Lennington et al., 1984, Amis et al., 1981). These methods generally require the identification of training samples or pure pixels, i.e., the association of Landsat observations with known targets. Each training sample consists of a soil and canopy combination with a spectral response representative of a larger area. This advantage is usually not present when classifying natural landscapes, since most targets possess unique spectral characteristics.

The following sections describe several techniques which have evolved for analyzing non-uniformly vegetated landscapes.

Vegetation Indices. Semi-empirical methods for reducing the amount of MSS data have led to the development of the vegetation index (VI). The use of the VI for identifying vegetation parameters has received much attention in the last few years. Perry et al. (1984) summarize the numerous VI's which have been proposed. A typical VI is a normalized ratio of the form,

$$VI = \frac{a_{IR} - a_{VIS}}{a_{IR} + a_{VIS}}$$

where a_{IR} and a_{VIS} represent the surface albedo in the IR and visible ranges, respectively. Low VI indicates low vegetation amount, whereas high VI indicates either high vegetation amount or high productivity (Curran, 1980). Sellers (1985) discussed the functional relationship between normalized VI and several vegetation parameters, including the Leaf Area Index (LAI), greenness, and photosynthetic rate. Tucker et al. (1983) correlated a normalized VI (computed from NOAA's AVHRR data) to actual biomass obtained from field sampling in a semi-arid region of Senegal, West Africa. However, much scatter of the data exists. Recently, the effect of soil background on VI's computed from hand-held or airborne radiometer data has been evaluated (Elvidge et al., 1985, Huete et al., 1985).

While the functional relationship between the VI and several vegetation parameters has been qualitatively identified, the quantification of these parameters (based on VI's computed using Landsat data) has attained only limited success. Additional research is warranted in at at least two areas. First, the functional relationship between the VI and percent canopy cover needs to be clearly established. Secondly, the usefulness of the VI in analyzing natural landscapes needs to be examined.

Theoretical Models. The problem of resolving a mixed-pixel has been approached by assuming that its total spectral response is a linear combination of the individual spectral responses of its components (McCloy, 1980; Dozier, 1981; Ungar et al., 1981; Chhikara, 1984). McCloy (1980) proposed that under conditions of negligible canopy transmission or multiple reflection, the response proportions of the various land covers will closely approximate the physical proportions of each type of cover. McCloy (1980) suggested that up to four sub-pixel categories be used including three levels of vegetation greenness cover and one soil background cover.

Ungar et al. (1981) reported successful delineation of forest canopy types in Maine using a similar approach which they termed the "Fanning algorithm". Ungar et al (1981) assumed that the total radiance received from a mixed pixel, L_λ, can be expressed

$$L_\lambda = \eta A_\lambda + (1-\eta) B_\lambda \qquad (2)$$

where A_λ and B_λ are the energies received in the λ th band from sub-pixel surface elements A and B, respectively. The coefficient η is the fractional area occupied by cover type A. The value η was determined by Ungar et al (1981) by minimizing the error between observed and theoretical radiances.

Dozier (1981) also proposed a similar method using two infrared bands for differentiating radiant temperature fields of sub-pixel spatial resolution. Corrections for atmospheric effects were included.

The theoretical nadir radiance observed by a satellite has been derived by several authors (Dave 1980, Otterman et al. 1979, 1980, and Otterman 1978, 1981) for a pure pixel in a background of different reflectivity. The nadir radiance is expressed in terms of three components. The direct beam from the object pixel which has been attenuated due to atmospheric effects, $L_{nr\lambda}$, is

$$L_{nr\lambda} = r\, G_t \exp(-\tau)/\pi \qquad (3)$$

where r = reflectivity of object pixel

G_t = global surface irradiance on object pixel

τ = total vertical optical thickness.

The total optical thickness is a sum of optical thicknesses due to Rayleigh scattering by gas molecules, τ_R, and Mie scattering by aerosols, τ_M.

Assuming a Lambertian surface, the portion of diffuse radiance from the surrounding vicinity which is scattered to the satellite by the atmospheric column above the object pixel is

$$L_{na\lambda} = (a\, G_t/\pi\tau) \int_0^{\pi/2} [1-\exp(-\tau/\cos\phi)] \cos\phi [\tau_R P_R(\phi) + \tau_M P_M(\phi)]\; 2\pi \sin\phi\, d\phi \quad (4)$$

where

- a = average reflectivity of the surrounding vicinity
- P_R, P_M = phase functions associated with Rayleigh and aerosol (Mie) scattering, respectively
- ϕ = zenith reflection angle.

Finally, the radiance scattered from the direct solar beam back to the satellite is written

$$L_{nd\lambda} = \frac{\mu_o [1-\exp[-\tau(1+\sec\theta_o)]] [\tau_R P_R(180^\circ - \theta_o) + \tau_M P_M(180^\circ - \theta_o)]}{\tau(1+\mu_o)} \quad (5)$$

where $\mu_o = \cos\theta_o$

θ_o = solar zenith angle

The total nadir radiance is the sum of equations (3), (4) and (5). The amount of area to be considered in determining the average surrounding reflectivity is discussed by Otterman et al. (1979). Otterman et al. (1980) reduced the above equations to a simpler form in the case of an optically thin atmosphere. Otterman (1981) also developed an expression for reflection from sparsely vegetated soils in terms of a surface cover parameter. While accounting for the shadowing effects of vegetation clumps, the formulation assumes that reflection from the top of the clumps is negligible. Thus, this method is not directly applicable to the determination of percent canopy cover.

Summary of Literature Review.

The literature review has led to the following conclusions regarding techniques available to estimate canopy cover at a subpixel level of resolution:

1) Techniques for evaluating mixed-pixels have focused primarily on distinguishing cropped lands. Most techniques require the identification of training samples, which prevent their application to inhomogeneous canopies. The application of these methods to natural landscapes has received very limited attention and needs to be developed further.

2) While the correlation of the VI with several vegetation parameters, such as biomass or greenness, has demonstrated definite success, no quantitative information has been found relating the VI to percent canopy cover. Further, the use of VI over natural landscapes has received little, if any, attention.

3) The theoretical framework for modeling the observed vegetation cover from satellites exists, but has been tested only to a limited degree. No studies reviewed applied the modeling approach to semi-arid systems. Current available models need to be extended to model a mixed target pixel. The substantial amount of information on plant canopy and soil reflectances will facilitate testing of a theoretical model.

Formulation of Percent Canopy Cover Algorithms

Two approaches for determining the percent canopy cover at a sub-pixel scale of resolution have been formulated based on the empirical and theoretical relationships reviewed above. A first approach involves developing an empirical or semi-empirical relationship between the normalized vegetation index and the percent canopy cover. A theoretical approach involves adapting the developments of Otterman (1978, 1981), Otterman et al. (1979, 1980), Dave (1980), Ungar et al. (1981), Dozier (1981), and McCloy (1980) to a mixed target pixel. Both procedures can be verified using ground truth obtained from existing photographs.

Empirical Approach

Since the canopy cover is functionally related to other plant and soil parameters (Rosenberg et al., 1983), it is reasonable to expect good correlation between the normalized vegetation index and percent canopy cover. The first approach being considered is simply to test this hypothesis using MSS data and ground truth obtained from existing aerial photographs.

Several variations to the simple correlation scheme are envisioned. For instance, it is possible that the presence of only a few pure or nearly pure pixels (either completely bare soil or completely green vegetation) may be sufficient for providing bounds on the range of the numerical value of the VI which occurs within the segment. These bounds would appear at the extreme ends of a histogram indicating the number of occurrences versus VI as shown in Figure 1. Once these end points are defined, the relative percentage of each cover type can be estimated by methods reviewed earlier.

The validity of this approach relies on the assumption that there exists a clear distinction between soil and canopy reflectances, and that the inhomogeneities within the two separate classes are smaller than those between the soil and canopy. The assumption is more apt to be valid if the

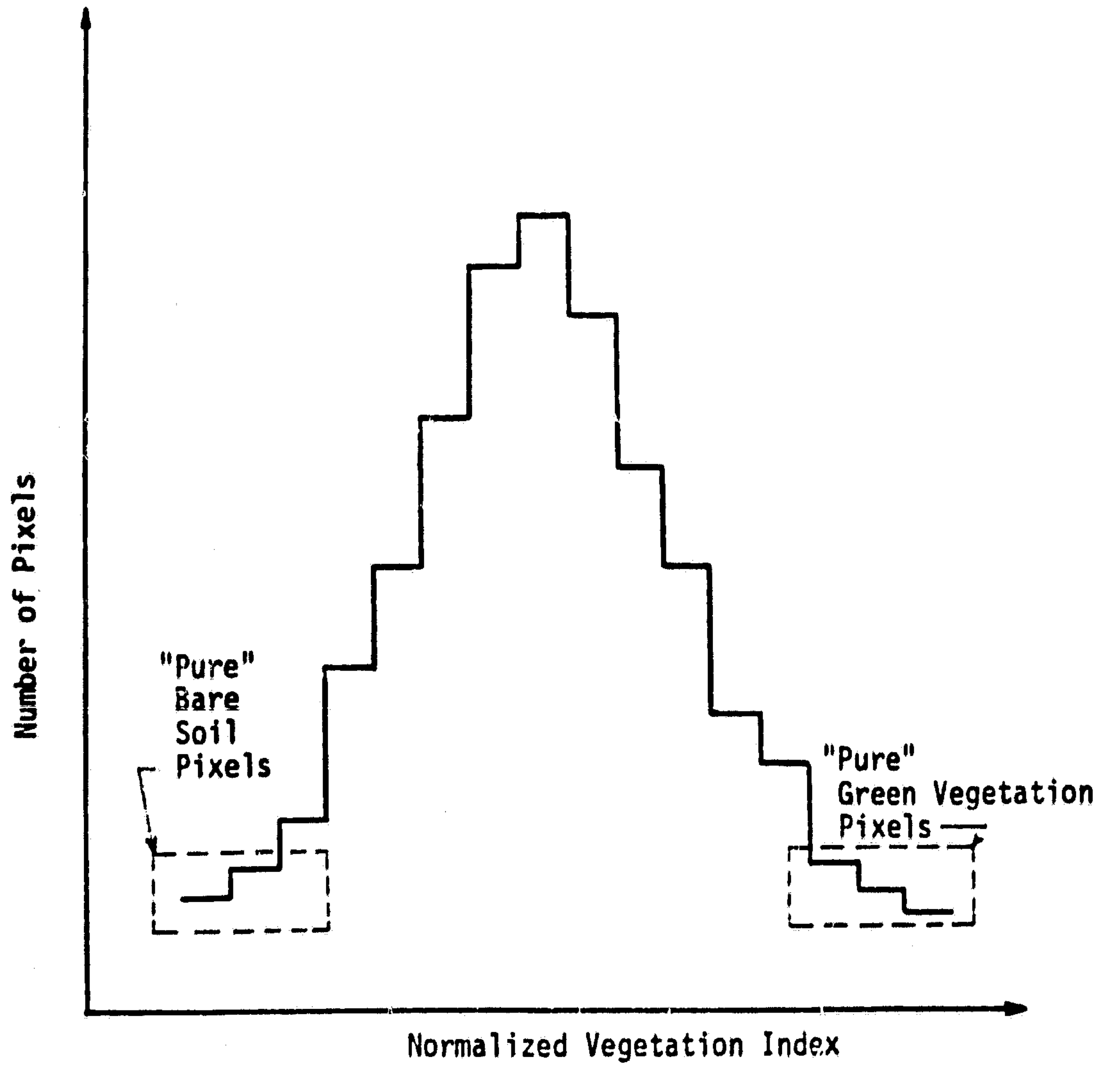

Figure 1. Hypothetical Histogram of Number of Pixels versus Normalized Vegetation Index

segment analyzed is not "large", such that the variability in different soil and plant types is small.

Theoretical Approach

This procedure treats the direct beam from the target pixel as a linear combination of two or three individual sub-pixel elements. Equation (3) can thus be reformulated for the simple two cover model as

$$L_{nr\lambda} = \eta L_{\lambda v} + (1-\eta) L_{\lambda s} \qquad (6)$$

where η = the effective portion of a pixel covered with vegetation

$L_{\lambda v}$ = Radiance emitted from vegetation canopy in band λ

$L_{\lambda s}$ = Radiance emitted from the soil in band λ.

The total nadir radiance will be the sum of equations (4), (5), and (6).

The analysis will be limited to an optically thin atmosphere (clear sky) to reduce the influence of the scattering terms (Equations (4) and (5)). Equations (4), (5), and (6) will be evaluated by assuming reflectances for the different cover types in each band, as well as the clear sky scattering and absorption parameters τ_R, P_R, τ_M, P_M as previously defined. These parameters can be effectively estimated based on meteorologic conditions (Iqbal, 1983). An iterative scheme will be developed to minimize the difference between the computed and observed radiances, based on successive estimates of η.

Finally, since there are four MSS bands, it is theoretically possible to extend the above procedure to the case of a pixel containing several cover types. For example, the presence of brown herbage can significantly affect the overall canopy reflectance (Tucker, 1980). To account for this third cover type, the expression for the direct beam from a pixel can be modified as

$$L_{n\lambda} = \eta L_{\lambda v} + \gamma L_{\lambda b} + (1-\eta-\gamma) L_{\lambda s} \quad (7)$$

where, in addition to the previously defined terms,

γ = the effective portion of a pixel covered with brown vegetation

$L_{\lambda b}$ = Radiance emitted from the brown vegetation in band λ.

The use of two bands will be required in this situation. The practical application of this approach depends on the ability to define unique spectral characteristics for each of the three cover types. This condition is important not only for resolving the data but also to maintain linear independence between the two direct beam equations.

Selection of Test Sites.

Significant progress has been achieved toward the selection of appropriate test sites for objectives 2 and 3 of the research (see page 1). For the testing of the mixed-pixel algorithms, Objective 2, the two major criteria are that 1) the region not be fully vegetated at a sub-pixel level of resolution and 2) the area must contain Landsat reconnaissance and a corresponding aerial photographic survey at approximately the same time. The aerial survey must be of sufficient detail that percent vegetation cover can be delineated.

The criteria for selecting a test site for testing Eagleson's hypothesis, Objective 3, are more stringent. Test sites must be water-limited, naturally vegetated, and at a near climate-climax state. Additionally, long term hydrologic and climatologic records must be available. It is also desirable that climatologic data during the time of the surveys be available.

The above constraints have directed the site-selection process toward the semi-arid regions of southwest United States. Numerous agencies located in those regions have been contacted including the National Park Service, the Forest Service, the Soil Conservation Service, the Bureau of Land Management, the U.S. Geological Survey, Arizona State Parks, the Agricultural Research Service (ARS), and the University of Arizona. The information provided by the various regional and state offices is currently being examined. However, it appears that the criteria for Objective 2 can be easily met. For Objective 3, it is likely that the eventual site be located in the ARS experimental watersheds and/or the National Parks. The sites currently under consideration are the Walnut Gulch Experimental Agricultural Watershed, near Tombstone, Arizona, the Big Bend and Guadalupe Mountains National Parks, Texas, and the Carlsbad Caverns and Bandelier National Parks, New Mexico. These locations are near or in the Sonoran or Chihuahuan Deserts.

The feasibility of obtaining concurrent aerial photographic and Landsat data has already been shown to be very encouraging. The selection process is being facilitated through the aerial photographic and Landsat search services conducted by the EROS Data Center, Sioux Falls, South Dakota. Additional sources of aerial photographic surveys which have been contacted include the U.S. Department of Agriculture, Agricultural Stabilization and Conservation Service, Salt Lake City, and the U.S. Geological Survey, Flagstaff. As of this date, one search request has been made through EROS for the Walnut Gulch Hydrologic Experimental Watershed, Arizona. Matching of the results for the aerial photographic and Landsat searches resulted in one period in October, 1978 in which both data were taken within two weeks. Since this period is one in which canopy cover is not likely to change, both surveys can be used to test the selected canopy cover algorithm. Sample photographs have been ordered from ASCS and EROS for the Walnut Gulch site.

Additional searches for other areas are currently underway. The most effective procedure is first to select the geographic location, then to request the aerial photographic search. If an aerial survey of appropriate scale can be found for a period later than about 1972, it is very likely that corresponding satellite data will be available in light of the frequent coverage of the entire United States by Landsat and NOAA satellites.

FUTURE RESEARCH

Future research will concentrate on refining the two canopy cover formulations outlined above and then applying them to several selected areas in the southwestern United States. Once the final sites have been selected, the entire aerial photographic coverage will be purchased and analyzed for percent canopy cover. The corresponding Landsat data will then be analyzed in accordance with the above proposed techniques at the GSFC. Any refinements to the above procedures will then be made.

Once a suitable canopy cover procedure is established, it will be applied to the appropriate test watershed. Soil hydraulic properties will be estimated using Eagleson's hypothesis. Results will be verified using actual streamflow data.

The feasibility of using Landsat data to compute soil hydraulic properties will thus be established. A program will then be designed to extend this procedure to other natural systems.

REFERENCES

Amis, M.L., R.K. Lennington, M.V.Martin, W.G. McGuire, and S.S. Shen (198), "Evaluation of Large Area Crop Estimation Techniques," Proceedings of the Fifteenth International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, May, 1981, pp. 1047-1056.

Chhikara, R.S. (1984), "Effect of Mixed (Boundary) Pixels on Crop Proportion Estimation," Remote Sensing of Environment, Vol. 14, p. 207-218.

Colwell, J.E. (1974), "Vegetation Canopy Reflectance," Remote Sensing of Environment, Vol. 3, pp. 175-183.

Curran, P. (1980), "Multispectral Photographic Remote Sensing of Vegetation Amount and Productivity," Proceedings of the Fourteenth International Symposium on Remote Sensing of Environment, Ann Arbor, Michigan, pp. 623-637.

Dave, J.V. (1980), "Effect of Atmospheric Conditions on Remote Sensing of a Surface Nonhomogeneity," Photogrammetric Engineering and Remote Sensing, Vol. 46, No.9, September 1980, pp. 1173-1180.

Dickinson, R.E. (1983), "Land Surface Processes and Climate-Surface Albedos and Energy Balance," in Advances on Geophysics, Vol. 25, pp. 305-353.

Dozier, J. (1981), "A Method for Satellite Identification of Surface Temperature Fields of Subpixel Resolution," Remote Sensing of Environment, Vol. 11, pp. 221-229.

Eagleson, P.S. (1982), "Ecological Optimality in Water-Limited Natural Soil-Vegetation Systems 1. Theory and Hypothesis," Water Resources Research, Vol. 18, No. 2, pp. 325-340.

Eagleson, P.S. and T.E. Tellers (1982), "Ecological Optimality in Water-Limited Natural Soil Vegetation Systems 2. Tests and Applications," Water Resources Research, Vol. 18, No. 2, pp. 341-354.

Elvidge, C.D., and R.J.P. Lyon (1985), "Influence of Rock-Soil Spectral Variation on the Assessment of Green Biomass," Remote Sensing of Environment, Vol. 17, p. 265-279.

Estes, J.E., E.J. Hajic, and L.R. Tinney (1983), "Fundamentals of Image Analysis: An Analysis of Visible and Thermal Infrared Data," in Manual of Remote Sensing, American Society of Photogrammetry, Chapter 24, pp. 987-1124

Huete, A.R., R.D. Jackson and D.F. Post (1985), "Spectral Response of a Plant Canopy with Different Soil Backgrounds," Remote Sensing of Environment, Vol. 17, pp.37-53.

Iqbal, M. (1983), An Introduction to Solar Radiation, Academic Press.

Kondratyev, K.Y.A. (1969), Radiation in the Atmosphere, Academic Press.

Lennington, R.K., Sorenson, C.T., and R.P. Heydon (1984), "A Mixture Model Approach for Estimating Crop Areas from Landsat Data," Remote Sensing of Environment, Vol. 14, pp. 197-206.

McCloy, K.R. (1980), "The Response Characteristics of Vegetation in Landsat MSS Digital Data," Remote Sensing of Environment, Vol. 10, pp. 185-190.

Meador, W.E., and W.R., Weaver (1980), "Two-Stream Approximations to Radiative Transfer in Planetary Atmospheres: A Unified Description of Existing Methods and a New Improvement," Journal of Atmospheric Sciences, Vol. 37, March 1980, pp. 630-643.

Myers, V.I. (1983), "Remote Sensing Applications in Agriculture," in Manual of Remote Sensing, American Society of Photogrammetry, Chapter 33, pp. 2111-2228.

Otterman, J. (1978), "Single-Scattering Solution for Radiative Transfer through a Turbid Atmosphere," Applied Optics, Vol. 17, No. 21, 1 November 1978, pp. 3431-3438

Otterman, J., and R.S. Fraser (1979), "Adjacency Effects on Imaging by Surface Reflection and Atmosheric Scattering: Cross Radiance to Zenith," Applied Optics, Vol. 18, No. 16, 15 August 1979, pp. 2852-2859.

Otterman, J., Ungar, S., Kaufman, Y., and M. Podolak (1980), "Atmospheric Effects on Radiometric Imaging form Satellites under Low Optical Thickness Conditions," Remote Sensing of Environment, Vol. 9, pp. 115-129.

Otterman, J. (1981), "Reflection from Soil with Sparse Vegetation", Advances in Space Research, Vol. 1, pp. 115-119.

Perry, C.R. Jr., and L.F. Lautenschlager (1984), "Functional Equivalence of Spectral Vegetation Indices," Remote Sensing of Environment, Vol. 14, pp. 169-182.

Robinove, C.J. (1981), "The Logic of Multispectral Classification and Mapping of Land," Remote Sensing of Environment, Vol. 11, pp. 231-244.

Rosenberg, N.H., Blad, B.L., and S.B. Verma (1983), Microclimate, The Biological Environment. 2nd Edition, Wiley-Interscience, 1983.

Sellers, P.J. (1985), "Canopy Reflectance, Photosynthesis and Transpiration," Draft Report, NASA/Goddard Space Flight Center, Hydrological Sciences Branch, Greenbelt, Maryland.

Smith, J.A. (1983), "Matter-Energy Interaction in the Optical Region," in Manual of Remote Sensing, American Society of Photogrammetry, Chapter 3, pp. 61-113.

Suits, G.H. (1972), "Calculation of the Directional Reflectance of a Vegetation Canopy," Remote Sensing of Environment, Vol. 2, pp. 117-125.

Tucker, C.J., and L.D. Miller (1977), "Soil Spectra Contributions to Grass Canopy Spectral Reflectance," Photogrammetric Engineering and Remote Sensing, Vol. 43, No. 6, p. 721-726.