MULTISPECTRAL SENSING OF MOISTURE STRESS

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INTRODUCTION

Multispectral sensing is an effective tool for acquiring spectral signature data which permit recognition of several kinds of environmental phenomena. Ongoing research at the University of Michigan School of Natural Resources has identified moisture stress as a major factor affecting spectral signatures of woody plants. Laboratory studies have revealed consistent changes in foliar reflectance and emittance characteristics when plants are subjected to high moisture stresses. Many of these changes occur at wavelengths too long, or at threshold levels too low, to be detected by the human eye. Existing remote sensors can record these wavelengths, and have considerably lower thresholds than human interpreters.

During 1969 and 1970 tests were conducted at the Ann Arbor Test Site (NASA Site 190) with multispectral camera and line-scan systems to evaluate the field applicability of previously acquired laboratory data relating moisture stress and reflectance characteristics. In assessing the importance of the results, it is important to remember that moisture stress can result from any of several independent factors, including species differences, insect or disease attacks, leakage of natural gas, and variations in available soil moisture. Furthermore, the interaction of wind, relative humidity, temperature, and incoming solar radiation with plant foliage may result in large, but short term, water stresses. Since symptoms of moisture stress are similar regardless of cause, moisture stress is not a positive indicator of a particular damaging agent. Nevertheless, detection of differences in moisture stress may be a first step in identifying tree species, and in previsual detection of attacks by many types of damaging agents.

MOISTURE STRESS: A DESCRIPTION

Water in plants is part of a continuum extending from the foliage, down through the stem and roots, and out into the soil where it exists as capillary films among the soil particles. When water is lost at one point, moisture film adjustments occur that equalize the effects of the loss throughout the entire system. As the amount of water in the system decreases, moisture films become thinner and the forces holding the water to soil particles and walls of conducting cells reduce the rate at which moisture film adjustments can occur. Under drought conditions, these forces produce a tension in the water film which can exceed -35 bars (tension is expressed as negative pressure, and 35 bars is approximately 500 pounds per square inch). This tension is directly related to the level of moisture stress in the plant.

Moisture film adjustments occur slowly in a soil-plant system and differential stresses exist within the system until the adjustments are completed. During daylight, plants lose copious amounts of water through transpiration and increasing moisture tensions develop in their foliage. Transpiration slows in late afternoon and ceases at night, permitting slow moisture film adjustments from soil to root to replace water in the plant tissues faster than it is lost. Under very dry conditions the adjustment rate may be so slow, however, that equilibrium in the foliage is not attained before dawn; and, even if attained, equilibrium may be reached at an appreciable tension. Plants then begin the new day already under stress.

MEASURING MOISTURE STRESS

The ideal way to measure moisture stress would be to measure the water tension within the plant. Because of the difficulties in accomplishing this, indirect estimates of moisture stress based upon measurements of soil moisture have been, and are being used extensively. The usefulness of such measurements is dependent upon the degree to which moisture release characteristics of the soil are known. Estimates based solely on total moisture content of the soil are apt to be badly misleading, for they ignore the water content and water deficits in the plant.

The ability of plants to extract water from the soil is limited and some soil water is so tightly held that it is unavailable to plants. Much of the unavailable water is held closely to the surface of the soil particles, and the greater surface area of fine-textured soils makes more of the water in them unavailable than is true of coarse-textured, sandy soils. Soil texture may change markedly with small changes in depth and careful analysis of the soil profile in the root zone is needed to determine the amount of available water present at any given time.

The fact that moisture stress exhibits a diurnal rise and fall makes standardization of the time of measurement important when long-term trends are of concern. The period just before dawn would be ideal, for at this time the soil-plant-water system is most apt to be at equilibrium. Measurements at other times of day may more nearly represent actual stress levels at the time remote sensor data are acquired, however.

The above discussion suggests that considerable advantages are gained by direct measurement of internal moisture tensions. Such a method was proposed by Dixon (1914) but was not used until the apparatus needed was assembled by Scholander et. al. (1965). A good description of the method,and a diagram of the apparatus, is presented by Kramer (1969). The method requires cutting one leaf, or a twig, from the plant and inserting it into a pressure cylinder so that only the cut end of the stem is exposed. Nitrogen is bled slowly into the cylinder until water is forced back out of the cut end of the stem. The pressure in the cylinder when this first occurs is considered equal, but opposite in sign, to the tension in the water conducting tissues at the time the leaf was cut from the plant. Measurements are considered accurate to within ±1 bar. When the necessary apparatus is available, this method is faster, cheaper, and more accurate than any other method now in use for determining levels of moisture stress in woody plants.

REFLECTANCE AND MOISTURE STRESS

Reflectance characteristics of leaves are more strongly affected by moisture stresses at the time the leaves form and unfold than by moisture stresses existing at the time the reflectance is measured (Weber and Olson, 1967; Olson, Ward and Rohde, 1969; Olson, 1969). Leaves which form during periods of high moisture stress are significantly less reflective at all wavelengths between 0.4 and 2.5 micrometers than are leaves which form during periods of low stress. Leaves which form and grow to essentially full size under low stress conditions show a slight increase in reflectance (or no change) when the plants are subsequently subjected to high moisture stresses.

Some species produce new leaves (flush) only at the beginning of the growing season while others flush almost continuously throughout the growing season. Continuous leaf flushing results in crowns whose outer, more visible, leaves are formed under moisture conditions existing only a few days earlier. For those species in which flushing occurs only once, the outer, more visible, leaves maintain reflectance characteristics typical of moisture conditions at the time the leaves formed, and this may have been five months earlier. Differences in leaf flushing patterns result in differences in the way that reflectance of plants changes as moisture stresses develop. Leaf flushing patterns are closely related to the structure and arrangement of the water conducting cells in the stem, and it is easier to predict the effects of moisture stress on plant reflectance when this structure is known and considered.

Woody plants of the temperate zone can be grouped into three classes based upon the type and arrangement of their water conducting cells. The conifers with their non-porous conducting systems form one class. The two distinct arrangements of the water conducting vessels in broad-leaved, woody plants provide the other two classes. These are referred to as <u>ring-porous</u> and <u>diffuse-porous</u> because the vessels are concentrated in a narrow band in the spring-wood of the former, but dispersed through the entire annual ring of the latter. With few exceptions, ring-porous species flush only at the beginning of the growing season, while diffuse-porous species usually flush continuously. Since foliar reflectance characteristics are largely controlled by moisture conditions at the time the leaves form, it is easier to detect moisture stress in diffuse- than in ring-porous species.

ACKNOWLEDGEMENTS

The work described in this paper is part of a continuing series of studies of the effects of morphological and physiological changes on remote sensing of trees under stress. Work was begun at the University of Illinois in 1959, with sponsorship of the Office of Naval Research, and shifted to the University of Michigan in 1963. Since 1966 primary financial support has been provided by the National Aeronautics and Space Administration as part of the Earth Resources Survey Program in Agriculture/Forestry (Contract No. R-09-038-022). The current work is a cooperative undertaking of the Forest Service, U. S. Department of Agriculture, and the School of Natural Resources, University of Michigan. Flight and data processing services were provided by NASA directly, and through terms of facilities contracts with the University of Michigan, Willow Run Laboratories.

Laboratory studies have been centered at the University of Michigan Botanical Gardens and the generous support of its director, Dr. Warren H. Wagner, Jr., and staff is gratefully acknowledged.

PROCEDURES

During the 1969 and 1970 growing seasons multispectral data were collected over areas of known vegetation stress within the Ann Arbor Test Site. The University of Michigan C-47, with four 70mm cameras and multispectral scanner, provided low altitude (1,500 to 9,000 feet) coverage of selected parts of the Site; and the NASA RB57F, with three 9 x 9 and six 70mm cameras, provided high altitude (40,000 to 60,000 feet) coverage of the entire Site.

THE ANN ARBOR TEST SITE

The Ann Arbor Test Site (NASA Site 190) is located on morainal topography and includes both upland and lowland sites supporting a diverse mixture of natural and planted forest stands interspersed with active and abandoned agricultural fields. Data on land use and stand growth go back to 1903 for some locations. The Site is located approximately 40 miles west of Detroit, Michigan, and includes the active urban-rural tension zones adjacent to Ann Arbor and several smaller cities.

Active infection centers of a number of tree diseases are present and have been monitored for several years. Infestations of *Fomes annosus*, an important root-rotting fungus of conifers, and at least two needle cast diseases caused by *fungi imperfecta*, are included. In 1970, tipburn damage, believed caused by ozone, was discovered within the Test Site. All of these disease centers were monitored during each overflight.

CALIBRATION MEASUREMENTS

Foliar reflectance of healthy and stressed trees was measured with a Beckman DK-2a spectrophotometer for both greenhouse-grown and field-grown plants. Emittance data were collected for the same plants with Barnes PRT-10 or IT-3 radiometers. Levels of moisture stress were determined with a pressure cylinder similar to that described by Kramer (1969). These data were used in determining optimum wavelength bands for subsequent processing with the University of Michigan Spectral Processing and Recognition Computer (SPARC).

DATA PROCESSING

Data from the multichannel scanner were used to prepare simulated normal-color and infrared-color imagery for comparison with the actual color and false-color photographs from the cameras carried by both aircraft. The relative value of the simulated and real photography in detecting tree diseases was determined with conventional photographic interpretation techniques.

An attempt was made to obtain automatic recognition of tree species on the basis of naturally occurring differences in moisture stress. On the basis of laboratory reflectance data and visual inspection of imagery from individual channels of the scanner, six spectral bands were selected for use in the SPARC processor. The 0.58-0.62, 0.62-0.66, 0.72-0.80, and 0.80-1.0 micrometer channels were used in all cases; supplemented by the 0.40-0.44 and 0.55-0.58 micrometer bands for separation of broadleaved species, and the 0.46-0.48 and 0.52-0.55 micrometer bands when separation of coniferous species was desired.

As a side-line to the 1970 field tests, detailed statistical analyses were made of the relationship between reflectance and moisture content for 356 leaves. Step-wise regression techniques were used with several types of transformations in an attempt to derive a means of evaluating moisture content of fine forest fuels which would be of value to forest fire control organizations.

RESULTS AND DISCUSSION

Results of the step-wise regression analyses provide substantial confirmation of the importance of changes in moisture conditions on foliar reflectance. Because previous work (Olson, 1969) had shown that the slope of the infrared reflectance plateau between 0.8 and 1.1 micrometers changes as a leaf unfolds and enlarges to full-size, ratioed combinations of reflectances at several wavelengths were tested. Two such combinations were found to improve predictive capability and the final regression equations (Figure 1) were based on three variables:

$A = R(1.00)$ or the reflectance at 1.00 micrometer.

$$B = \frac{R(2.00) + R(2.19) + R(2.30) + R(2.60)}{R(1.64) + R(1.75) + R(1.78)}$$

$$C = \frac{R(1.64) + R(1.75) + R(1.78)}{R(0.80) + R(0.90) + R(0.96) + R(1.00)}$$

We believe that these transformations can be accomplished as a preprocessing technique with data from a multispectral scanning system.

The high multiple correlation coefficients obtained with the three regression equations shown in Figure 1 (0.98, 0.94, and 0.92) support the hypothesis that the relationship between moisture content and foliar reflectance is significant. Even if these equations do not prove valuable in airborne remote sensing, they do provide a non-destructive method of estimating moisture content of plant foliage which should be of value in other research.

AUTOMATIC RECOGNITION OF TREE SPECIES

Automatic recognition of tree species was attempted with the SPARC for the 80-acre Saginaw Forest property controlled by the University of Michigan School of Natural Resources, and located within the Ann Arbor Test Site. This property contains several broadleaved and several coniferous plantations (Figure 2). Because available reflectance data supported the hypothesis that moisture stress effects are different for ring- and diffuse-porous species, the first test of the SPARC was an evaluation of its capability for separating ring-porous, diffuse-porous, and coniferous species. The results were highly successful (Figure 3). In subsequent tests successful separation of the major broadleaved species present on the property was achieved, including separation of red oak from white oak with an accuracy of about 70 percent (Figure 4). Although not perfect, results of this test of the SPARC's ability to identify tree species represent at least an order of magnitude improvement over previous attempts which were not based on moisture stress considerations.

SIMULATED vs. REAL COLOR FILMS

This phase of the data analysis is not complete. To date, no consistent superiority has been found for either simulated or real color films. Both seem to have their place.

Analysis of the needle cast infestation on Scots Pine demonstrates the importance of repetitive coverage in assessing severity of damage. The disease is readily apparent in the low altitude color photography obtained in August 1969, but is not apparent in either the color or false-color photography obtained in July 1970 (Figure 5). Ground data confirmed that the disease was much less severe in 1970 than in 1969.

The false-color photograph in Figure 5 illustrates one consistent abnormality observed between the low (C-47) and high (RB57F) altitude photography obtained in both 1969 and 1970. At low altitudes the pine stands (P) and the broadleaved stands (B) appear in nearly equal red tones. From high altitude the conifers appeared distinctly blue-green rather than red.

Figure 6 provides another example of the value of sequential coverage in assessing changing severity of damage symptoms. The slight browning of several trees in the color photography from June 1970 went unnoticed until it had become more obvious in July. Subsequent comparison of the June and July imagery revealed the rapidly increasing severity of the damage symptoms, believed due to the effect of an abnormally high ozone concentration of undetermined origin.

Figure 7 presents both a real false-color photograph and a simulated false-color image prepared from the scanner data. The apparent enhancement of the *Fomes annosus* infection centers (the small pock-mark like openings in the crown canopy) in the simulation may be due to shadow enhancement or to more sensitive recording of differences in moisture stresses. Further analysis of this imagery is in process.

CONCLUDING REMARKS

Laboratory reflectance data, and field tests with multispectral remote sensors at the Ann Arbor Test Site during 1969 and 1970, provide support for this hypotheses that differences in moisture content and water deficits are closely related to foliar reflectance from woody plants. When these relationships are taken into account automatic recognition techniques, such as those utilized with the University of Michigan Spectral Processing and Recognition Computer, become more powerful than when they are ignored. Evidence is increasing that moisture relationships inside plant foliage are much more closely related to foliar reflectance characteristics than are external variables such as soil moisture, wind, and air temperature. Short term (often diurnal) changes in water deficits seem to have little influence on foliar reflectance, however. This is in distinct contrast to significant short-term changes in foliar emittance from the same plants with changing wind, air temperature, incident radiation, or water deficit conditions.

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Sugar maple (*Acer saccharum*)

$r = .94$

$$\log \text{M.C.} = 8.4181 - 3.1378 \log A + 1.9490 \log B - 1.7609\ B^2$$

Yellow birch (*Betula alleghenensis*)

$r = .98$

$$\log \text{M.C.} = 1.5872 + 7.6537\ B^2 + 67.8304\ C^2$$

White ash (*Fraxinus americana*)

$r = .93$

$$\log \text{M.C.} = 7.5649 - 2.6119 \log A - 0.6581\ B^2 - 1.4915\ C^2$$

M.C. — leaf moisture content

r — multiple correlation coefficient

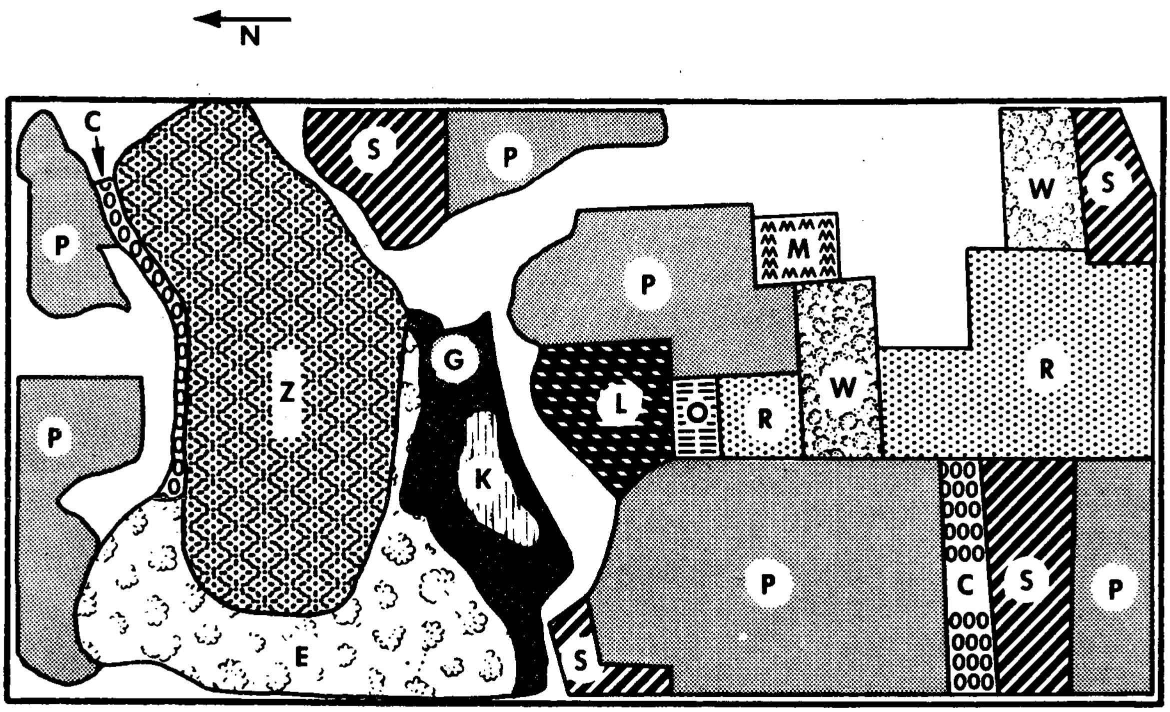
R — reflectance

$$A = R_{(1.00\ \mu m)}$$

$$B = \left[\frac{R_{(2.00\ \mu m)} + R_{(2.19\ \mu m)} + R_{(2.30\ \mu m)} + R_{(2.60\ \mu m)}}{R_{(1.64\ \mu m)} + R_{(1.75\ \mu m)} + R_{(1.78\ \mu m)}} \right]$$

$$C = \left[\frac{R_{(1.64\ \mu m)} + R_{(1.75\ \mu m)} + R_{(1.78\ \mu m)}}{R_{(0.80\ \mu m)} + R_{(0.90\ \mu m)} + R_{(0.96\ \mu m)} + R_{(1.00\ \mu m)}} \right]$$

Figure 1. Leaf moisture content prediction equations for three tree species derived with stepwise multiple regres-ion techniques.



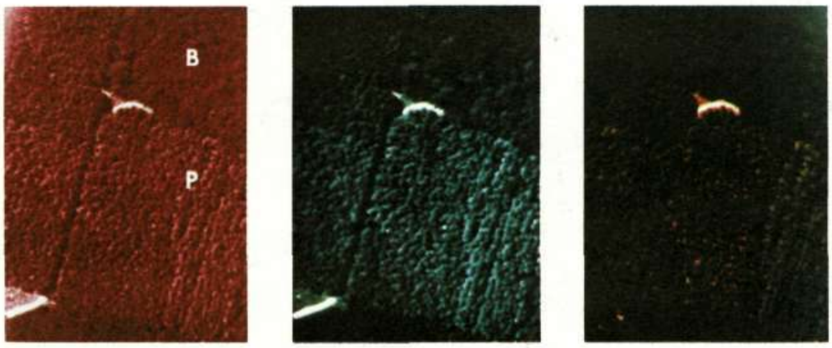
C - Cottonwood, Aspen, Willow
E - Elm, Red Maple
G - White Cedar
K - Swamp
L - Black Locust
M - Sugar Maple
O - White Oak
P - Pine
R - Red Oak
S - Spruce
W - Black Walnut
Z - Lake

Figure 2. Distribution of trees species at the University of Michigan Saginaw Forest near Ann Arbor, Michigan.

Figure 3. Recognition map of Saginaw Forest generated by the University of Michigan Spectral Analysis and Recognition Computer (SPARC). Conifers are shown in green, ring-porous species in red, and diffuse-porous species in black.

Figure 4. Recognition map of Saginaw Forest generated by the University of Michigan Spectral Analysis and Recognition Computer. Conifers are shown in green, red oak in red, white oak in orange, black locust in gold, black walnut in light blue, and sugar maple in pink.

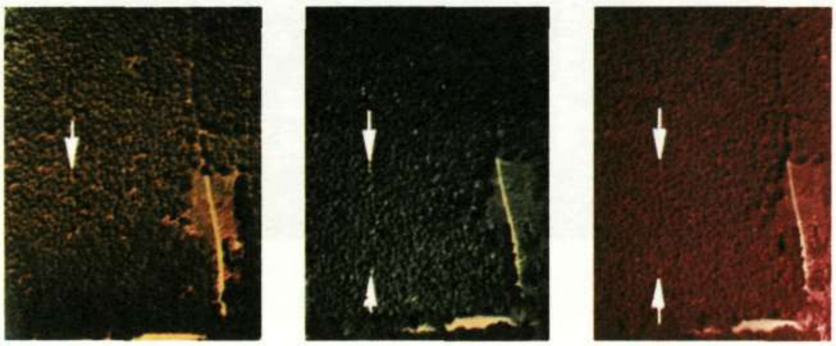
Color IR — Normal Color — Normal Color



July 1970 — July 1970 — August 1969

Figure 5. Needle cast on Scots Pine was much more severe in 1969 than in 1970 as indicated by these photographs taken from 3,000 feet. The brown trees in the August 1969 photo are severely infected. Note that the broadleaved (B) and pine (P) trees in the Color IR photo show nearly equally red tones.

Normal Color | Normal Color | Color IR



August 1969 | July 1970 | July 1970

Figure 6. Damage believed due to ozone became more severe in 1970 as indicated by these photographs taken from 3,000 feet. Arrows point to affected trees.

Figure 7. Simulated Color IR image prepared from data obtained with the University of Michigan multispectral scanner. The small holes in the crown canopy indicated by arrows are centers of infection by Fomes annosus.