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TECHNICAL REPORT

QUANTITATIVE ESTIMATION OF PLANT CHARACTERISTICS USING SPECTRAL MEASUREMENT: A SURVEY OF THE LITERATURE

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QUANTITATIVE ESTIMATION OF PLANT CHARACTERISTICS USING SPECTRAL MEASUREMENTS: A SURVEY OF THE LITERATURE

Job Order 73-312

This report describes Vegetation/Soils/Field Research activities of the Supporting Research project of the AgRISTARS program.

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ACRONYMS

AgRISTARS	Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing
AID	Agency for International Development
ATCOR	atmospheric correction model
CMI	Crop Moisture Index
C/P	Conservation and Pollution
DCLC	Domestic Crops and Land Cover
ERIM	Environmental Reserve Institute of Michigan
ERTS-1	Earth Resources Technology Satellite
EW/CCA	Early Warning/Crop Condition Assessment
FCPF	Foreign Commodity Production Forecasting
FY	fiscal year
GIN	Green Index Number
LACIE	Large Area Crop Inventory Experiment
LAI	leaf area index
NASA	National Aeronautics and Space Administration
RRI	Renewable Resources Inventory
SM	Soil Moisture
SR	Supporting Research
TVI	Transformed Vegetation Index
USDA	U.S. Department of Agriculture
USDC	U.S. Department of Commerce
USDI	U.S. Department of Interior
USGP	U.S. Great Plains
YMD	Yield Model Development
YTD	young tree decline

1. INTRODUCTION

The Agricultural and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) is a 6-year program of research, development, evaluation, and application of aerospace remote sensing for agricultural resources beginning in fiscal year (FY) 1980. The program is a cooperative effort of the National Aeronautics and Space Administration (NASA), the U.S. Departments of Agriculture, Commerce, and Interior (USDA, USDC, and USDI) and the U.S. Agency for International Development (AID).

The goal of the program is to determine the usefulness, cost, and extent to which aerospace remote sensing data can be integrated into existing or future USDA systems to improve the objectivity, reliability, timeliness, and adequacy of information required to carry out USDA missions. The overall approach is comprised of a balanced program of remote sensing research, development, and testing which addresses domestic resource management, as well as commodity production information needs.

The Technical Program is structured into eight major projects as follows:

1. Early Warning/Crop Condition Assessment (EW/CCA)
2. Foreign Commodity Production Forecasting (FCPF)
3. Yield Model Development (YMD)
4. Supporting Research (SR)
5. Soil Moisture (SM)
6. Domestic Crops and Land Cover (DCLC)
7. Renewable Resources Inventory (RRI)
8. Conservation and Pollution (C/P)

The majority of these projects will make use of spectral information to estimate crop-related parameters.

This literature review is intended to be a comparative summary of the significant research results relative to the quantitative use of spectral data to measure the properties of leaves, plants, and canopies. The rapidly expanding interest in this topic has resulted in a spectacular proliferation of pertinent literature. The authors have attempted to select a cross-section of the technical literature which illustrates the state of the art in remote sensing as applied to AgRISTARS research. This report is intended as a supplement to the recent commentary by Stuff and Barnett (1979).

The dependent variables which have been the objective of most research and which will be treated in this paper have been divided into three categories:

a. Yield and yield components [leaf area index (LAI), biomass, percentage of ground cover, and height]

b. Stress factors (disease, insects, drought, malnutrition, physical damage, and salinity)

c. Growth phenomena (emergence, leaf formation, reproductive phases, ripening, and harvest)

Research has been conducted on several scales, including single leaves (and stacks thereof), plots, fields, Large Area Crop Inventory Experiment (LACIE) segments (5 by 6 nautical miles in size), and Landsat full frames (100 by 100 nautical miles). Spectral properties have been measured by instruments which can be classified according to both wavelengths and number of wavebands used; e.g., continuous (narrow band), two-band, four-band, and thermal devices. Emphasis will be placed on the Landsat spectral range, 0.5 to 1.2 micrometers (500 to 1200 nanometers). The following topics will be addressed:

a. Fundamentals of Vegetative Reflectance - brief summaries of current opinions on value of measurements of the visable, near-infrared, and infrared water absorption bands

b. Calibration: Corrections and Transforms - brief statements on principal procedures used to standardize spectral measurements over space and time

c. Correlation Studies - discussion of representative or unique studies which have statistically related spectral measurements to yield and stress variables

d. Temporal Trajectories and Crop Calendars - discussion of attempts to identify changes in plant appearance over time due to physiological development; i.e., growth phenomena

e. Large Area Studies - qualitative evaluation of methods and performance of models or schemes for multiple site application

f. Summary and Conclusions

The following exclusionary rules have been applied in the selection of documents and titles to be included.

a. Reject articles dealing primarily with classification.

b. Omit articles and discussion of thermal and microwave techniques.

c. Reject papers based purely on photographic interpretation.

d. Omit discussion of radiative transfer models (atmospheric or plant).

e. Reject articles not formally published.

2. THE FUNDAMENTALS OF VEGETATIVE REFLECTANCE

Eight comprehensive reviews on the fundamentals of vegetative reflectance have been identified. The authors are:

a. Colwell, R. M., et al. (1963)

b. Knipling (1967)

c. Gates (1970)

d. Knipling (1970)

e. Myers et al. (1970)

f. Gausman (1974)

g. Myers et al. (1975)

h. Harlan and Erickson (1977)

A discussion of these reviews incorporated with views held by the authors of this paper are presented in this section.

2.1 VISIBLE WAVELENGTHS (0.4 to 0.7 MICROMETERS)

The visible region is the best understood part of the spectrum. This is to be expected since its interpretation can be tested directly against the millennia of agronomic experience. Spectrophotometric measurements of vegetation in this region are determined primarily by the amount of chlorophyll in the leaves. Normal concentrations cause most (80 to 90 percent) of the incident light to be absorbed. Because somewhat more absorption occurs in the blue spectrum (0.4 to 0.5 micrometers) and the red spectrum (0.6 to 0.7 micrometers) than in the green spectrum (0.5 to 0.6 micrometers), the latter dominates vegetative reflectance patterns (signatures). As chlorophyll concentration decreases from normal, the overall absorption in the visible region decreases but the green dominance remains. Hence, for individual leaves in the laboratory, an increase in albedo (overall visible reflectance) is usually the first visible indication of stress. However, in the field, many stress factors tend to reduce vertically observed leaf area (reduced canopy) leading to an increase in the ground contribution to spectral reflectance. Whether the overall visible albedo is increased or decreased depends upon the nature of the soil surface cover, including the degree of shadow and the moisture content. Row direction, of course, affects the degree of shadow. Also, the degree of contrast between soil and plant will affect the level of reflectance which is detected. This effect is especially important as resolution

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Increasing stress normally leads to drastic reduction in chlorophyll content to the point where other plant pigments dominate spectral response. The carotenoids and anthocyanins thus become the main determinants if they are present, but some plants are low in such pigments and will simply increase in overall reflectance while band differences lessen. In other words, the spectral pattern becomes both lighter and brighter. Once again, the background soil surface contribution may have major effects, particularly at the Landsat scale of resolution.

Finally, extreme stress leads from chlorosis (yellowness or blanching) to necrosis (dead tissue formation), producing a spectral signature that increases steadily with wavelength for individual leaves. This change is combined with an increasing and eventually dominant role of the background whatever it may be (green weeds, red soil, yellow debris). Clearly, the net result is difficult to predict.

In summary, stress effects in the visible range are well documented and understood, but the interpretation of an unknown target's signature can be exceedingly complex. The problem is further complicated by the fact that plants naturally display symptoms similar to those of increasing stress as they mature and ripen. Therefore, stress symptoms can be interpreted only if the growth history and stage of the crop are known. This point will be reiterated in the following discussion. One other complication that should be mentioned is that the dorsal (under) sides of leaves reflect more strongly in the visible range than do the ventral (upper) sides. Thus, wind-induced patterns can also confuse the interpretation of the spectral reflectance measurements.

2.2 NEAR-INFRARED WAVELENGTHS (0.7 to 1.2 MICROMETERS)

One of the most distinctive features of vegetation is that it reflects (and transmits) more in the near-infrared region than do most other natural objects. Many models have been proposed to explain the pathways of incoming radiation to and from vegetation which lead to the phenomenon. Most agree that this radiation is first scattered and then reflected to the sensor by index of refraction differences at cell wall, air, and water interfaces. Actually, the underlying cause of the strong reflectivity is the almost total lack of absorption, which means that all irradiance is potentially available for reflectance or transmittance. This leads to considerable variability in reflectance, since it is largely controlled by the varying leaf and canopy geometries of the multiple refractive interfaces. (By contrast, the strong absorption by pigments in the visible band tends to stabilize reflectance patterns, so that only major physiological changes are identifiable.) The sensitivity of the near-infrared means that this region is a valuable source of information when the variations in reflectance can be reliably associated with a particular physiological change. Much of the success of remote sensing in local areas has been in such cases. In fact, most of the specific examples discussed in the section of correlation studies involve the near-infrared. Unfortunately, interpretation has proved to be difficult in large, complex areas where any of a number of factors may be affecting reflectance. Often, the directions of change of leaves and canopy have different signs. Also, canopy changes often lead to changes in the background exposure, which may further complicate the interpretation. Several of the other caveats mentioned in the discussion of the visible range also apply to the near-infrared; e.g., row direction and wind effects.

2.3 NEAR-INFRARED WAVELENGTHS (1.2 to 2.5 MICROMETERS)

Laboratory studies indicate that there is very strong water absorption of irradiance at these wavelengths. However, the authors of this paper have not encountered many instances in the literature where this fact has been tested for possible use in estimating water stress. Probably this is due in part to the relative scarcity of instruments which measure in these wavelengths. Since the Landsat thematic mapper includes provisions to collect data in these regions, their utility will probably be explored more thoroughly in the future. A few instances of such measurements are noted in the commentary on individual correlation studies.

3. CALIBRATION: CORRECTIONS AND TRANSFORMS

The interpretation of Landsat measurements in terms of laboratory and field reflectance measurements, the presumed research base, presents a serious problem because it is virtually impossible to establish a "maximum" from which to calculate true reflectance. In the absence of a calibration standard, Landsat "counts" have little meaning from day to day and from scene to scene. Possible solutions fall into three categories:

a. Absolute calibration - This entails atmospheric radiative transfer models to correct for all significant distortion factors and thus permit estimates of reflected energy in absolute terms.

b. Relative calibration - This requires an internal standard such as the scene mean, the scene maximum, and the scene minimum to permit conversion of "counts" to something like reflectance.

c. Mathematical standardization - This relies on mathematical indexes, such as ratios and normalized differences to substitute for reflectance calculations. There is no direct connection between these calculated values and reflectance. Hence, reflectance-based ground truth must be converted to these indexes, or a new ground-truth data base must be created using new measurements expressed in these mathematical terms.

3.1 ABSOLUTE CALIBRATION

The principal attempts at absolute calibration via atmospheric radiative transfer models are those of Lambeck (1977), Potter (1976), Potter and Mendlowitz (1975), and Turner et al. (1971). None of these has proved sufficiently useful to achieve general acceptance. However, the Lambeck model, XSTAR, is an integral part of the approach developed by the Environmental Research Institute of Michigan (ERIM). This approach will be treated separately.

3.2 RELATIVE CALIBRATION

So far as the authors know, there have been no successful demonstrations of relative calibration methods although the scene minimum has been used in one version of the atmospheric correction model (ATCOR) developed by Potter (1976).

3.3 MATHEMATICAL STANDARDIZATION

Most of the research aimed at normalization of Landsat data can be placed in the third category, that of mathematical standardization. The simplest of these transformations are the band ratios. Of these, the most studied have been those of band 4 to band 5 and band 7 to band 5. The rationale for the first is that it is an indicator of the presence or absence of chlorophyll. The band 7/band 5 ratio is justified as a combined indicator of chlorophyll and mesophyll development. The reasoning is that it maximizes the vegetative-nonvegetative difference by folding into one variable the facts that band 5 measures maximum chlorophyll absorption, whereas band 7 measures maximum leaf reflectance. (Some argue that maximum reflectance is band 6.)

The use of band ratios implicitly corrects for major variations due to differences in Sun angle. For other transformations, a simple cosine correction is often used. In general, the digital data may be corrected to a reference solor elevation angle as follows. Let X_i represent the Landsat signal in band i; the Sun-angle correction, X_i, is calculated as follows:

$$X_i' = \frac{\cos \Theta_0}{\cos \Theta} X_i$$

where Θ is the solar zenith angle and Θ_0 is the reference solar zenith angle. The resulting data will appear to have been acquired at the reference solar elevation angle.

The second major type of transformation is the normalized difference, an example of which is the Transformed Vegetation Index (TVI) [Rouse et al., (1973)]. This transform has seen frequent use as an indicator of green biomass. The TVI may be calculated using either Landsat bands 7 and 5 (TVI7) or bands 6 and 5 (TVI6). Let X_i represent the Landsat signal in the *ith* band after Sun-angle correction.

$$TVI6 = \sqrt{\frac{X_6 - X_5}{X_6 + X_5} + 0.5}$$

$$TVI7 = \sqrt{\frac{X_7 - X_5}{X_7 + X_5} + 0.5}$$

For some reason which we have been unable to identify, band 7 is not multiplied by two in this calculation, even though it would reduce the number of cases in which the 0.5 term is necessary to prevent taking the square root of a negative number. Recent users [e.g., Tucker, Elgin, and McMurtrey (1979); Tucker, Elgin, McMurtrey, and Fan (1979); and Tucker, Holben, et al. (1979)] have dropped the use of the square root and are examining the normalized differences directly.

The best known of the mathematical standardizations is probably the Kauth and Thomas (1976) Tasselled Cap transformation system used extensively by ERIM. The full flavor of this imaginative approach should be savored in the original. Briefly, it consists of four mutually orthogonal transformations of the four Landsat bands, using empirically derived coefficients. Let X_i be the Landsat signal in the *ith* band after Sun-angle correction and haze correction.

$$\text{Brightness} = 0.433X_4 + 0.632X_5 + 0.586X_6 + 0.642X_7$$

$$\text{Greenness} = -0.290X_4 - 0.562X_5 + 0.600X_6 + 0.491X_7$$

The most important of the transformations is usually considered to be that which contrasts bands 4 and 5 with bands 6 and 7. Paradoxically, this transformation was christened Greenness even though it gives negative weights to bands 4 and 5, whose ratio forms the true basis of green. The other important transformation in this system is called Brightness, since it is essentially an albedo equivalent. The other two orthogonal transformations involve complementary contrasts and are known as Yellowness and Nonesuch. They seem to have little informational content. However, Yellowness is incorporated in the XSTAR atmospheric haze correction algorithm.

The XSTAR haze correction is applied after a Sun-angle correction. Let $\hat{X}_i$ be a scene diagnostic signal for the *ith* Landsat band; let α_i and X_i^* be coefficients. Let γ represent the change in optical thickness from the reference condition. Let Y* be a reference yellow value for the scene.

$$\alpha = \begin{pmatrix} 1.2680 \\ 1.0445 \\ 0.9142 \\ 0.7734 \end{pmatrix} \qquad X^* = \begin{pmatrix} 61.9 \\ 66.2 \\ 83.2 \\ 33.9 \end{pmatrix}$$

$$Y^* = -11.2082$$

Calculate the following:

$$a = \sum_{i=4}^{7} \alpha_1^2 (\hat{X}_i - X_i^*) R_i$$

$$b = \sum_{i=4}^{7} \alpha_i (\hat{X}_i - X_i^*) R_i$$

$$c = \left(\sum_{i=4}^{7} \hat{X}_i R_i \right) - Y^*$$

$$\gamma = \frac{-b}{a} \left\{ 1 - \sqrt{1 - \frac{2ac}{b^2}} \right\}$$

where

$$R_i = \begin{pmatrix} -0.89952 \\ 0.42830 \\ 0.07592 \\ -0.04080 \end{pmatrix}$$

The corrected value, X_i', is calculated from the Sun-angle-corrected band value, X_i, as follows.

$$X_i' = e^{\alpha_i \gamma}(X_i - X_i^*) + X_i^*$$

Misra and Wheeler (1977) and Wheeler et al. (1976) have derived a transform that is essentially equivalent to the Kauth-Thomas transform from theoretical considerations.

The most common use of the Tasselled Cap transformation system is a pixel scatter diagram in Greenness (Y) and Brightness (X) space. The horizontal lower boundary of the plotted data is called the soil line. (Another definition is the horizontal line below which falls 1 percent of the pixels.) Some investigators [e.g., Thompson and Wehmanen (1977 and 1979)] have subtracted the soil line value from Greenness and called the result the Green Number. The intent of this is to reduce the scene-to-scene variability in Greenness which is due to soil differences. Finally, an idealized multispectral temporal Greenness and Brightness plot produces the pattern which suggested the name Tasselled Cap and is a form of spectral crop calendar.

The Kauth-Thomas transform has been discussed at some length because it has a fundamental advantage over the other mathematical standardizations, such as ratios and normalized differences. This advantage is: the Kauth-Thomas transform preserves at least two dimensions in the data, whereas the others reduce the Landsat signals to a single index. We have already indicated that stress can only be measured if growth stage is known, and vice versa. Clearly, if only one independent predictor is available, the distinction between stress and growth stage effects will be difficult. There is an additional reason why at least two dimensions of variability are desirable. If vegetative cover is incomplete, the yield component percentage of ground cover is totally confounded with the other yield components, such as biomass and LAI. This is true because the percentage of ground cover is essentially a classification of vegetation versus bare soil. The other yield components are very highly correlated with the areal extent of the crop since bare ground possesses no plant attributes. Thus, plants can only be compared with each other after the soil contribution is removed; i.e., when complete coverage exists. Otherwise there is no way of distinguishing 4 metric tons of grass, 50 centimeters high, and covering parts of the field equal to 1/2 hectare between the same amount of grass, 25 centimeters high, and spread evenly over an entire hectare. This confounding would cause serious problems for coefficient estimation if a grass production model were attempted using spectrally determined percentage of ground cover and spectrally determined plant height as independent variables. The problem of confounding will always be a serious one. However, if it is ever to be overcome, the multidimensionality of the data, whatever it may be, must be preserved. It should be obvious that it is undesirable to collapse all of the potential information into one variable and then expect to construct three models using that one variable to predict crop type <u>and</u> crop age <u>and</u> crop condition.

In comparison, the ERIM approach is conceptually sound because it seeks to avoid these complications by first making an absolute calibration via XSTAR and then does a mathematical calibration which retains at least two dimensions of information.

4. CORRELATION STUDIES

The health status of a crop has always been the main concern of the producer because a crop stressed by nutrient deficiencies, drought, unfavorable weather, disease, insect infestation, and/or weed competition will not yield to its potential. Hence, the diagnosis of problems as early and quickly as possible allows managers to alleviate the stress and limit the yield reduction.

Historically, this has been accomplished by field inspections and diagnosis of the symptoms, hopefully making correct judgments (e.g., distinguishing nitrogen deficiency from nematode damage) to permit proper action. This personal touch approach to crop protection requires a bit of luck and much time on the part of the inspector, who must be in the correct location at the proper time in order to spot problems while they are controllable.

With the advent of remote sensing, researchers recognized it as a useful tool for the rapid assessment of crop conditions over large areas. [See, for example, review articles by Heller (1978), Knipling (1967), and Wiegand, Gausman, and Allen (1972).] Even today people are impressed with aerial photographs and satellite images in which one can locate fields. Although some advancement in quantitative uses of these data have been made, the literature continues to report studies in which stress is dealt with in qualitative terms. For example, healthy plants appear one color (or false-color) whereas stressed plants appear as another with no attempt to separate stresses caused by different agents or report the severity of damage. Few guidelines for application of their findings are offered [e.g., Myers et al. (1970), Malingreau (1978), Rohde (1971), Rohde and Olson (1971), and Seevers, Drew, and Carlson (1975)].

Fortunately for the producer, the number of quantitative studies that attempt the exploitation of information available from aerial photography and satellite imagery is increasing. To investigate relationships between spectral and agronomic properties (such as LAI, percentage of greenness, percentage of ground cover, biomass, yield, disease, and nutritional status), researchers observe plants grown either in normal production situations or under specific stresses, measure those properties of interest, and apply statistics to generate equations to predict agronomic variables from remotely sensed data. These studies will be discussed in two sections: crop condition and yield.

4.1 CROP CONDITION

As discussed earlier, the reflectance curves of normal and malnurtured crops have a similar shape (e.g., where local maxima and minima occur), although the stressed crop may be more (or less) reflective in certain wavebands.

Corn was raised under different nutrient treatments to determine whether spectral information should be used to differentiate between normal, nitrogen-deficient, potassium-deficient, and phosphorous-deficient plants (Younes et al., 1974). They reported that, dependent upon age, separation could be made between nitrogen-deficient, potassium-deficient, phosphorous-deficient, and normal plants in the visible bands.

Al-Abbas et al. (1974) found potassium-, magnesium-, and calcium-deficient and normal corn to be more reflective than sulfur-deficient corn but less reflective than phosphorous-deficient corn between 0.75 and 2.6 micrometers. However, when they measured absorptivity, differences between treatments increased.

According to Gausman, Escobar, and Rodriguez (1973), Mexican squash also reacted to nutrient stresses (nitrogen, phosphorous, potassium, iron, sulfur, magnesium, and calcium) by a shift to greater (or lesser) reflectance in certain portions of the spectra (0.500- to 0.900-micrometer range). Iron and magnesium deficiencies were distinguishable from those of potassium and sulfur in the 0.550- to 0.650-micrometer band.

According to several authors, nitrogen deficiency increases leaf reflectance in the 0.500- to 0.700-micrometer band (as evidenced by the lighter [illegible] to yellow appearance) in many crops: cotton (also as a result of salinity) reported by Thomas et al. (1966), cabbage reported by Thomas and Gerbermann (1977), and sweet pepper reported Thomas and Oerther (1972). In the latter, regression equations were developed at two wavelengths to estimate leaf nitrogen content from reflectance.

Sorghum is readily susceptible to iron deficiency and becomes chlorotic as a result. Gausman, Cardenas, and Gerbermann (1973) took field and laboratory measurements of reflectance spectra and found that they differed from one another; although, in both sets, stressed plants were more reflective in the visible region than healthy plants. A later study by Gausman et al. (1975) of a sorghum field containing iron-deficient areas confirmed the earlier findings of field reflectance. In addition, the 1975 study showed that chlorotic areas larger than 1.1332 hectares (2.8 acres) could be identified from Earth Resources Technology Satellite (ERTS-1) data, using only one acquisition. Unfortunately, the investigators offered no discussion of areas which were identified as chlorotic but were actually healthy according to ground truth.

Reflectance also changes with leaf water content because of various physiologic responses to leaf water such as turgidity and transpiration (especially in the thermal bands). As with nutrient stresses, decreasing water content generally increases the reflectance while retaining characteristic peaks and valleys in the curve. Thomas et al. (1971) found this to be the case in field and greenhouse studies of cotton, corn, and citrus. Linear regression allowed estimation of leaf water content from reflectance at two of the water absorption bands (1.45 micrometers and 1.93 micrometers). Cotton grown on saline soil was slightly more reflective (at 1.25, 1.45, and 1.93 micrometers) than that grown on nonsaline soil. In addition, nonsaline-grown cotton was more turgid throughout the season. An earlier study also led by Thomas presented equations which related leaf moisture and reflectance in this region of the spectrum [1.45, 1.75, 1.93, and 2.22 micrometers (Thomas et al., 1966)].

The effects of the age of cotton and corn leaves on reflectance, water content, leaf structure, thickness, and chlorophyll content have been researched by the Soil and Water Conservation Research Division of the

Agricultural Research Service in Weslaco, Texas. Gausman et al. (1971) noted that the age of cotton leaves caused the greatest variation in reflectance in the near-infrared (0.75 to 1.35 micrometers) with leaf reflectance increasing from node 2 to node 8, and then decreasing gradually downward to node 13. At all ages, maxima and minima in the reflectance spectra were retained. Gausman, Allen, Cardenas, and Richardson (1972 and 1973) confirmed the earlier cotton research and found similar effects in the reflectance spectra of corn of various ages. These experiments used field-grown crops. Not surprisingly, chlorophyll content at all ages was found to be significantly correlated with reflectance. Because of the continued compactness of corn mesophyll cells, reflectance in the 0.75- to 1.35-micrometer range changed little with age, whereas cotton leaves became more reflective in this region as the mesophyll cells expanded. Rate of nitrogen fertilization affects both chlorophyll and carotenoid concentrations, which in turn influence reflectance of visible light. Using five different nitrogen rates, Thomas and Gausman (1977) examined the relative effect of these pigments on the reflectance at 0.45, 0.55, and 0.67 micrometers by cantaloupe, corn, cotton, cucumber, head lettuce, grain sorghum, spinach, and tobacco. They concluded that reflectance was primarily governed by chlorophyll concentration alone, and there was only a slight reduction in the total variance with the addition of carotenoid concentration.

The state of the art in correlating remotely sensed data with diseased and insect-infested crops remains descriptive. However, the use of remotely sensed data in monitoring pests is feasible but requires a series of acquisitions to be accurate. Earlier workers sought previsual signs of stress, especially those due to insects and disease for the obvious reason of preventing outbreaks by controlling pests and disease in areas before they became unmanageable. The authors of this paper found no consistent evidence for previsual stress detection nor did Heller (1978) in his review of remote sensing applications.

The Corn Blight Watch Experiment [MacDonald et al. (1972) and Kumar and Silva (1973)] was performed in the midwest during the 1971 growing season, the year following an epidemic of Southern Corn Leaf Blight in the Corn Belt. Biweekly aerial reconnaissance (infrared and multispectral) and ground truth were collected; fields were separated into classes of blight severity. At early stages, blight was overestimated due to the (expected confusion with other diseases, insects, drought, and malnutrition. As blight severity increased, estimates from the aerial data became comparable to ground truth.

Edwards et al. (1975) were able to distinguish between healthy orange trees and those stricken with young tree decline (YTD), using 16-band multispectral scanner data from 457.2 meters (1500 feet). Tree health and YTD stage were assessed visually The best separation by computer into healthy, slightly affected, or moderately to severely affected trees occurred in the 1.05- to 1.1-micrometer band. Classification was accomplished with an overall accuracy of 83 percent. When only two classes were considered (healthy versus all stages of YTD), classification attained 89-percent accuracy. (In this latter case, the best waveband for classification was 0.82 to 0.88 micrometers.)

4.2 YIELD

Most of the spectral yield models have been developed for large areas with Landsat data as input and will be discussed in that section.

One much published approach to yield estimates is the "stress degree day" models developed and reported in Idso, Jackson, and Reginato (1977); Idso, Reginato, and Jackson (1977); Idso, Hatfield et al. (1977); and Reginato, Idso, and Jackson (1978). The "stress degree day" is a summation of the crop-air temperature difference. Further inclusion of ground-based albedo measurements determines the minimum albedo which drives a linear regression which predicts the yield. The original model was developed for wheat in Arizona (both dryland and irrigated) with extensions to alfalfa and wheat in California.

Tucker, Holben et al. (1979) modeled winter wheat yields from hand-held radiometer data (0.65 to 0.70 micrometers and 0.775 to 0.825 micrometers). They considered the spectral radiance of the two bands individually and in combination (the ratios of infrared to red and the normalized difference) over different periods (early-, mid-, and late-season) as predictors of final yield. Although the mid-season model gave high correlations, the regression relationships were not constant. Hence, Tucker et al. opted for integration of measurements over portions of the season as well as the entire season. Again, the midseason (stem elongation to anthesis) model had the greatest r^2 (66 percent for the normalized-difference ratio).

The reflectance of the short-grass prairie and its relationship to productivity has been the continuing subject of research at Colorado State University and the USDA, directed by Miller and Pearson (1971), Tucker et al. (1973), Pearson and Miller (1973), Pearson et al. (1976), and Tucker in two reports (1977 and 1977). Several thousand measurements were taken to obtain relationships between reflectance and several agronomic variables including biomass, chlorophyll content, percentage of ground cover, and height. From these, they developed a hand-held radiometer to quickly and nondestructively estimate biomass (from the ratio of reflectances at 0.80 micrometers to 0.68 micrometers). Estimated biomass (as well as conventionally measured biomass) was used as ground truth for aircraft and satellite mapping of the condition of the short-grass prairie. Aircraft measurements taken were 12 band multispectral scanner, infrared photography, and Landsat thematic mapper. Areas were classified according to their aerially assessed conditions. Estimates of biomass were obtained from multiple linear regression of band values.

In a report on grass canopy biomass classes, Tucker (1977) states that Landsat data could resolve only three classes of biomass on the short-grass prairie. Further, resolution was best at low biomass values (before full cover), implying that the classification was actually identifying only two levels of productivity.

4.3 TEMPORAL TRAJECTORIES

Temporal trajectories of spectral changes first proved their practical application in the classification of crop acreage. Since plants have basically similar reflectance curves, discrimination between crops is best done when the sequence (and timing) of colors is followed as well as the reflectance at a particular instant.

Hlavka et al. (1978) reported a phenological crop classification scheme using multispectral, multitemporal Landsat data from five LACIE intensive test sites in Kansas. They converted the data to a gray scale (0 to 31) and developed classification techniques by associating a growth state (determined in the ground truth) with each set of signals. [Although they did not define the growth states (up to 36 were used), they stated that, at any particular time, several states could be observed within a LACIE segment and that results improved somewhat when states were pooled.] Growth-state signatures were not unique; hence, the earliest possible growth state was assigned to an observation. These growth states had to occur in sequence for classification. The scheme identified 89 percent of the corn and 83 percent of the wheat, with only about 5-percent false classification. They also reported that soil corrections and band ratio methods aided classification only slightly.

In a crop, reflectance changes with time not only because of the changes at the cellular and leaf level but also because of the amount of soil cover. (Two common parameters of this are percentage of ground cover and LAI.) In addition, a series of acquisitions gives the most information on the progress and severity of stress on a crop.

Other studies besides the previously discussed Soil and Water Conservation Research Division's cotton and corn projects and the Colorado State University and USDA's short-grass prairie projects have been conducted to determine the changes of reflectance with time and the reflectance relationship to biomass. Eleven crops (red fescue, quack grass, Kentucky blue grass, perennial rye grass, mixed grasses, potatoes, sugar beets, beans, barley, oats, and wheat) were grown in field plots and their reflectances measured several times throughout the season with a field spectrometer for purposes of classification (DeBoer et al., 1974). They found that the relationship between the biomass of grasses (in particular, Kentucky blue grass) and reflectance (at 0.871 and 1.265 micrometers) was linear until the canopy closed; it became nonlinear after the canopy closed.

Leamer et al. (1978) observed seasonal reflectance patterns in two wheat cultivars in field plots with a ground-based spectroradiometer. They found that seeding rate affected the rate at which ground cover occurred but not the reflectance once 25-percent ground cover was reached. Wavelengths considered were midpoints of the four Landsat bands and in between the water absorption bands (1.65 and 2.2 micrometers). The latter were found to be good indicators of vegetative density, as soil is more reflective at these wavelengths and, consequently, easily separated from vegetative signals. Correlation coefficients of reflectances with percentage of ground cover varied with the development of the crop, indicating the time dependency of reflectance.

Kanemasu (1974) also considered field spectral measurements of wheat, sorghum, and soybeans on two soil types. He advocated the use of ratios as a means of removing solar elevation variations in order to compare data across the season. Although the ratio of reflectances at 0.54 micrometers to 0.65 micrometers (corresponding to Landsat bands 4 and 5) could not discriminate between LAI and percentage of ground cover, equations were developed by Kanemasu to estimate these parameters from either the ratio or infrared reflectance.

Collins (1978) observed what he termed a "red-shift" of 0.007 to 0.010 micrometer in the 0.745 to 0.785-micrometer band in both sorghum and wheat at heading. In addition, the degree of heading and canopy density were indicated. This red-shift was observable with high resolution spectral measurements taken of 300 fields during two airborne runs in California's Imperial Valley. A smaller red-shift was also noticed in alfalfa, cotton, and other nongrains as they approached maturity. Collins hypothesized that the shift is due to increased chlorophyll concentrations during growth, causing stronger absorptance in the green band and the subsequent shift of the spectrum toward red.

Tucker and others monitored the spectral changes of corn and soybean plots with time [Tucker, Elgin, and McMurtrey (1979); Tucker, Elgin, McMurtrey and Fan (1979); and Tucker (NASA TM 79620, 1978)]. Red and infrared reflectances and vegetative indexes (from ground-based measurements) were correlated with agronomic variables (percentage of ground cover, plant height percentage of chlorosis, wet biomass, and dry biomass). All showed a definite time dependency. Tucker et al. identified five distinct, spectrally measurable stages for both crops as follows: emergence to about 25-percent cover, rapid foliar growth and development, fall vegetative cover, onset of senescence and maturity, and crop maturity and harvest readiness. They comment on confusion due to stress and weeds and express hope that these considerations, along with stage information, can be incorporated into yield models.

On a larger scale, the use of satellite data in the monitoring of the natural progression of vernal greening and autumnal browning across continents (termed "green wave" and "brown wave") was one of the first patterns to be noticed when satellite imagery became available. Consequently, the work done was more descriptive than practical, leaving countless regression equations which relate band ratios and vegetative indexes to the percentage of greenness of various target areas of known vegetation. Lilac, alfalfa, wheat, and range were considered in the cooperative study headed by Dethier (1974). Extensions of this work were published by his coworkers [Ashley and Rea (1975) and Blair and Baumgardner (1977) on forests].

Carneggie et al. (1975) described the color change of California's annual grasslands with time as observed by Landsat. Ground spectral reflectance was measured at two sites to determine ratios to be used in interpreting the satellite data. They reported that the seasonal growth and dormancy cycles could readily be monitored. They found that the ratio of band 7 to band 5 was the best indicator of production and the green-feed period. These authors suggested that regressions or experience be used to obtain quantity of production, acknowledging that, at the present, only relative range conditions could be deduced from Landsat.

5. LARGE AREA APPLICATIONS

There are several problems in the evaluation of large-scale attempts to estimate stress from spectral measurements. In the first place, the ground truth comparison standard tends to be subject to considerable measurement error. Second, if bias is small, compensating prediction errors can indicate excellent agreement with ground truth overall, despite large standard errors. Third, some large area models have included nonspectral variables. This makes it difficult to evaluate the spectral contribution. Fourth, since failures are less apt to be published, the apparent significance of published results may be fortuitous. Some of all of these problems may be involved in the consideration of the following examples.

ERIM personnel [Colwell et al. (1977) and Nalepka et al. (1978)] compared the use of TVI, SQ75 (i.e., $\sqrt{\frac{MSS7}{MSS5}}$), and all-band models to predict winter wheat yields of several fields at three sites in Kansas. The study was based on previous results showing high correlation between percentage of ground cover and yield and between percentage of ground cover and SQ75. Results with all Landsat measures were remarkably good on both training and test fields. No clear superiority was demonstrated for any particular Landsat combination. The SQ75, at heading, was later used to predict wheat production in several counties (6 and 10) with excellent results. No formal evaluation of significance was performed.

Schubert and Mack (1977) used percentage of ground cover to estimate yield. The authors call these biomass indexes. They actually are the percentage of pixels within an area of a particular vegetative class (wheat and all vegetation) that are classified as having a closed green canopy based on the band 7/band 5 ratio. These indexes were calculated for three phenological phases: emerged (from emergence to 2 weeks before heading), heading (from 2 weeks before to 2 weeks after heading), and ripe (all subsequent dates up to harvest). When these indexes were compared with yields over 3 years (1973 through 1975) and several sites, the correlation coefficients averaged above

0.9 for the first two phases. The ripe phase correlations were much poorer. A test of predicted versus published yields in a later year (1976) showed that only the wheat index was satisfactory. No formal statistical analysis was performed, but this type of variable appears promising, since it introduces spatial information.

Helman et al. (1977) used a complex Landsat multichannel regression equation to estimate LAI over a five-state winter wheat region. The LAI estimates were combined with an evapotranspiration model to estimate soil-water depletions and yields. The results were not evaluated statistically.

Thompson and Wehmanen (1977, 1979) used a Green Index Number (GIN) technique developed in South Dakota to detect and monitor agricultural vegetative water stress over the U.S. Great Plains (USGP), the U.S.S.R., and Australia. The GIN is defined as the percent of pixels in a segment with green numbers greater than 15. Green number is obtained by subtracting the soil line from ERIM Greenness. The soil line is the lowest Greenness in the segment after eliminating the 228 (1 percent) pixels of lowest Greenness. A chi-square test showed that, in the USGP, the drought versus normal designations using GIN had a highly significant correlation with comparable splits based on the Crop Moisture Index (CMI) which is a measure of relative water availability. Results in the U.S.S.R. and Australia could not be evaluated statistically.

6. CONCLUSIONS

The technical literature demonstrates that while remarkable progress has been achieved in the uses of remote sensing in agricutural research a number of problem areas remain. The properties of electromagnetic waves are reasonably well known both in terms of propagation through realistic atmospheres and interaction with simple surfaces. However, the relationships between variations in typical sensor data and events of agricultural interest are less clear.

General applications of remote sensing to the estimation of plant growth, stress, and yield are dependent upon a number of factors. Improved resolution (spectral, temporal, and spatial) will certainly help. More immediate attention can be given to a number of specific actions, which are feasible with existing sensors and within existing programs, these actions are:

a. A strong and continuing commitment to a field measurements program is needed. This includes Landsat and aircraft sensor data coordinated with ground truth observations. Experimental sites should include normal agricultural as well as specially designed field experiments.

b. Research data bases containing spectral, meteorological, and ground truth observations are a prime requirement. Wide temporal and geographical coverage for a number of crops is needed. Documentation and easy availability to the general research community are essential.

c. Renewed research into signature extension techniques is needed for large area quantitative estimation of plant characteristics. The lack of conclusive evidence that any current approach has general applicability to large areas argues that existing normalization techniques are inadequate. Priority should be given to the development of alternative approaches to this problem.

d. Priority should be given to the development of spectral crop calendars. Yield components and stress indicators cannot be reliably estimated unless spectral crop calendars are available.

e. Additional research is required on the effects of the averaging of spectral data at both pixel and field levels. The assumption that simple arithmetic averages are satisfactory is probably unwarranted. The use of spatial information (within field) should be investigated.

f. Research into simple atmospheric correction algorithms should be supported.

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