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REFLECTANCE OF VEGETATION, SOIL, AND WATER

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16. Abstract

Iron deficient (chlorotic) and normal (green) grain sorghum (Sorghum bicolor (L.) Moench) plants were sufficiently different spectrally in ERTS-1 band 5 CCT data to detect chlorotic sorghum areas 2.8 acres (1.1 hectares) or larger in size in computer printouts of the MSS data. The ratio of band 5 to band 7 (5/7) or band 7 minus band 5 (7-5) relates to vegetation ground cover conditions and helps to select training samples representative of differing vegetation maturity or vigor classes and to estimate ground cover or green vegetation density in the absence of ground information. The four plant parameters leaf area index (LAI), plant population, plant cover, and plant height explained 87 to 93% of the variability in the band 6 digital counts and from 59 to 90% of the variation in bands 4 and 5. A ground area 2244 acres in size was classified on a pixel by pixel basis using simultaneously acquired aircraft support and ERTS-1 data. Overall recognition for vegetables, immature crops and mixed shrubs, and bare soil categories was 64.5% for aircraft and 59.6% for spacecraft data, respectively. Overall recognition results on a per field basis were 61.8% for aircraft and 62.8% for ERTS-1 data.

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INTRODUCTION

The work planned under this contract had three stated objectives:

1. To compare experimental results using ERTS-1 data with predictions of analytical models for interaction of light with vegetation.
2. To determine the seasonal changes of the various crops and soils in Hidalgo County, Texas and discriminate them by means of reflectance measured from ERTS-1.
3. To gain experience developing an operational system of satellite data analysis tailored to the needs of the U.S. Department of Agriculture.

The objectives can be logically grouped into substudies in the following categories:

1. Crop vigor and potential crop yield
   a. Relation to leaf area index (LAI) and to MSS signal strength
   b. Iron deficiency detection
   c. Crop vigor categories within crops and their relation to yield.
2. Crop discrimination
   a. Cotton versus sorghum
   b. Among vegetables
   c. Optimum time of year to discriminate citrus
   d. Dominant rangeland plants
   e. Rangeland condition

3. Soil

   a. Bare versus cropped land

   b. Major soil types

   c. Spectral contrast between freshly irrigated and nonirrigated soil

   d. Spectrum of saline soil and distribution of salt-affected soil.

The crop vigor and potential crop yield studies are based on laboratory and aircraft experience that resulted in an understanding of the interaction of light with vegetation and the subsequent definition of most useful wavelengths for indicating physiological stress and for discriminating among crop genera. Analytical models were also produced relating reflectance to crop vigor and leaf area index.

The second and third groups of studies are based on computer identification procedures. Procedures developed using film optical densities and aircraft scanner data are being refined and applied to ERTS-1 data.

GROUND DATA COLLECTION

Hidalgo County, Texas has been chosen as the base area from which data are collected and analyzed. The complete County was chosen as the base unit because this is the governmental unit by which agricultural census data are collected and summarized, and is the unit by which crop allotment and acreage restrictions are most commonly administered.

Because of the need for extensive ground truth representative of the County to use as a basis for comparing the reliability and accuracy of the ERTS-1 data interpretations, statisticians of the Statistical Reporting Service, USDA, were asked to design a sound sampling procedure for the County that would allow a valid summary of data for the County

from the sample. Hidalgo County contains three major agricultural areas which may be designated as Northern, Central, and Southern. The Northern region is mainly pasture and rangeland with a little irrigated farming located around local water supplies. The Central region is practically all under irrigation. The cultivated land is generally broken into small fields, of typically medium-textured terrace soils devoted to mixed field and vegetable row-crops, citrus, and miscellaneous farm enterprises. The Southern region of Hidalgo County is generally fine-textured soil that is used extensively for winter vegetable production. The majority of land in the Southern region is irrigated. Urban and other non-agricultural areas are found mainly in the Central region. The urban areas are not included in the survey.

The sampling procedure used was to divide the County into approximately 160-acre segments and assign each segment a number. By the random start and increment method, four interpenetrating samples of 43 segments each were selected. These were distributed through all three regions. Four more interpenetrating samples were selected, but only the segments located in the Southern region were designated sampling sites. These 25 additional segments in the Southern region were chosen because of the concentration of winter vegetables in the Southern region when few crops are growing in the other regions. A total of 197 sampling segments was chosen from the 3,927 segments listed for the County. The sampling area is thus approximately 4% of the total area.

Each of the 197 segments was located on a base aerial map of the County and assigned a unique number designation. Each field in each segment is being ground-truthed and each is numbered. Fields are, by definition, plots of land devoted to the same crop or use. The number of fields fluctuates slightly. The total number of fields being ground-truthed each satellite pass is approximately 1,400.

After each sample segment has been visited, the field information is coded by the technician in charge of ground-truthing and recorded on 80-column computer punch cards. The data on the computer cards are later edited and stored on magnetic tape for use in the analysis of the satellite data. A print-out of these tapes is given to the ground truth personnel. The magnetic tapes and computer cards are stored in separate buildings to minimize the chances of data loss.

Considerable information of agricultural importance can be extracted from these ground truth data; however, the main reason for collecting such a complete set of records is their use as an independent data set to judge the reliability and accuracy of the county-wide interpretation of ERTS-1 data. Such data also provide the training fields used in computerized recognition algorithms. The various steps in processing computer compatible (CCT) ERTS-1 tapes at Weslaco are described in Appendix C of the Type II report for the period December 19, 1972, to June 19, 1973.

RESULTS

Technique Development

Satellite Band Ratio Procedure

An ERTS satellite band-ratio procedure has been developed at Weslaco, Texas that enhances line printer gray maps for more efficient experimental test site location. The ratio process was developed while looking for preprocessing techniques that would improve crop and soil discrimination for the December 16, 1972, ERTS overpass using digital data from satellite CCT (one of the continuing research objectives listed in the Weslaco Type II Report; December 19, 1972, to June 19, 1973).

Using the three training categories vegetables, citrus, and a category composed of immature row crops, bare soil, weeds, and grasses (December 16, 1972, ERTS overpass) discrimination results were compiled for all possible pairwise ratios of the 4 MSS ERTS bands. As can be seen in Table 1, the ratio of MSS (5/6) and MSS (5/7) each gave an overall correct recognition of 86.9%. Table 1 also shows that the highest overall correct recognition among all 4 bands taken singly was band 7 at 81.4%. Another interesting aspect of the results from Table 1 is that the ratio of a visible band to an infrared band yields relatively high recognition results (81.7 to 86.9% recognition) while a ratio of the two visible (4/5) or the two infrared (6/7) bands yield relatively low recognition results (74.6 and 58.3% recognition). These results support previous results (Type II Report; December 19, 1972, to June 19, 1973) that the visible ERTS bands 4 and 5 and the infrared ERTS bands 6 and 7 are spectrally interdependent.

Table 1. Pattern recognition results from ERTS December 16, 1972, data for the three training categories vegetables, citrus, and a category composed of immature row crops, bare soil, weeds, and grasses.

All possible pairwise ratios of ERTS bands	Overall recognition results	ERTS bands taken singly	Overall recognition results
4/5	74.6	4	60.0
4/6	81.7	5	64.1
4/7	82.5	6	74.1
5/6	86.9	7	81.4
5/7	86.9	-	--
6/7	58.3	-	--

From these results it appeared that the ratio of a visible band and an infrared ERTS band probably would make a useful method of enhancing ERTS scenes. Specifically, line printer gray maps using ERTS MSS ratios 5/6 or 5/7 would be very useful for identification and location of ERTS experimental sites in the CCT. A comparative study using the ERTS MSS (5/7) ratio was made with line printer gray maps such as Figs. 1, 2, and 3. These figures are gray maps of one typical experimental site (segment 5177). The ratio range is determined by the mean plus and minus two standard deviations of all data values encountered in the CCT. The gray map display is made up of 5 symbols that differ in amount of printer paper obscured per symbol. Figure 1 is a display of band 5 data values only; Fig. 2 is a display of band 7 data values only; and, Fig. 3 is a display of the 5/7 ratio data values.

The display of band 5 (Fig. 1) shows good contrast in land features, but the river boundary cannot be discerned. Band 7 (Fig. 2) shows the river boundary, but land features are not as distinct as in Fig. 1. The ratio of 5/7 expresses the best of both bands; that is, the river boundary is distinct and the land features have good contrast. As a result of these comparative studies, gray maps using the MSS (5/7) ratio have been used to locate the 197 experimental sites in the Weslaco ERTS investigations (Data Analysis Plan). Several sites that could not be located on single band gray maps have now been located and the boundaries of other tentatively located sites have been corrected, indicating the usefulness of this image display technique.

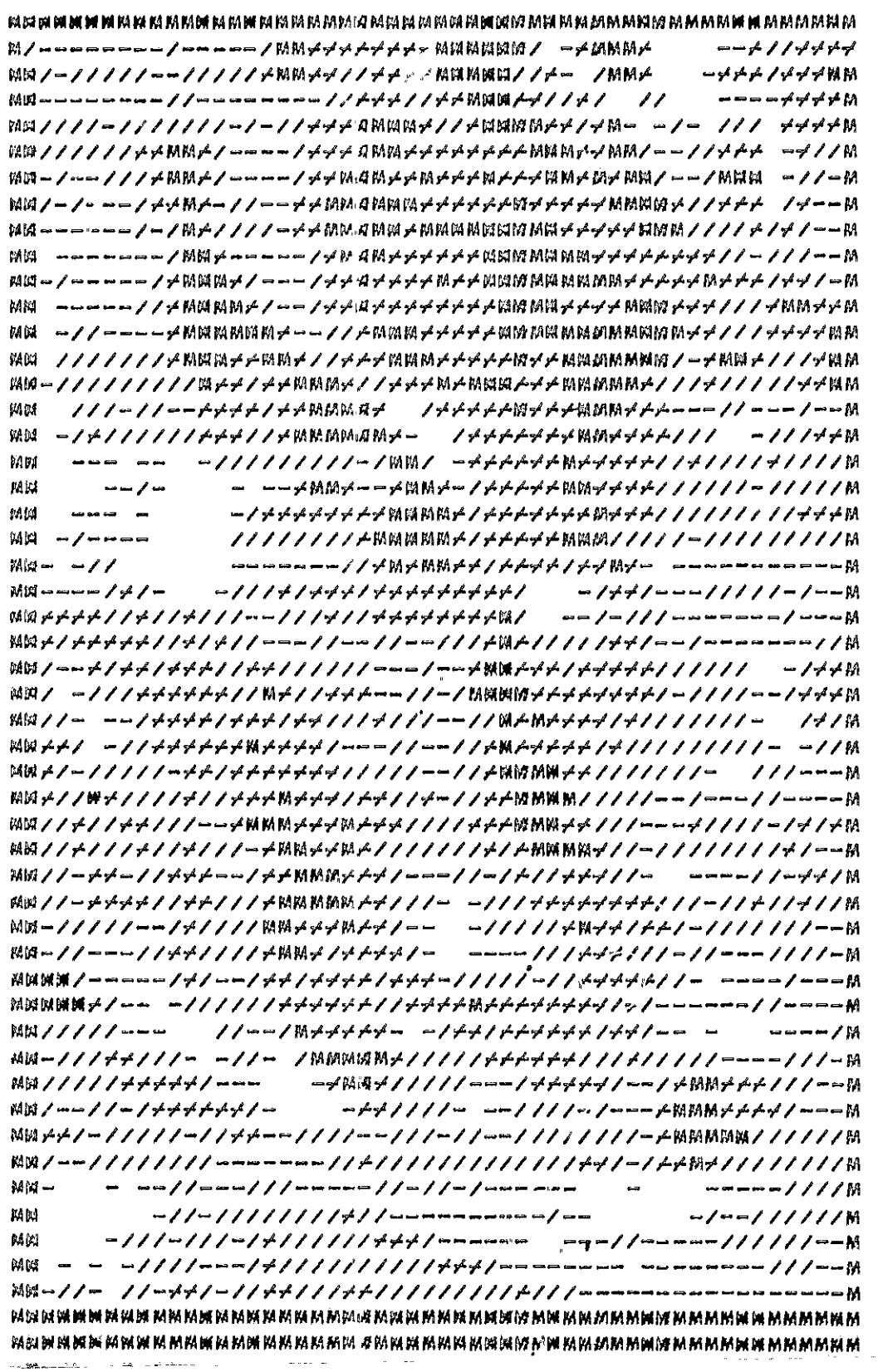

Figure 1. Five level line printer gray map of segment 5177 using ERTS MSS band 5. December 16, 1972, ERTS overpass.

Figure 2. Five level line printer gray map of segment 5177 using ERTS MSS band 7. December 16, 1972, ERTS overpass.

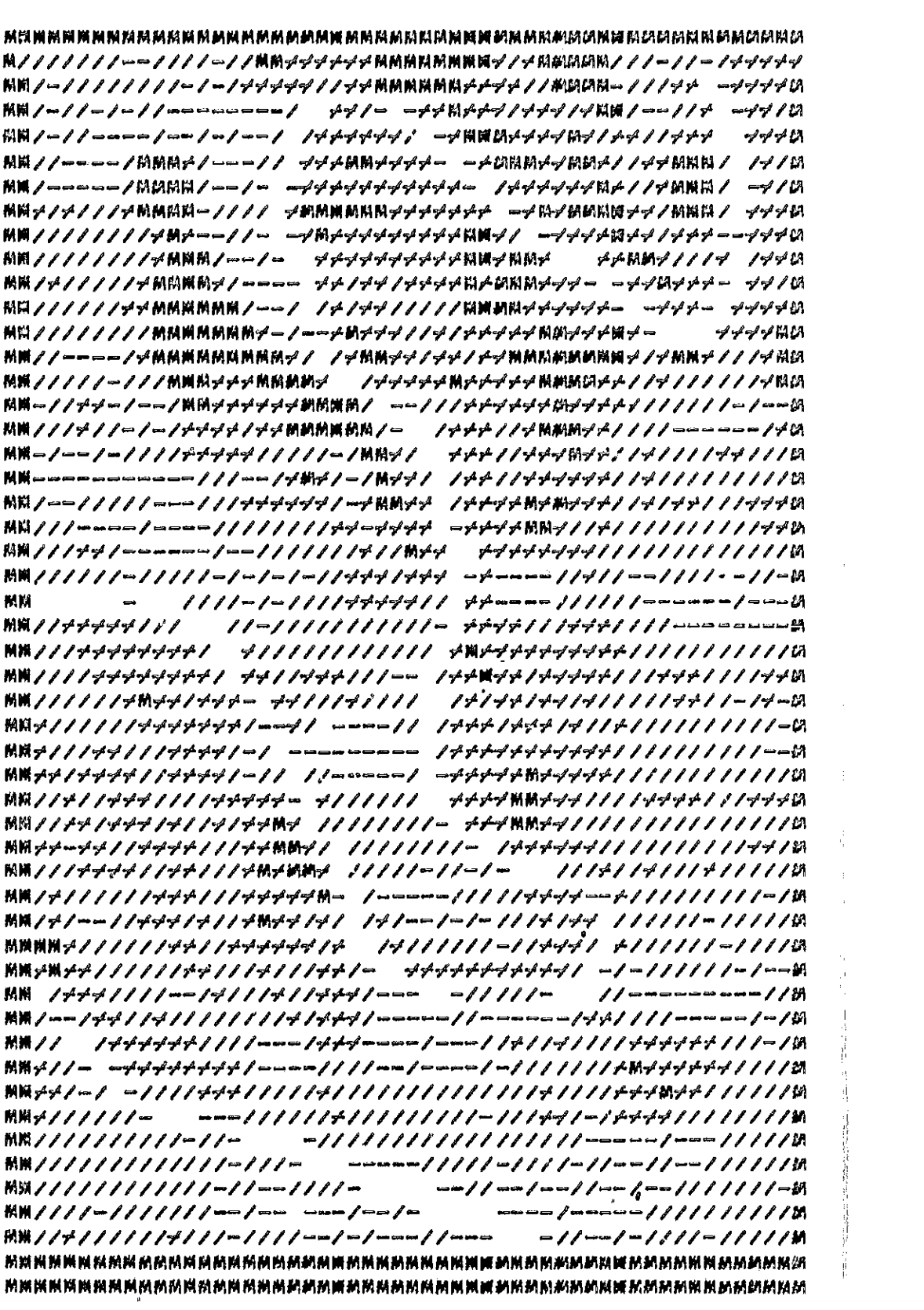

Figure 3. Five level line printer gray map of segment 5177 using ERTS MSS band ratio 5/7. December 16, 1972, ERTS overpass.

Three-Dimensional Display of ERTS Data

Two methods have been developed to present ERTS MSS signal strengths in three dimensions. One method displays the points in a two-dimensional drawing representing the distribution three variables would take in three-dimensional space. The proportions and angle of perspective are adjusted to match the limits of a single page of computer printout. Both ends of a rectangular box are drawn by the computer and the edge lines are indicated on the drawing. Data points are located within the box in proportion to their vector lengths along the X, Y, and Z axes. The vectors along the three axes can represent signal strength, ratios between signal strength, numerical differences between signals, variation from the mean signal strength, or proportion of the total signal strength from each channel. Any of the three axes can represent any of the desired variables.

The data for the ground-truthed areas in Hidalgo County are grouped into categories that represent similar ground cover. For example, one grouping used is: vegetables, citrus, forage, weeds, field crops, bare soil, harvested fields, and non-agricultural areas. A three-dimensional diagram can be generated from each category, or any combination of categories.

The completed scatter diagram shows the relation between the three variables chosen. The center of the cluster of points for each category is indicated by a distinctive symbol so the center of the various clusters can be compared with clusters formed by other categories.

The other three-dimensional technique is a cubic histogram in which the three edges of a cube are ratioed to three variables similar to the isometric drawing. The cube is divided into cells arranged in rows, columns, and layers along the three axes. The number of data points falling into each cell within the cube is counted as the data are read by the computer. When all data points have been read, each layer of the cube is printed as a two-way histogram with the number of data points in each row and column shown for each layer.

Where the data are divided into multiple categories, two cubes are generated simultaneously. One cube contains the number of data points falling in each cell; the other lists the categories having data falling in each cell. The two cubes are printed side-by-side, layer-by-layer making it possible to locate clusters of data points along the three axes and to tell which categories are represented in each cell. Clusters of data points and their distribution pattern are thus readily apparent as well as overlapping of clusters and the categories included in the overlapping.

Acreage Estimates of Major Land Uses in 1973

Spring-Summer Crop Season

Acreage data have been compiled for all the cotton, sorghum, citrus, rangeland and improved pastures found in the 197 segments used for ground truth. The 197 segments comprise approximately 40,000 acres. The citrus was considered in three categories--oranges, grapefruit, and mixed (plantings of more than one variety in an orchard).

Table 2 lists acreages for each crop by interpenetrating sample series. The total acreage for each crop or land use is also given. Estimates on a county-wide basis were calculated from the interpenetrating sample series acreage using instructions supplied by the SRS. To estimate the acreage of cotton, for example, acreage for each of the 1000 to 4000 series was multiplied by 91.3256 (the factor supplied by SRS). The grand total of the four series was then divided by four to yield the County estimate, 129,714 acres, shown in Table 2. Table 2 gives the County estimate in acres for each crop considered. The estimates include the farmable land devoted to turnrows.

Table 2. Acreages devoted to various crops and land uses in Hidalgo County in 1973 as ground-truthed in four interpenetrating sample series and the resultant estimate for the whole County. August ground truth used to estimate acreages.

CROP	SERIES 1000	2000	3000	4000	COUNTY ESTIMATE
	- - - - - - - - - - Acres - - - - - - - - - -				
Cotton	1170.36	1256.89	1537.35	1716.77	129,714
Sorghum	1070.87	1277.43	3220.59	2436.87	182,783
Mixed Citrus	792.91	717.17	461.98	391.09	53,954
Oranges	287.82	166.36	86.93	200.35	16,929
Grapefruit	145.33	85.15	192.27	184.42	13,863
Rangeland	3596.17	2629.46	2515.41	2867.86	137,845
Improved Pastures	848.95	2616.11	392.11	774.09	57,169

A study was made on a few selected segments to determine the amount of farmable land devoted to turnrows for certain crops. On the average, 8.18% of the area in cotton fields was devoted to turnrows. Not enough data were available to determine the percentage for citrus. The small amount of data available for sorghum suggested that, on the average, 8% of the fields was used for turnrows. The acreage estimate for cotton of 129,714 acres reduced by the 8.18% used for turnrows leaves an estimated 119,103 acres actually planted in cotton. The Agricultural Stabilization and Conservation Service of the USDA reported a total of 113,348 acres in cotton in Hidalgo County in 1973.

It is planned to classify all of Hidalgo County by computer for the January 21, 1973 (scene I.D. 1182-16322) and May 27, 1973 (scene I.D. 1308-16323) cloudless overpasses and compare the acreage estimates obtained from the ERTS-1 MSS data classification with those of the ground truth for as many spectral categories as can be distinguished.

Fall-Winter Crop Season

The predicted acreage of the three most extensively planted winter vegetables in Hidalgo County, Texas, as of December 11, 1973, were cabbage, 11,300 ± 7254; carrot, 8,800 ± 4486; and, onion, 12,500 ± 6376 acres.

Between August 25 and December 11, 1973, the sample segments were ground-truthed seven times.

Figure 4 shows that cabbage was the first of the three crops to be planted. Cabbage seedlings were observed first on August 25, while first onions were observed on October 18, 1973.

The major portion of the cabbage was planted the latter part of October and the early part of November. By December 12, 1973, about 1500 acres had been harvested at least once and 1000 acres had been harvested twice.

The majority of the carrots were planted during the month of November. However, earliest fields were being harvested by December 11.

Most of the onions were also planted during November. Harvest will not occur until spring.

The planting patterns in 1973 were affected by the weather. Rainfall at Weslaco totaled 7.4 inches in June and 10.22 inches in August. Hence, it was September or later before fields were dry enough to plant in many cases.

ERTS-1 overpasses on December 11 and December 29, 1973, occurred under cloudless conditions so that ERTS-1 MSS CCT tapes should become available for studying the acreage of fall vegetables.

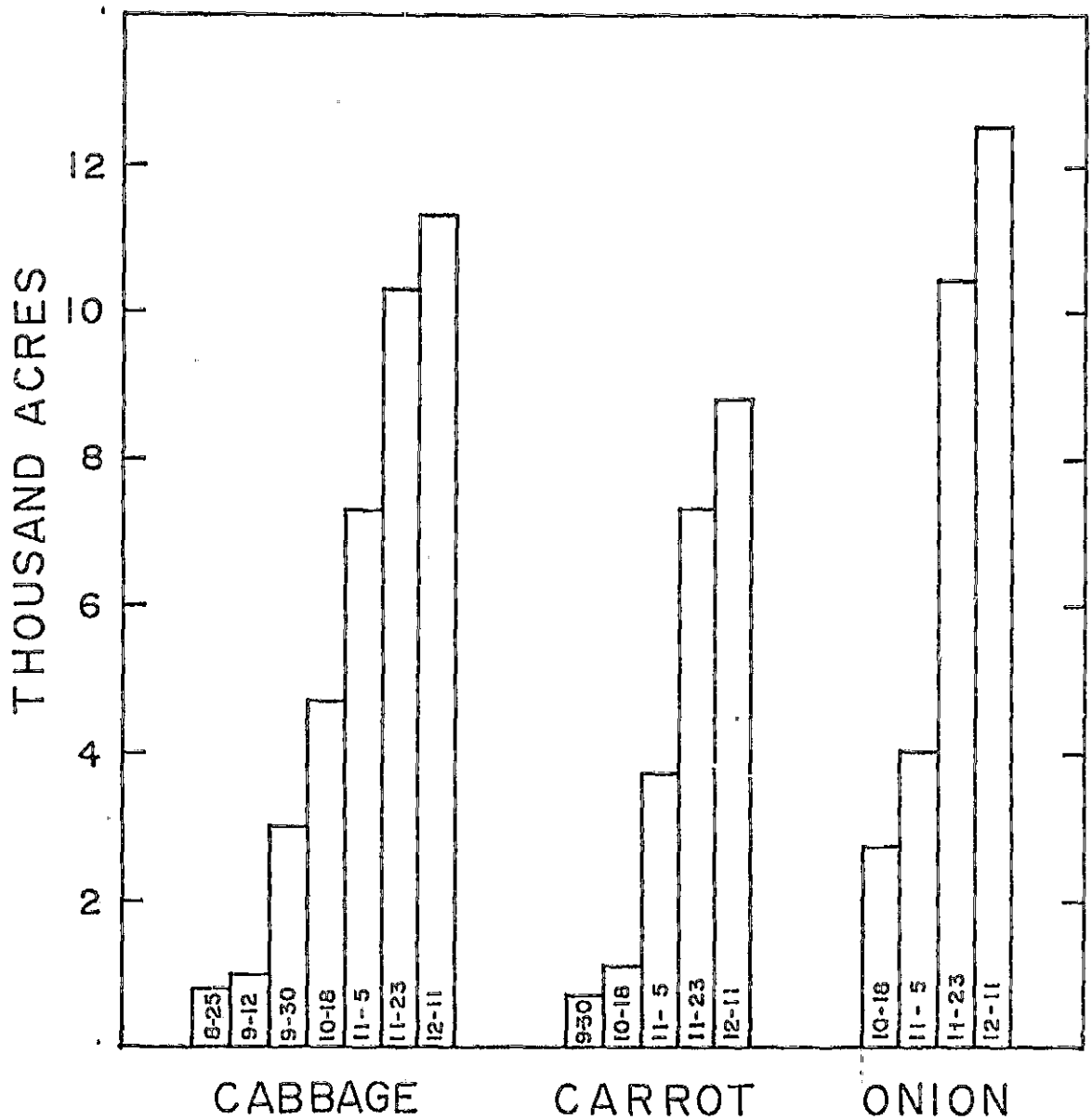

Figure 4. Acreage estimate of three winter vegetables in Hidalgo County, Texas, from County sample segments observed on ERTS-1 overpass dates August 25 through December 11, 1973.

Detection of Iron-Deficient Grain Sorghum

A study was conducted to determine if multispectral data from ERTS-1 could be used to detect differences in chlorophyll concentration between iron-deficient (chlorotic) and apparently normal (green) grain sorghum (*Sorghum bicolor* (L.) Moench) plants in a 340-acre (139 hectares) field. Channel 5 (0.5 to 0.7 μm) data were selected, representing the chlorophyll absorption band at the 0.65 μm wavelength. Chlorotic sorghum areas 2.8 acres (1.1 hectares) or larger in size were identified on a computer printout of channel five data. This resolution is sufficient for practical applications in detecting iron-deficient sorghum in otherwise uniform fields. The complete manuscript for publication in *Photogrammetric Engineering* describing this work is included as Appendix A of this report.

Vegetation Density Deduced from ERTS-1 MSS Response

Allen and Richardson ("Interaction of light with a plant canopy," J. Opt. Soc. Amer. 58:1023-1028, 1968) showed theoretically that reflectance from plant canopies, as measured from space, in the 0.75- to 1.35-μm wavelength interval could be used to predict leaf area index (LAI) of vegetation. Since LAI is a well known indicator of plant maturity and vigor, inferences based on space imagery should be possible regarding the maturity and probable yield of crops, or the animal-carrying capacity of rangeland.

In this contract, the digital counts measured in ERTS-1 bands 4, 5, 6 and 7 are being related to the LAI and other plant parameters such as plant height, plant population, and plant cover measured in 4 corn, 10 sorghum, and 10 cotton fields to test the relation between LAI measured in these selected fields and the predictions of the mathematical model, and to determine the extent to which the ERTS-1 MSS digital counts are explained by the plant parameters measured in ground-truthing.

Work on developing an operational system has required assessment of ways to differentiate among fields of the same crop that differ in amount of vegetative cover. It has been found that the ratio of band 5 to band 7 (5/7) or band 7 minus band 5 (7-5) relates to differing cover conditions. This allows a given crop to be subdivided into narrower spectral categories depending on stage of maturity or vigor class, or conversely to estimate ground cover or green vegetation density from ERTS-1 bands 5 and 7 in absence of ground information. The paper presented at the Third ERTS Symposium in Washington, Dec. 10-14, 1973, is included as Appendix B of this report.

Detection of Dry Plant Debris and Dead Vegetation

A Beckman model DK-2A spectrophotometer, equipped with a reflectance attachment, was used to measure the reflectance over the 0.5- to 2.5-μm wavelength interval of dry avocado, citrus, corn, cotton, grain sorghum, and sugarcane leaves and the reflectance of respective soils on which the dry leaves were lying. The largest reflectance difference between dry leaves and soil and the corresponding wavelength for each crop were avocado, 15.7%, 1.05 μm; citrus, 15.3%, 0.95 μm; corn, 24.5%, 1.3 μm; cotton, 18.1%, 0.9 μm; grain sorghum, 22.1%, 0.95 μm; and sugarcane, 19.2%, 1.9 μm. With the exception of sugarcane, the largest reflectance differences between dry leaves and soils for the crops occurred on the near-infrared plateau over the 0.75- to 1.35-μm wavelength interval. The largest reflectance difference for sugarcane on the near-infrared plateau was 18.7% at the 0.65 μm wavelength.

These results suggest that the differences in reflectance between dry crop debris on the soil surface and the soil itself might be large enough in certain wavelengths to detect the difference in satellite data.

A quick check was run on this possibility using data from the December 16, 1972, ERTS-1 CCT. The data were selected from among fields that differed in percent dry plant debris at the time of the satellite overpass.

The reflectance data from MSS channel 6 were plotted against percent dry plant debris cover. The plotted data points formed a line that had zero slope. When the data from MSS channel 5 was ratioed to the data from channel 6 the data points formed a line with at most a 2° slope.

These preliminary results suggest that discrimination between plant debris and bare soil using ERTS-1 MSS data needs further study. Such a study is in progress even though the wavelengths available on ERTS-1 are not the most appropriate ones, as indicated by the laboratory reflectance data cited. Dry vegetation is also of interest in estimating winter range conditions, especially where ranchers depend on the dry forage to overwinter their stock. Sugarcane and other agricultural crops are also susceptible to damage or destruction by freezing temperatures. Thus freeze damage assessment, along with the other applications mentioned, are worthy uses of data involving spectra of dry vegetation.

Rangeland Segment Characterization

Eight of the segments in the rangeland part of Hidalgo County are being studied to determine the total percent cover and percent composition of woody species. They represent 4 principal range sites. Based on Soil Conservation Service (SCS) soil maps the range sites are distinct and generally uniform. All these segments are native rangeland areas on which no brush control methods have been practiced.

These rangeland segments were chosen because they represent the majority of the rangelands in the ERTS study area. They will be used as training samples for automatic classification (computer) of rangelands.

To determine percent cover and percent composition of woody species present, the line transect method described by Canfield (Canfield, R. H. 1941. Application of the line interception method in range vegetation. J. of For. 39:388-394) was used. This method consists of ten lines 100 feet long located randomly within each range type. The name and distance along the line occupied by any woody species intercepted by the line is recorded on a field data sheet. From these data both percent cover and percent composition are calculated.

The deep sand range site represented by segments 3087 and 3088 is an open, brushy site with many grasses and forbs associated with Nueces, Sarita, and Falfurrias soils. This site is best characterized as a savannah type with large mature mesquite (*Prosopis glandulosa* Torr.) trees scattered in small motts, or singly over grasslands. The total percentage of woody cover for this site is 23%. Although mesquite is the dominant species here, other woody plants are granjeno (*Celtis pallida*, Torr.), catclaw (*Acacia greggii* Gray), tasajillo (*Opuntia leptocaulis* DC.), and lotebush (*Ziziphus obtusifolia* (T and G) Gray). It has moderate to heavy herbaceous ground cover with little bare ground visible.

The improved rangeland sites typified by segments 2047 and 2051 have been cleared of native brush and have been seeded to buffelgrass (*Cenchrus ciliaris* L.). Approximately 90% of the plants are buffelgrass, the remaining percentage being native grasses and forbs. Little bare ground is visible on this site, as the herbaceous cover is quite dense.

The gray sandy loam range sites represented by segments 1022 and 2065 are mixed brush sites associated with Brennan, McAllen, and Pharr fine sandy loam soils. The brush is thick and it is composed of a large variety of woody species. The woody cover for this site is 50-55%. Major woody species here are Cenizo (Leucophyllum frutescens (Berl.) I.M. Johnst.), mesquite, granjeno, resin-bush (Viguiera stenoloba Blake.), blue salvia (Salvia ballotaeflora Benth.), and blackbrush (Acacia rigidula Benth.). This site is very productive and supports a large variety of native grasses and forbs with uniform plant cover; little bare ground is visible.

The red sandy loam range site typified by segments 1003 and 4132 is a mixed brush site associated with Delmita-Randado soils. It is best described as rather open with mostly low brush species except for occasional large mesquite trees. The percentage of woody cover is 24%. Dominant woody species are mesquite, blackbrush, lime prickly ash (Zanthoxylum fagara Sarg.), and bluewood condalia (Condalia hookeri M. D. Johnst.). This site is only fair to moderate in productivity and has many bare areas between plant ground cover. It supports a variety of native grasses and forbs.

Figure 5 depicts the average raw digital counts for 4 different range sites on 3 different ERTS-1 overpass dates. The figure depicts only one set of data for each range site; however, more than one set of data was extracted for each from the CCT, and they were in close agreement.

The data for channels 4 and 7 were closely grouped within channels for all dates suggesting range sites differ little in these 2 bands. Data in channels 5 and 6 varied more within channel and may contain useable information.

The red sandy loam range site had the highest reflectance on all dates. This high reflectance could be caused by low vegetative cover. The gray sandy loam range site had the lowest reflectance on all dates. The low reflectance agrees with its high percent woody cover causing a large percent of ground shadow; shadow areas have low reflectance.

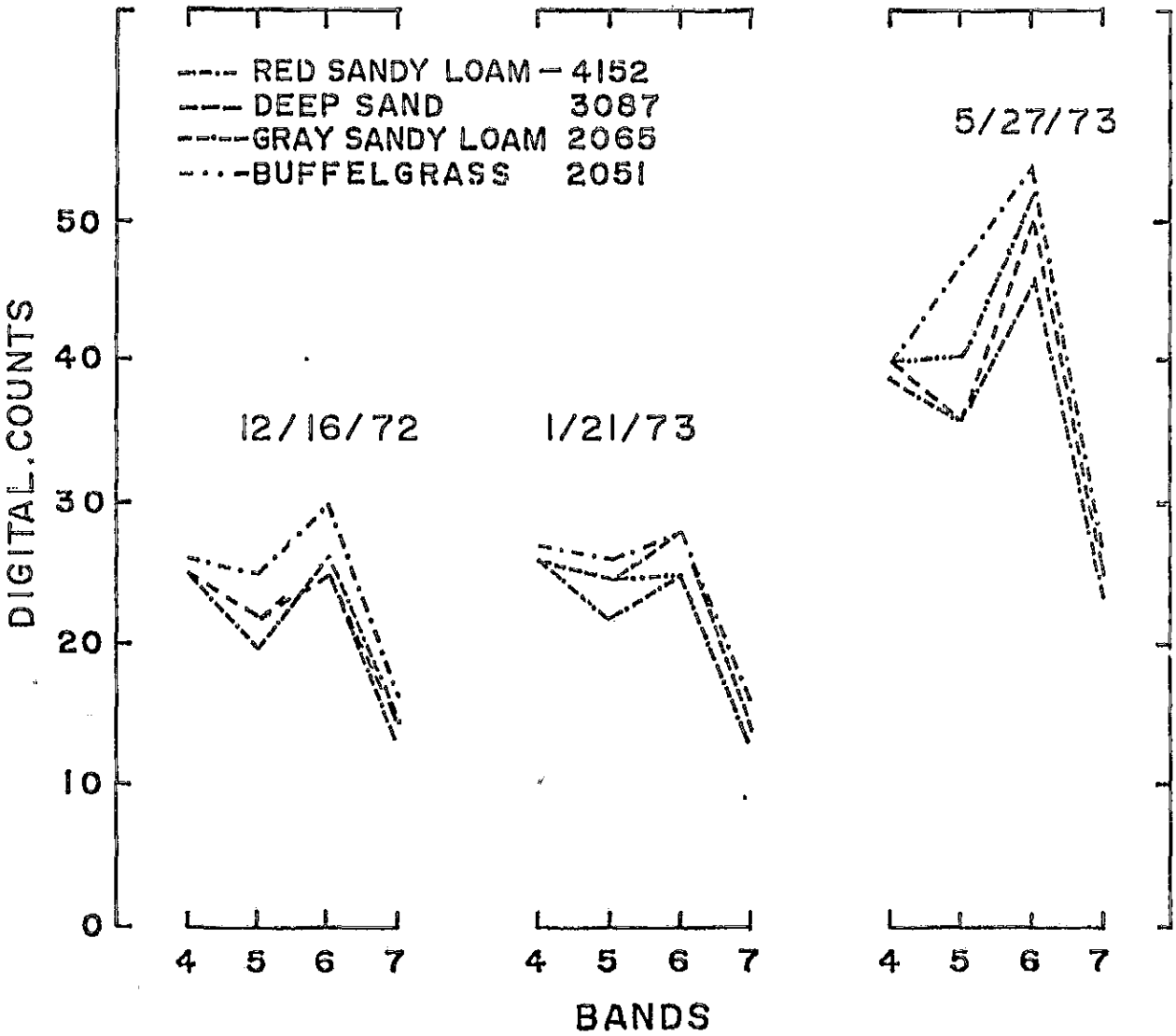

Figure 5. Digital counts in the 4 ERTS-1 MSS bands for 4 range sites on 3 dates (overpasses). Scene I.D.'s are 1146-16323, 1182-16322, and 1308-16323 in chronological order.

The deep sand site and the buffelgrass site had similar spectral signatures. A large amount of herbaceous ground cover (grasses and forbs) is common to both sites.

The digital counts for channel 5 are closer to those for channels 4 and 6 on the January 21, 1973, overpass than they are on the December 16, 1972, overpass. A hard freeze occurred between December 16, 1972, and January 21, 1973, causing most of the vegetation to be defoliated. The loss of the leaves eliminated chlorophyll absorptance in channel 5 (red light) and reduced near-infrared light reflectance in channel 6. The net effect appears to have been a reduction in the band 6 response in January compared with December.

The higher overall reflectance values for the May 27, 1973, data is probably due to sun angle (higher incident solar energy) and seasonal vegetation production differences. In May 1973 the rangelands had maximum green biomass due to ample antecedent rainfall.

Simultaneously Acquired Aircraft and ERTS-1 MSS Data

Multispectral scanner (MSS) data simultaneously collected by the NASA 24-channel MSS (flown at 10,000 feet, 3.048 km) and by Earth Resources Technology Satellite (ERTS-1) on January 21, 1973, were used to compare crop recognition results and acreage estimates using the two data sources.

Optimum channel selection programs selected aircraft channels 3, 5, and 8 (0.466-0.495 μm, 0.588-0.643 μm, and 0.770-0.810 μm, respectively) and spacecraft channels 4, 5, and 7 (0.5-0.6 μ, 0.6-0.7 μ, 0.8-1.1 μ, respectively) as the best channels for distinguishing among five vegetal categories: carrot, cabbage, onion, broccoli, and mixed shrubs. Correlations among aircraft, spacecraft, and ground truth (plant cover, maturity, height, and condition) data indicated a closer relation between aircraft and spacecraft MSS data than between MSS data and ground truth. The aircraft MSS data were slightly better related to ground truth data than spacecraft MSS data. The overall recognition performance using a maximum likelihood classifier on the data for 94 agricultural test fields was low for both aircraft and spacecraft data (61.8 and 62.8%, respectively), but individual field classifications agreed closely between aircraft and ERTS-1 data sources. The main difficulty was that crop fields that had low vegetative cover were misclassified as bare soil, the category they are spectrally most like. Recognition maps and acreage estimates for both aircraft and spacecraft data, of one aircraft flight line (61.6 square kilometers) indicated that agricultural surveys using spacecraft data are comparable in reliability to aircraft surveys.

A comprehensive summary of this work is presented in Appendix C.

PROGRAM FOR THE REMAINING CONTRACT PERIOD

Activities for the remaining contract period will include:

1. Study the difference in spectral signatures between lying plant debris and bare soils and the effect of dry standing vegetation on estimations of rangeland green biomass.

2. Study ground data and spectral signatures in the rangeland part of the County and produce technical articles on rangeland resources of the County including extent, vegetation composition, and discriminability and mapability of major range sites using ERTS-1 data.

3. Improve training sample signature selection through the use of the band 5 to band 7 ratio and incorporate this, scene stratification, and other procedures into improved ERTS data processing procedures.

4. Locate test segments and individual fields in May 27 overpass CCT, determine recognition results on both this and the January 21, 1973, overpass for each of the approximately 1400 fields on which detailed ground truth is available. Determine effects field size, surface moisture conditions, row direction, and other variables have on classification results.

5. Produce County-wide estimates of acreages devoted to various major crops and land uses from January 21 and May 27, 1973, overpasses. Compare acreages with those determined from the ground truth statistical estimate for the County. Also, compare estimates obtained using a single training set for the whole County with composite estimates obtained using training signatures representative of southern, central, and northern subsections of the County.

6. Prepare manuscripts on characteristic field sizes, land uses, acreages in various crops, crop calendars, farmable versus legal description acreages, cloud cover conditions and other factors and considerations discovered or studied during the ERTS-1 investigation.

7. Continue to investigate relations among MSS digital counts and various ground truths to identify the most meaningful ground truth in terms of the ERTS-1 MSS signals and to determine the extent that ground truth explains the ERTS-1 CCT digital counts.

8. Further examine the analytical model for predicting leaf area index (LAI) from the ERTS-1 MSS CCT data, with emphasis on deriving coefficients in the model from the ERTS digital data and on sun angle and measured plant parameter effects on the observed MSS digital counts.

9. Examine spectral signature differences among major soil types in the test County (Hidalgo) and the effect of this background signal on discrimination of crops and vegetation types.

CONCLUSIONS

See individual appendix contributions.

RECOMMENDATIONS

None.

APPENDIX A

USE OF ERTS-1 TO DETECT IRON-DEFICIENT GRAIN SORGHUM

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ABSTRACT

This study was conducted to determine if multispectral data from ERTS-1 could be used to detect differences in chlorophyll concentration between iron-deficient (chlorotic) and normal (green) grain sorghum (Sorghum bicolor (L.) Moench) plants. Band five (0.6 to 0.7 μm) data were selected, representing the chlorophyll absorption band at the 0.65-μm wavelength. Chlorotic sorghum areas 2.8 acres (1.1 hectare) or larger in size were identified on a computer printout of band five data. This resolution is sufficient for practical applications in detecting iron-deficient sorghum in otherwise homogenous fields.

Grain sorghum (Sorghum bicolor (L.) Moench) is one of the annual crops most sensitive to iron deficiency (Krantz and Melsted, 1964). The deficiency symptom is easily identified; leaves are yellow with dark-green veins (Amador et al., 1970). The interveinal chlorosis (striping) extends the full length of the blades. When iron deficiency (chlorosis) is very severe, plants become white, stunted, and die.

The iron chlorosis problem is common whenever sorghum is grown on alkaline soils (Gauch, 1972). Because sorghum is a drought tolerant plant and soils of most semiarid and sub-humid regions are alkaline, iron chlorosis occurs throughout the world.

Chlorotic areas in sorghum fields are easily detected on aerial photographs taken from aircraft (Gausman et al., 1974). This imagery is useful to identify sorghum areas that require foliar applications of iron (Krantz et al., 1962) to attain maximum production and to survey large areas to determine the acreage of iron-deficient sorghum.

This study was conducted to determine if multispectral data from an orbiting satellite (ERTS-1) could be used to detect differences in chlorophyll concentration between iron-deficient (chlorotic) and apparently normal (green) grain sorghum plants.

MATERIALS AND METHODS

A 340-acre (138 hectares) commercial grain sorghum (*Sorghum bicolor* (L.) Moench) field was selected at Faysville, Texas that contained areas of normal and iron-deficient (chlorotic) plants. Chlorotic areas ranged in size from a very small fraction of an acre to 21 acres (8.5 hectares).

Multispectral scanner data used were from an ERTS-1 overpass of the Faysville area on May 27, 1973, at 1130 central DST, during cloudless and haze-free conditions. At this time, the grain sorghum was in the early heading stage. The iron deficiency was moderately severe--essentially all leaves of affected plants were yellow, but stunting was not evident.

On May 25, two days prior to the ERTS-1 overpass, plants in the largest chlorotic area and in the normal area (Plate 1) were sampled for total chlorophyll analysis (Horwitz, 1965). Within each area, a typical plant was selected every 60 feet (18.3 meters) until 10 plants had been sampled; a top leaf was excised from each plant. Leaf samples were placed on ice immediately and transported to the laboratory where they were stored in a freezer at -15°C overnight. All samples were analyzed for total chlorophyll on May 26.

Also on May 25, a ground based, Exotech Model 20 Spectroradiometer[1] described by Leamer *et al.* (1973) was used to measure reflected radiation from chlorotic and normal plant canopies in the field over the 0.4- to 0.74-μm wavelength interval. Measurements were made 20 feet (6.1 meters) above the plants, with a 15° field of view. Spectroradiometric measurements were made to aid in interpreting ERTS-1 multispectral scanner imagery.

The sorghum field was aerially photographed by exposing Kodak Aerochrome infrared film 2443 at f8 for 1/500 sec at an altitude of 6,000 feet (1,830 meters) during cloudless and medium-haze conditions on May 30, 1973, at 1142 central DST. A Hasselblad 500 EL camera was used equipped with a 120-mm lens and Hasselblad combination 2X CB6 and 4X O filters.

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[1] Mention of company or trademark is for the readers' benefit and does not constitute endorsement of a particular product by the U.S. Department of Agriculture over others that may be commercially available.

Computer printouts (gray maps) were obtained from ERTS-1 magnetic tape; symbols were used to represent increments of digital counts (see Plate 1 caption for explanation of symbols). Chlorotic areas on computer printouts for bands 4 (0.5 to 0.6 μm), 5 (0.6 to 0.7 μm), 6 (0.7 to 0.8 μm), and 7 (0.8 to 1.1 μm) were identified by comparing the printouts with aerial photographs.

Chlorotic areas on photographs were planimetered to determine the smallest acreage that could be identified on the printouts.

To test the statistical significance of mean differences between ERTS-1 digital counts of the normal area and the largest chlorotic area (Plate 1), 15 resolution elements were randomly selected from printouts of each area for each of bands 4, 5, 6, and 7, and the unpaired t test was applied for each band (Snedecor, 1965).

RESULTS AND DISCUSSION

There was a statistically significant ($p = 0.01$) difference between mean total chlorophyll concentrations of chlorotic (iron deficient) and apparently normal green sorghum plants. Chlorophyll concentrations in leaves were 9.4 ± 1.05 (standard deviation) and 0.4 ± 0.15 mg/g of plant tissue on a dry weight basis for normal and chlorotic plants, respectively.

Chlorophyll concentrations of chlorotic and normal plants significantly ($p = 0.01$) affected reflectance measurements made in the field with a spectroradiometer (Fig. 1). Reflectance was 9.4, 27.7, and 26.3 percent higher for chlorotic than for normal plant canopies at the 0.45-μm (chlorophyll absorption band), 0.55-μm (green reflectance peak), and 0.65-μm (chlorophyll absorption band) wavelengths, respectively. These reflectance differences were caused by the chlorophyll concentrations because chlorotic and normal plants had the same soil background, and their size and geometry were essentially the same.

The upper oblique photo in Plate 1 is a positive print of an infrared transparency that readily shows the color difference between chlorotic and normal areas; chlorotic areas appear white, and normal areas appear magenta. Oblique photographs delineated chlorotic areas better than overhead photographs. The lower photo in Plate 1 depicts the computer printout for band 5 (6 to 7 μm). Although there was a statistically significant ($p = 0.01$) difference in mean digital counts between the normal area and the largest chlorotic area for all bands (4, 5, 6, and 7), band 5 was selected because it contains the chlorophyll absorption band at the 0.65-μm wavelength; differences in mean digital counts were 5.3, 7.7, 7.2, and 2.4 for bands 4, 5, 6, and 7, respectively.

A comparison of encircled areas in the lower photo of Plate 1 with the chlorotic areas in the upper photo shows that most of the chlorotic areas can be identified on the computer printout of the ERTS-1 band 5 data. Chlorotic areas on the printout have higher digital counts (higher reflectance) than normal areas (see Plate 1 caption for explanation of symbols). This occurred because chlorotic plants had less chlorophyll than normal plants, and therefore, chlorotic plants absorbed less radiation than normal plants at the 0.65-μm chlorophyll absorption band.

Chlorotic areas were planimetered on photographs, and their size was calculated. From these results it was determined that chlorotic areas 2.8 acres (1.1 hectare) or larger in size could be identified on the band 5 printout in Plate 1. This resolution makes practical applications feasible. For example, ERTS-1 multispectral data could be used to detect chlorotic grain sorghum growing on alkaline soils throughout the world.

Results show that ERTS-1 multispectral data detected differences in chlorophyll concentration between chlorotic and apparently normal sorghum plants. Chlorotic areas 2.8 acres (1.1 hectare) or larger in size were identified. This resolution is sufficient for practical applications in detecting iron-deficient sorghum in otherwise homogenous fields.

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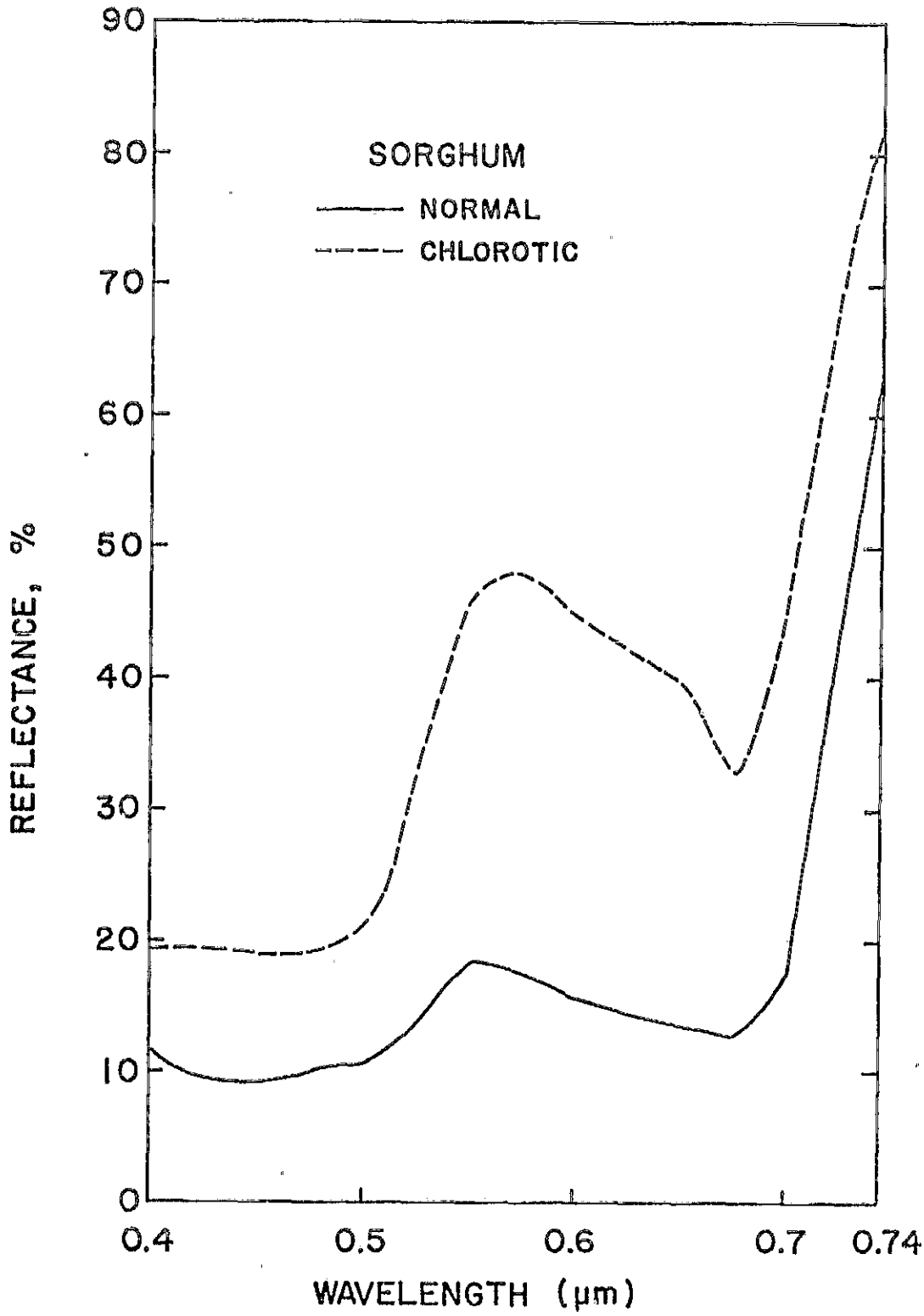

Figure 1. Reflectance of normal and chlorotic grain sorghum canopies measured in the field with a spectroradiometer at the 0.4- to 0.74-μm wavelength interval.

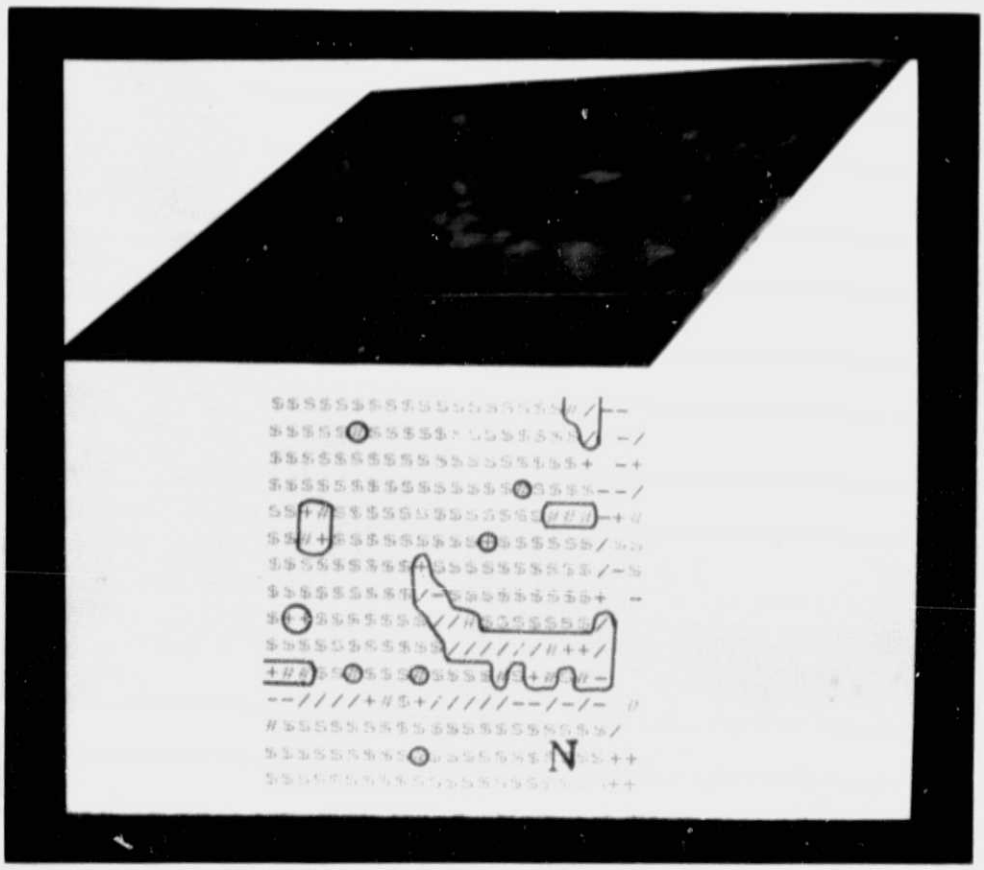

Plate 1. Upper photo is a positive print of an infrared transparency showing areas of white-appearing chlorotic sorghum and magenta-appearing normal (N) sorghum. Lower photo is a printout of ERTS-1 band 5 data; chlorotic areas corresponding to those in the upper photo are encircled. Digital counts corresponding to the printout symbols are:
$ = 30 to 33, # = 33 to 36, + = 36 to 39, / = 39 to 42,
- = 42 to 45, and blank = $\geq$ 45.

APPENDIX B

VEGETATION DENSITY AS DEDUCED FROM ERTS-1 MSS RESPONSE

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ABSTRACT

Reflectance from vegetation increases with increasing vegetation density in the 0.75- to 1.35-μm wavelength interval. Therefore, ERTS-1 bands 6 (0.7 to 0.8 μm) and 7 (0.8 to 1.1 μm) contain information that should relate to the probable yield of crops and the animal carrying capacity of rangeland. On the other hand, reflectance from vegetation is typically less from vegetation than from bare soil and is essentially constant in the visible wavelengths as vegetation density increases; consequently, the decreased response observed in ERTS bands 4 (0.5 to 0.6 μm) and 5 (0.6 to 0.7 μm) as vegetation increases is mainly caused by vegetation obscuring soil reflectance. The ratio of band 5 to band 7 (5/7) or band 7 minus band 5 (7-5) are, in addition to bands 6 and 7, practical indicators of vegetative cover and density for users of ERTS-1 data.

The results of an experiment designed specifically to test the relations among leaf area index (LAI), plant population, plant cover and plant height, and the ERTS-1 MSS responses for 3 corn, 10 sorghum, and 10 cotton fields are also given. Because of clouds, only one ERTS-1 pass (May 27, scene 1308-16323) yielded MSS data and that for only bands 4, 5, and 6. The coefficient for the linear correlation between LAI and band 6 digital counts was 0.823** for the 10 cotton fields and 0.841** for the combined sorghum and corn fields. The correlation coefficient between LAI and band 6 minus band 5 digital counts was 0.888** for cotton fields and 0.768** for the corn and sorghum fields. The four plant parameters explained 87 to 93% of the variability in the band 6 digital counts and from 59 to 90% of the variation in bands 4 and 5. Plant population was as useful as LAI for characterizing the sorghum and corn fields, and plant height was as good as LAI for characterizing cotton fields. These findings generally support the utility of ERTS-1 data for explaining variability in green biomass, harvestable forage and other indicators of productivity.

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INTRODUCTION

The earth's vegetation is one of its most valuable resources. Plants are the traceable source of most of the food and fiber needed by humans and other animals, and past generations of plants provide the energy reserves of coal and petroleum that concern us today. Plants are also intimately involved in the hydrologic and energy balances of the earth.

Net assimilation, or dry matter production, by vegetation is related to the number and photosynthetic area of leaves. Fortunately, the spectral response observed when viewing vegetation from space is dominated by the leaves. Thus the spectral response of vegetation in the ERTS-1 data is worth examining in terms of vegetation cover, vegetation density, and other productivity indicators of range, forest, and crop land.

Agriculturalists, foresters, and range scientists use various parameters to indicate the vegetation density or potential productivity of vegetation. Foresters use tree girth, crown diameter, tree height, leaf area index, and timber volume. Range scientists use harvestable forage and animal carrying capacity (acres or hectares required to maintain an animal year round). Ecologists use estimates of biomass. Agriculturalists use leaf area index (LAI), percent ground cover, plant height, plant population per unit ground area, and other measures of vegetation conditions.

The purposes of this paper are (a) to point out the information available to ERTS users about vegetative cover and density in the ERTS-1 multispectral scanner (MSS) data and (b) to report data relating the MSS response to leaf area index (LAI), plant population, ground cover, and plant height.

LITERATURE REVIEW

ERTS-1 bands 4, 5, and 7 color composites yield images with color tones similar to those of color infrared photographic film. Thomas et al. (1966, 1967) and Stanhill et al. (1973), respectively, have shown that light reflectance from cotton and wheat fields is strongly affected by the amount of plant material or percent ground covered by the vegetation. In their studies, light transmission of color infrared film accounted for 75 and 49% of the variation in cotton lint and wheat grain yields, respectively.

Von Steen, Leamer, and Gerbermann (1969) found statistically significant correlations among preharvest yield indicators (open bolls, number of plants, percent ground cover, plant height, weight plant material per plot) and optical density of aerial infrared film for cotton, grain sorghum, carrots, cabbage, and onions.

Stoner, Baumgardner, and Cipra (1972) related the LAI of corn to the ratio of visible and reflective infrared channels of aircraft optical mechanical scanner data on two flight dates in July. The combined MSS data for the two flight dates yielded a coefficient of determination, R^2, of 0.968 between LAI, that ranged from 0 to 4, and the ratio of two MSS channels (1.0 - 1.4 μm/0.61 - 0.70 μm).

Pearson and Miller (1972) developed and tested both a two-channel ratioing technique and a multispectral pattern recognition technique to compare spectral biomass estimates of grassland with biomass values taken from clipped plots. Biomass estimates were made with an accuracy greater than 95% with a two-channel spectral ratio method using a small hand-held radiometer. Eighty to 90% of the variation in biomass values taken from clipped plots along a flight line could be explained by the airborne MSS data over the same area. Kanemasu (In Press) found that the ratio of reflectances at 0.545 and 0.655 closely followed crop growth and development and concluded that it was a good indicator of soil exposure and crop maturity.

A number of practical applications of the ERTS-1 data to determining vegetation types and amounts, or seasonal effects were previously reported (Freden, Mercanti, and Becker, 1973). For example, Carneggie and DeGloria (1973) obtained information from the ERTS-1 scenes of California on the distribution, yield, condition and availability of forage. Seevers and Drew (1973) identified gross differences in forage density and range condition within given range sites in the sand hills of Nebraska. Heath and Parker (1973) used computer-aided interpretations to classify timber stands and range plants in the Houston area. Dethier (1973) reported that the brown wave (fall vegetation senescence) could be readily detected in the Appalachian and Mississippi Valley corridors and suggested that specific phenological events such as crop maturity and leaf fall could be mapped for specific sites and possibly entire regions from the ERTS-1 data.

PRINCIPLES

The wavelengths of light that are effective for photosynthesis cover the interval from 0.4 to 0.7 μm. Bands 4, 5, 6 and 7 of the ERTS-1 MSS correspond to the spectral intervals 0.5 to 0.6, 0.6 to 0.7, 0.7 to 0.8, and 0.8 to 1.1 μm, respectively. Laboratory data on the spectral reflectance of leaves in terms of the number of leaf layers is given in Fig. 1, taken from Allen and Richardson (1968), except that the ERTS-1 MSS bands have been superimposed. Notice that in the 0.75- to 1.35-μm interval, the reflectance of vegetation is very high and that the signal strength increases as the number of leaf layers, or the vegetation density, increases. This finding indicates that ERTS-1 band 7 responses, and to a lesser extent band 6 responses, should clearly indicate differences in vegetation density.

There is a one-to-one correspondence between yield and vegetation density of crops grown for hay or forage. For plants grown for their seed, fruit, roots, or fiber, there is usually a close correlation between potential production and plant vigor. Axiomatically, healthy non-stressed plants develop larger and more dense canopies and yield better than those growing under suboptimal conditions.

The ERTS-1 responses can be related to the stage of crop development. Spectral crop calendars useful in temporal analyses are possible (Steiner, 1970; Lauer, 1971). The ERTS-1 responses can also be directly related to percent ground cover, plant height or other crop parameters that are correlated with reflectance.

Figure 1 also shows that in the interval 0.5 to 0.75 μm, the reflectance from vegetation is virtually the same regardless of the number of layers of leaves in the plant canopy. The implication here is that the photosynthetic potential of green plants can not be deduced directly from the photosynthetically active wavelengths. Physiological disturbances in plants that decrease chlorophyll content may be detectable, compared with healthy plants, because chlorophyll is a strong absorber of visible light. Thus, the ERTS-1 bands 4, 5, and 6 are valuable to help identify deviations from healthy plants. Plants with physiological disturbances are less vigorous than healthy plants as manifested by fewer leaves or foliar discoloration (Wiegand, Gausman, and Allen, 1972). The information about plant density inferred from the reflective infrared bands 6 and 7 and the information about plant pigmentation obtained from bands 4 and 5 complement each other.

In ERTS-1 bands 6 and 7, the observed reflectance of the soil background is usually less than that of vegetation whereas in bands 4 and 5 it is typically greater than that of vegetation. Therefore, in ERTS-1 band 4 and 5 wavelengths, the soil background dominates the signal up to a fairly high vegetative cover.

Because the ERTS-1 MSS signals recorded for variable ground cover conditions (vegetation density conditions) are a mixed signal for soil and vegetation, the ratio of band 5 to band 7 (5/7) or band 7 minus band 5 (7-5) are practical indicators of vegetative cover and density for users of ERTS-1 data. The decreased radiance observed in ERTS-1 bands 4 (0.5 to 0.6 μm) and 5 (0.6 to 0.7 μm) as vegetation density increases is mainly caused by the increasing amount of soil obscured by the vegetation.

Vegetation density is also dependent on stage of the growing season, or time of the year. Deciduous trees shed their leaves in fall but conifers retain theirs. Thus the two are best contrasted when the deciduous trees are dormant. The progress of the vernal advance (green wave) and fall senescence (brown wave) can be assessed for natural stands of plants and cultivated perennials. Development of annual crops can also be monitored and be interpreted in relation to major weather events such as freezes, drought, and rainfall distribution.

Figure 2 presents the observed radiometric response of the MSS bands 4, 5, and 6 for one corn and two sorghum fields in ERTS-1 scene 1308-16323 that had ground cover of 55, 90, and 90% and LAI of 2.46, 4.08, and 6.92. Also shown is the spectrum for bare soil (Mercedes clay). The radiances (Potter, 1972; conversion factors from digital counts to radiances are .19528, .15748, .13858, and .24286 for bands 4, 5, 6, and 7, respectively) decrease in bands 4 and 5 with increasing vegetation density, expressed as LAI, or with the increasing amount of soil obscured by the plants. The radiances in band 6 are in the order of LAI. The missing band 7 radiances should be about the same or slightly higher than those for band 6, but unlike band 6 they should be pure reflective infrared responses and not a mixture of visible and reflective infrared signals. The band 6 radiances do yield spectra similar in shape to the data for stacked leaves measured with a laboratory spectrophotometer given in Fig. 1. The radiance values for bare soil were obtained from a bare field close to the grain sorghum fields in the ERTS-1 scene. Compared with other ERTS-1 scenes, the radiance in band 6 is high for the particular bare field represented in Fig. 2.

THEORY

Allen and Richardson (1968) applied the Kubelka-Munk theory to reflectance of light by plant canopies and produced the equation

$$LAI = \frac{1}{2 \ln b} \ln \frac{(a-R)(1-aRg)}{(a-Rg)(1-aR)} \qquad [1]$$

for predicting leaf area index (LAI) of plant canopies from their reflectance measured remotely. The equation applies over the reflective infrared plateau wavelength interval, 0.75 to 1.35 μm. In eq. [1], R is the canopy reflectance, Rg is the reflectance of the soil background, and a and b are optical constants that have been determined for many plants (Gausman and Allen, 1973; Allen, Gausman, Richardson, and Wiegand, 1970; Gausman et al., 1973).

A completely different total reflectance model in terms of fractional plant cover can be expressed by

$$R_T = f\ Rc + (1-f)\ Rg \qquad [2]$$

wherein R_T is total reflectance, Rc is vegetation canopy reflectance, Rg is soil background reflectance, and f is an indicator of plant density, such as, percent ground cover, LAI, or plant height.

Upon rearranging eq [2],

$$R_T = Rg + (Rc-Rg)f. \qquad [3]$$

Comparing eq. [3] with the standard linear regression model

$$R_T = a_o + a_1 f \qquad [4]$$

it is seen that

$Rg = a_o$, the reflectance intercept when $f = o$, and
$(Rc-Rg) = a_1$ so that $Rc = a_o + a_1$.

Rc is the reflectance characteristic of the crop or plant community the data are from. If f is expressed in LAI, then it is the reflectance of the canopy with a leaf area index of unity. If in percent ground cover, it is the reflectance of the canopy when ground cover is 1%. In the ERTS-1 MSS signals, R_T is a mixed signal for the vegetation and soil background. The simplified model presented enables one to estimate Rg, and the regression coefficient (Rc-Rg) identifies the rate of change of reflectance per unit change in f.

As shown in Fig. 1 and discussed by Wiegand et al. (1971), the reflectance of vegetation in the visible region (ERTS-1 bands 4 and 5) is virtually the same for leaves one layer deep or stacked in enough layers to insure infinite reflectance, R_∞ (Allen and Richardson, 1968), and usually lower than that of soil. Thus R_T should be virtually constant for vegetation once the soil is obscured, and (Rc-Rg) in eq. [3] should be small and negative. In the reflective infrared, however, R_T should increase as the vegetation density increases up to a LAI corresponding to R_∞, requiring that (Rc-Rg) be positive.

R_T and Rc are expressed in the ERTS-1 MSS signal by the digital counts of the system-corrected digital tapes, by the data expressed as radiance (Potter, 1972), or as a normalized response relative to the digital count maximum (127 for bands 4, 5, and 6 and 63 for band 7) for each band. Calibration of the MSS data directly in terms of reflectance needed for eq. [1] is not available to the authors.

In practice ERTS-1 data users will want to express the MSS responses in terms of quantities that are highly correlated with reflectance--dry matter production, biomass, LAI, percent ground cover, e.g. Once the relation is calibrated for a particular crop, plant community, or ecosystem of interest, the ERTS-1 data should be expressible directly in the productivity estimator of interest to the user. Atmospheric conditions that vary from one ERTS-1 pass to another should shift the data along the axes for any one band, but should not greatly affect the relative position of the data points to each other. If differences between two bands

are used, such as band 7 minus band 5, atmospheric interference effects are reduced possibly permitting pooling of data from multiple ERTS-1 passes for analysis. A ratio of responses in bands both in the visible, as 4/5, or both mainly in the infrared, as 6/7, should minimize atmospheric interference effects in the absence of random noise since both numerator and denominator would be similarly affected by atmospheric attenuation.

METHODS

Data being presented in this paper arise from two different sources. One source is the ground truth that has been taken to support the ERTS-1 analysis effort for one whole county. It was taken to (a) have well-documented fields to judge the accuracy of ERTS-1 classification results against, (b) provide statistical estimates of the acreages devoted to various crops to compare with ERTS-1 estimates, and (c) help establish what ground truths are meaningful in terms of the ERTS-1 spectral data. The data consist of observations of the soil surface condition, species, plant height, percent ground cover by the crop and by weeds, stage of plant maturity, and observations on the general condition of the crop, and stresses in four interpenetrating samples located throughout the county. Almost 1500 fields are involved.

The other source of data is an experiment conducted in the spring of 1973 specifically to determine the leaf area index (LAI) of 3 corn, 10 grain sorghum, and 10 cotton fields selected from the 1500 fields to have a range in planting dates, hence crop maturity, over several ERTS passes. The overall purpose was to test eq. [1] using the ERTS-1 data. Ten average-sized plants were cut off at ground level at each of eight sites in each field, the leaves were removed, and the area of each leaf was determined using a photoelectric planimeter. The area of the leaves was cumulated for each plant and sampling site and expressed as the ratio of area of the leaves to the ground area occupied by the plants. This ratio is by definition, LAI.

The number of plants per 10 m segments of row was determined on four adjacent rows at each of eight locations in each field to establish the plant population and hence the LAI characteristic of each field. The LAI determination was to be repeated each 2 weeks in each field between April and June to insure data near ERTS-1 overpasses. However, the large manpower requirement for LAI determinations and heavy rainfall prevented maintenance of the schedule.

The procedure used to determine the percent of ground covered by the plant canopies differed depending upon whether the crop plants produced a solid canopy (bare soil exposed only in the inter-row area) or an open canopy (bare soil visible through the canopy as well as in the inter-row area). For the solid canopy crops, such as cotton and thick stands of corn and sorghum, the bare soil width (BW) and row spacing (RS) were measured. By definition, BW is the width of the bare soil showing between the leaf canopies of adjacent crop rows, and RS is the average spacing between crop rows. For the solid canopy the percent crop cover is calculated from these measurements using

$$\left(\frac{RS - BW}{RS}\right) 100 = \text{percent cover}$$

where RS and BW are measured in cm.

For the open canopy crops--such as onions, immature cantaloupe, and corn and sorghum planted to low plant populations--the "open" canopies were considered solid, and the above formula was used to determine the percent cover. Then a subjective estimate was made of the percent open spaces in the leaf canopy by looking downward on them and this percentage was subtracted from the estimate calculated by the formula to obtain an estimate of actual cover.

The computer compatible digital tapes (CCT) from the National Data Products Facility (NDPF) were displayed on a cathode ray tube (CRT), and a coordinate system was overlain to aid in locating the fields of interest in the CCT. The digital data corresponding to the approximate coordinates of the fields and sample segments of interest were transferred to a secondary tape. These data were displayed as gray maps using a line printer and were intensively studied to establish field locations and field boundaries. The digital counts for the pixels, or instantaneous ground resolution elements, within the test fields were averaged for each MSS band.

The space data were used as (a) digital counts, (b) radiance (mw/cm^2-sr-μm) using the conversion factors provided by Potter (1972), or (c) pseudo-reflectance by ratioing the CCT digital counts by the maximum possible count (127 for bands 4, 5, and 6 and 63 for band 7).

RESULTS

Due to excessive clouds, data are available for only three ERTS-1 passes, Dec. 16, 1972, Jan. 21, 1973, and May 27, 1973, corresponding to scene I.D. 1146-16323, 1182-16322, and 1308-16323, respectively. The May 27 scene is the only one for which LAI data are available; ERTS band 7 data for this scene delivered to date have a "venetian blind" effect in them and are not useable. The NDPF is redigitizing this scene.

Figures 3a and 3b present the relation between LAI and band 6 digital counts, the band 6 minus band 5 digital count difference, and the ratio of digital counts in bands 5 and 6 (5/6) separately for the combined grain sorghum and corn fields and for the cotton fields. LAI of sorghum and corn account for 67.7% of the variation in band 6 digital count, 59% of the variation in the 6-5 difference, and 45.2% of the variation in the band 5/6 ratio. Thus band 6 alone is superior to the difference, and to the ratio of visible-to-infrared response.

For the cotton fields, a quadratic equation was used to fit the band 6, and the band 6 minus band 5 optical count difference but a linear equation was fitted to the 5/6 ratio data. LAI explains 83%, 90%, and 78% of the variation in digital counts using band 6, 6-5, and 5/6, respectively. For cotton, then, the band 6 minus band 5 digital counts were the best indicator of vegetation density.

The sorghum and corn plants averaged 94 cm high and were approaching full canopy development, whereas the cotton plants averaged only 37 cm in height and were at or very near first bloom stage of development. The plants also differ considerably in growth habit or architecture. Corn and grain sorghum display their long curved leaves in umbrella fashion, whereas cotton plants are conical and their leaves are heliotropic. Such characteristic differences help to discriminate among crops and plant communities spectrally and must contribute useful information for texture analyses. They also suggest that crops or plant communities typical of a given locale or region might be spectrally "calibrated" against the ERTS-1 data one or more times during the year; identifications in subsequent years would be based on the calibration so that extensive ground truth would be unnecessary.

Most investigators use the ERTS-1 MSS digital counts as provided by the NDPF system-corrected CCT. Table 1 presents the linear and quadratic equations for the regression of CCT digital counts (DC) on LAI. For cotton, the quadratic equation explained a statistically significant amount of variance over the linear equation, but it did not for sorghum. The equations for band 6 are repeated from Figs. 3a and 3b but the equations for bands 4 and 5 are presented anew.

The sorghum and corn plants obscured the soil so the correlation in the visible, where responses are due mainly to soil, are poor. For the cotton, both the exposed soil and the vegetation yielded an appreciable signal so that correlation coefficients in both the visible and infrared are significant at 0.01 probability level. The improvement in fit for cotton using a quadratic expression is appreciable, and suggests that a more complicated physical model is required when plant cover is incomplete. Three considerations are sun angle as it affects the length of shadows cast by the plants, row direction, and row spacing.

LAI is only one measure that agriculturalists use to indicate vegetation density. The simple correlations between LAI and plant population (POP; plants per 40 meters of row), percent ground cover (PC), and plant height (PH) are given in table 2 as well as the multiple regression equations expressing LAI as a function of the other plant parameters. LAI of cotton is most highly correlated with PH (0.783) and least correlated with plant population (0.382), whereas LAI of sorghum and corn is most highly correlated with plant population (0.829) and least correlated with PH (0.165). These data seem to indicate that different plant parameters are needed to characterize different crops.

Any useful plant and soil parameters for characterizing crop, range, and forest scenes must necessarily account for most of the variation in the MSS data. Table 3 summarizes regression equations produced relating the CCT digital counts to the vegetation ground truths: LAI, plant population (POP), plant cover (PC), and plant height (PH).

As expected, the plant parameters explain more of the variation in digital counts in the reflective infrared than in the visible. The regression coefficient for the population term was zero for sorghum and corn in bands 4 and 5, causing this variable to be dropped from the estimating equation. Evidently the high correlation ($r = 0.829$) between LAI and POP shown in table 2 caused plant population to contribute nothing to the estimation of the digital counts that was not explained by LAI. This finding has practical consequences. Plant population is easy to determine by counting stalks at a number of locations in fields, or it can be estimated from the amount of seed planted per hectare. Determination of LAI, on the other hand, is laborious and the plants are destroyed in the process. Thus if plant population suffices to characterize corn and sorghum fields in terms of LAI and ERTS-1 radiances, verifying ground truth is easy to obtain. Of course, the plant population remains constant once a crop stand is established. The plants would grow and the radiances measured by satellite would change from one satellite pass to another as the plants develop. However, the radiances for a given set of fields would remain in the same relative position to each other as the plant populations do. Thus one population count should be good for a whole growing season (several ERTS passes).

If there is a good relation between plant population or ERTS radiances and yields, a procedure is suggested for determining the optimum population on a regional basis. Then one can work to get the optimum population widely adopted by growers.

As shown in table 2, PH for cotton was highly correlated with LAI. Coefficients for the linear correlation of LAI and PH with DC calculated in arriving at the equations of table 3 were:

			Band 4	Band 5	Band 6
			r		
DC	vs	LAI	-.726**	-.855**	+.823**
DC	vs	PH	-.769**	-.825**	+.925**

The similarity among correlation coefficients for the correlation of LAI and PH with DC in all bands and the very high coefficient for the correlation of DC with PH in band 6, suggest the possibility that PH can substitute for LAI at least during the prebloom and early fruit set periods of development of this crop.

The 93.4% and 87.3% (R^2 x 100) of the variation in digital counts explained in band 6 for cotton and the combined sorghum and corn, respectively, by the plant parameters used to characterize the crops indicate that (a) characteristics of the vegetation are mainly responsible for the recorded ERTS-1 signals, and (b) useful plant parameters are available for the crops studied.

As stated earlier, one objective of this study was to test eq. [1] for predicting LAI from the ERTS MSS data. Table 4 gives the optical constants a and b, defined by Gausman and Allen (1973), needed to solve eq. [1]. They are calculated from absolute reflectance and transmittance spectra obtained spectrophotometrically on leaves typical of the crops. The values given for "sorghum and corn" are an average of values for each of the two crops.

Inspection of eq. [1] shows that it is limited to conditions when the canopy reflectance R is larger than the soil background reflectance. Additionally, the last term becomes negative if 'a' gets very large.

LAI was calculated for band 6, using the digital count observed in the MSS data divided by 127 to obtain a pseudo-reflectance of the crop, R, and the intercept of the pseudo-reflectance at LAI = 0 was used as the reflectance of the soil background.

The coefficients for the linear correlation of calculated LAI with manually measured LAI were high at 0.815** for cotton and 0.872** for sorghum and corn, respectively. However, the calculated LAI never exceeded 2.0. Thus the predictions of LAI from eq [1] are not satisfactory.

The possible reasons for poor results include (a) the constants 'a' and 'b' are in inappropriate units for this application, (b) the pseudo-reflectance used is inappropriately normalized, (c) band 7 MSS data should be used, (d) the reflectance for soil estimated from the intercept at f = o is too high, (e) the theoretical requirements of the equation (diffuse isotropic incident radiation) are not met, and (f) the row pattern of crops distributes the leaves nonuniformly against the background. Optical constants derived from laboratory data have been successfully applied to other field studies.

Efforts to use eq. [1] will continue because of the potential it has as a practical tool for deducing biomass or yield from ERTS-1 and other remotely measured near-infrared reflectance.

The second model proposed, typified by eq. [3], was also applied. It should describe the physical events better in the visible (bands 4 and 5) than in the infrared; in the infrared it is too simple to describe the multiply-reflected light from successive leaf layers. In applying eq. [3] the digital counts from the ERTS-1 data, R_T, are plotted against any plant parameter of interest such as fractional cover, LAI, or even plant height. Rg is the intercept on the R_T axis when fractional ground cover, LAI, or height of the plants of interest is zero, that is, the soil is bare.

Table 5 gives the values of Rg, (Rc-Rg) and R_T calculated from eq. [3] for each MSS band for the three ERTS-1 scenes we have data from. For the May 27 pass, the calculated R_T value is given as a function of LAI, but for the other two dates as a function of percent ground cover. The calculated R_T values increase from the Rc value in the infrared bands as vegetation density increases from LAI = 1, but decrease in the visible with increasing LAI above 1. Even though LAI for the cotton plots ranged up to 3.0, the ground cover was only 18 to 40%; consequently considerable soil reflectance should be recorded in the ERTS signals. The measured LAI ranged up to 8.5 in the sorghum and corn fields, but the ground cover recorded ranged from 35 to 90%. Consequently some soil (or shadow) signals were included even for fields with high LAI.

The January 21, 1973, data represent 28 vegetable fields as follows: broccoli, 2; carrot, 6; cabbage, 6; onion, 8; tomato, 3; lettuce, 1; beet, 1; and spinach, 1. Ground cover ranged from 2 to 90%. The December 16, 1972, data represent 106 vegetable fields consisting of crop and number of fields, respectively, as follows: lettuce, 14; pepper, 5; tomato, 11; onion, 26; cabbage, 19; carrot, 25; broccoli, 5; and beet, 1. Percent ground cover of these fields ranged from 1 to 100%. The regression coefficient (Rc-Rg) is negative on all dates for the visible bands and positive for the reflective infrared bands.

The digital count values for the May 27 ERTS-1 scene are higher than for the other two scenes. The predominant soil type for the December 16 and January 21 data is Harlingen clay and other heavy-textured alluvial flood plain soils. The May 27 data were obtained from upland soils further from the Rio Grande, which are as light-textured as fine sandy loam. Local soils are generally more reflective the coarser the texture. This, combined with the higher incident solar radiation in May than in December or January would account for the higher digital count values in the scene in May than in the winter months. The higher (Rc-Rg) values in May than the winter months for vegetation also agree with the larger digital counts being due to more incident solar radiation available for reflectance in May than in winter. For all scenes, the ERTS-1 MSS operated on low gain, hence MSS gain is not a factor.

In summary, we have shown that the ERTS-1 MSS data do relate to vegetation density and potential productivity and that vegetation parameters explain most of the variation in band 6 and 7 responses. We also presented and discussed two different equations for relating vegetation reflectance to the ERTS-1 MSS responses. We trust that operational methods for assessing the condition and animal carrying capacity of rangeland and the yield of crops using space data will incorporate procedures based on the principles presented.

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Table 1. Linear and quadratic equation regressions of ERTS-1 MSS digital counts (DC) on leaf area index (LAI) for bands 4, 5, and 6, scene ID 1308-16323.

Crop(s)	Band	Regression equation	Correlation coefficient
Cotton	4	DC = 43.8-3.5(LAI)	r = -0.746*
		DC = 47.5-11.0(LAI)+2.5(LAI)^2	R = 0.867**
	5	DC = 40.0-5.0(LAI)	r = -0.856**
		DC = 42.6-10.3(LAI)+1.8(LAI)^2	R = 0.888**
	6	DC = 50.2+5.1(LAI)	r = 0.823**
		DC = 45.5+14.4(LAI)-3.1(LAI)^2	R = 0.911**
Sorghum &	4	DC = 42.9-0.9(LAI)	r = -0.441
Corn	5	DC = 38.8-1.5(LAI)	r = -0.464
	6	DC = 44.4+2.8(LAI)	r = 0.841**

**Statistically significant at the 0.01 level.

*Statistically significant at the 0.05 level.

Table 2. Simple correlation coefficients among LAI and plant population (POP), percent cover (PC), and plant height (PH) for cotton and for grain sorghum and corn, and LAI expressed as a function of the other plant parameters.

CROP		POP (Plants/40m of row)	PC %	PH (cm)
		r		
Cotton	LAI vs:	0.382	0.589	0.783**
	LAI = -2.392-0.00003(POP)+0.0211(PC)+0.0829(PH)			
	R^2 = 0.628			
Sorghum & corn	LAI vs:	0.829**	0.555**	0.165
	LAI = 0.234+0.0023(POP)+0.038(PC)-0.0046(PH)			
	R^2 = 0.753			

**Significant at the 0.01 level.

Table 3. Digital counts (DC) in ERTS-1 bands 4, 5, and 6 as estimated from four plant parameters, LAI, plant population (POP), percent ground cover (PC), and plant height (PH).

Crop	Band	Regression Equation	R^2
Cotton	4	DC = 47.51-2.215(LAI)-.006(POP)+.369(PC)-.367(PH)	.899**
	5	DC = 48.40-3.270(LAI)-.009(POP)+.006(PC)-.175(PH)	.853**
	6	DC = 31.09+1.243(LAI)+.005(POP)+.236(PC)+.391(PH)	.934**
Sorghum & corn	4	DC = 53.38-.600(LAI)-.034(PC)-.098(PH)	.590**
	5	DC = 56.11-1.049(LAI)-.023(PC)-.192(PH)	.653**
	6	DC = 45.93+3.09(LAI)-.00001(POP)-.111(PC)+.060(PH)	.873**

**Significant at the 0.01 level.

Table 4. Optical constants a and b for cotton, sorghum, and corn needed to solve eq. [1] over the ERTS-1 MSS wavelengths. Eq. [1] applies best to the reflective infrared wavelength interval 0.75 to 1.35 μm.

Wavelength	Cotton		Sorghum and Corn	
μm	a	b	a	b
.50	10.1149	12.4133	7.2990	28.2740
.55	8.3252	7.5888	5.9500	11.1809
.60	12.4855	14.4815	7.9804	34.5618
.65	13.0149	24.0333	9.8553	235.3162
.70	3.1282	2.9818	3.5587	3.9962
.75	1.4551	1.4357	1.4636	1.4417
.80	1.3295	1.3161	1.3193	1.2968
.85	1.3178	1.3024	1.2939	1.2706
.90	1.3446	1.3251	1.2914	1.2659
.95	1.4000	1.3736	1.3422	1.3082
1.00	1.3546	1.3318	1.3013	1.2704
1.05	1.3015	1.2825	1.2483	1.2224
1.10	1.3462	1.3226	1.2702	1.2408
1.15	1.5294	1.4858	1.4426	1.3885
1.20	1.5337	1.4875	1.4426	1.3862
1.25	1.5097	1.4640	1.4038	1.3504
1.30	1.6882	1.6114	1.5390	1.4596
1.35	2.0774	1.9230	1.8046	1.6679
1.40	4.2764	3.5637	3.3571	2.9117

Table 5. Digital count values of Rg, Rc, and R_T calculated using eq.[3] for ERTS-1 MSS bands 4, 5, 6 and 7 from three ERTS-1 scenes.

ERTS Scene and Date	Crop	Band	Rg	(Rc-Rg)	R_T LAI 1	2	4	6	8
			Digital Counts						
1308-16323 5/27/73	Cotton	4	43.8	-3.5	40.3	36.8	29.8	--	--
		5	40.0	-5.0	35.0	30.0	20.0	--	--
		6	50.2	+5.1	55.3	60.4	70.6	--	--
	Sorghum and Corn	4	42.9	-0.9	42.0	41.1	39.3	37.5	35.7
		5	38.8	-1.5	37.3	35.8	32.8	29.8	26.8
		6	44.4	+2.8	47.2	50.0	55.6	61.2	66.8
			DC	$\%^{-1}$	(PC (%)				
					10	20	40	60	80
1182-16322 1/21/73	Vegetables (8 crops; 28 fields)	4	27.82	-.024	27.6	27.3	26.9	26.4	25.9
		5	25.63	-.058	25.0	24.5	23.3	22.2	21.0
		6	20.69	+.180	22.5	24.3	27.9	31.5	35.1
		7	26.59	+.187	28.5	30.3	34.1	37.8	41.5
1146-16323 12/16/72	Vegetables (8 crops; 106 fields)	4	31.35	-.037	31.0	30.6	29.9	29.1	28.4
		5	28.60	-.065	27.9	27.3	26.0	24.7	23.4
		6	29.91	+.063	30.5	31.2	32.4	33.7	35.0
		7	28.65	+.108	29.7	30.8	33.0	35.1	37.3

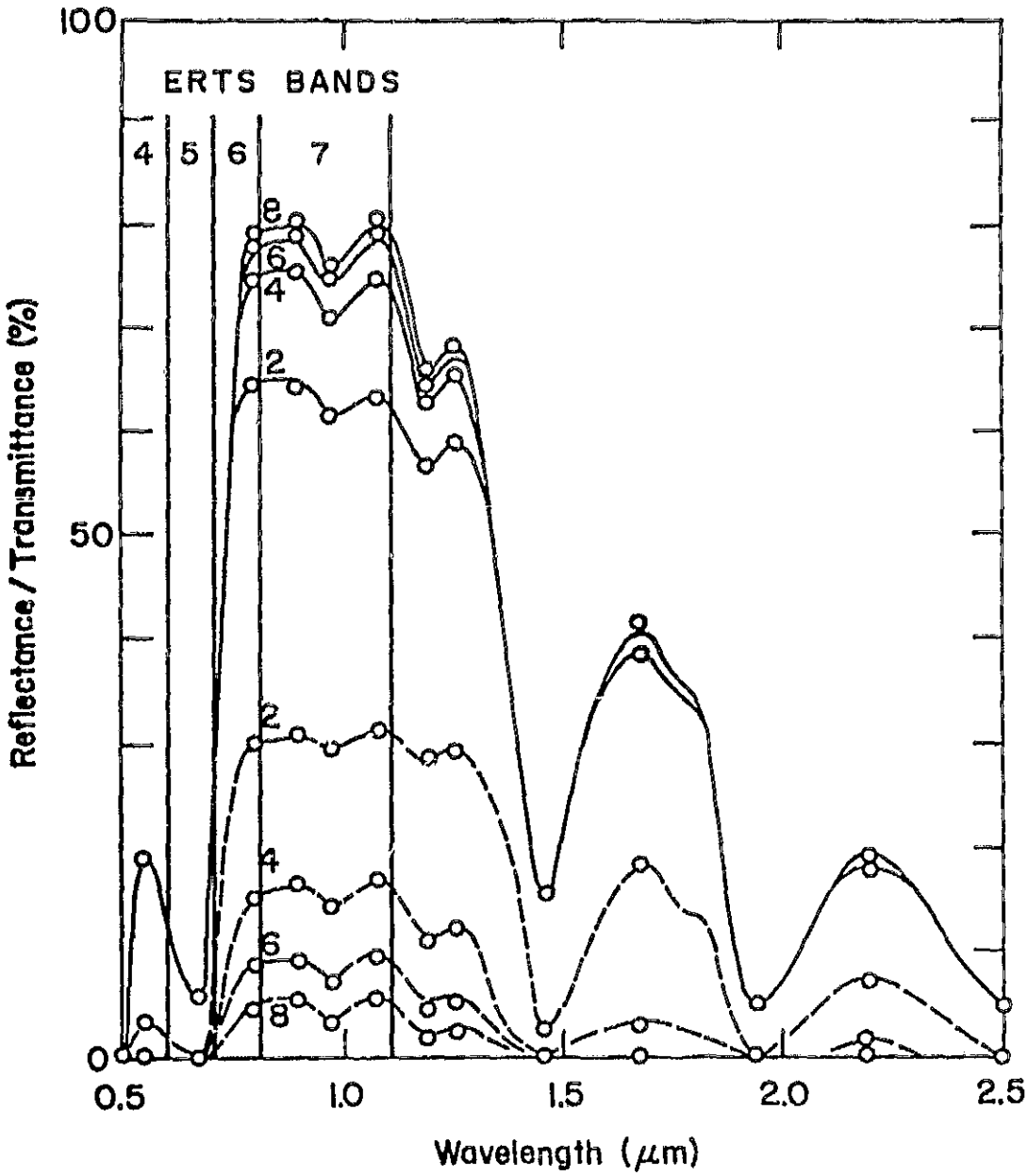

Fig. 1. Reflectance (solid lines) and transmittance (dashed lines) of 2, 4, 6, 8, stacked mature cotton leaves. The lines are theoretical; the circles are experimental. (Allen and Richardson, 1968.) Reflectance from vegetation is dependent on leaf area index in ERTS bands 6 and 7 but not in bands 4 and 5.

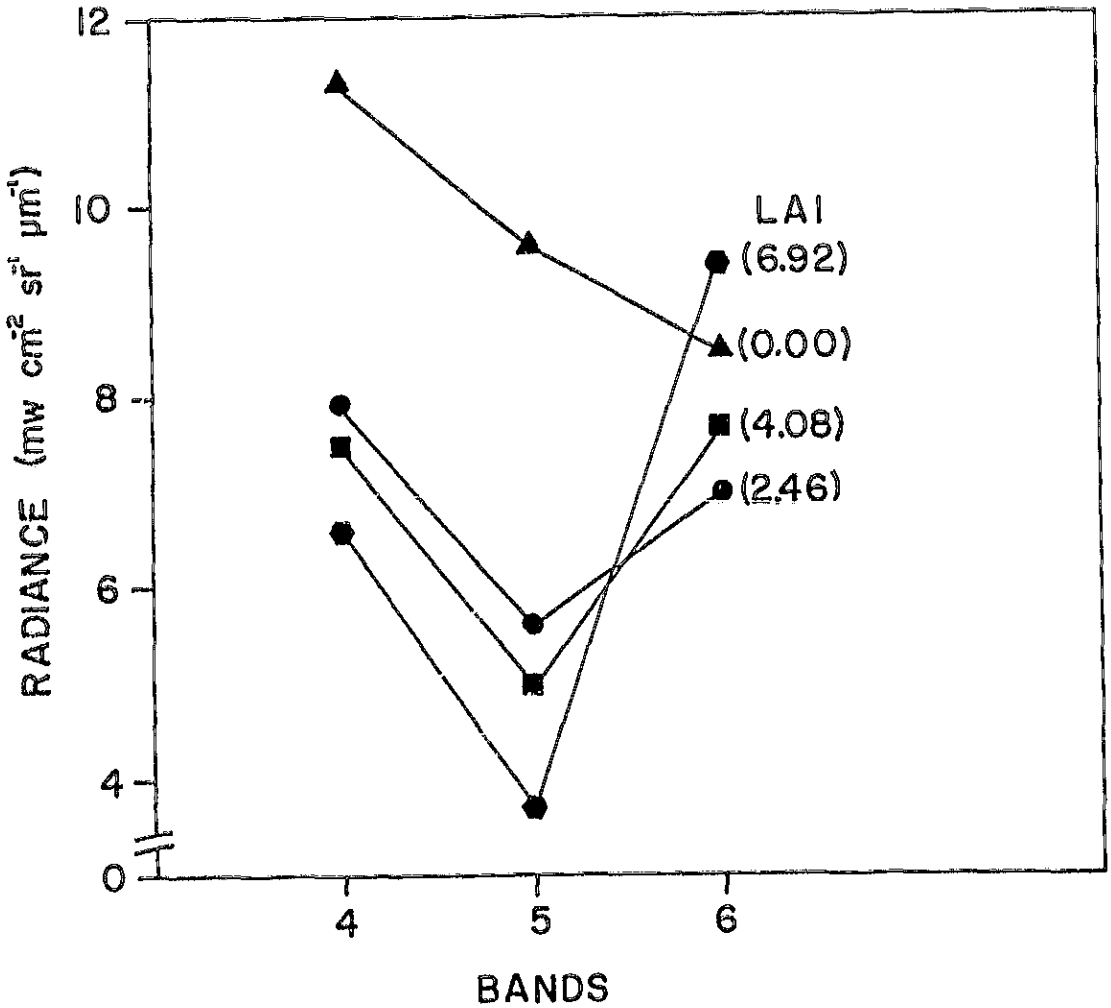

Fig. 2. ERTS MSS bands 4, 5, and 6 radiometric response for a corn, two sorghum, and a bare soil field with leaf area to ground area (leaf area index, LAI) of 2.46, 4.08, 6.92, and 0.0, respectively. ERTS response in bands 4 and 5 is mainly due to the soil obscured by vegetation, whereas in the reflective infrared vegetation dominates the ERTS signals. Note: Radiance of bare soil is that observed in ERTS data for lone bare field located near sorghum fields; its radiance is believed to be atypically high by approximately 2 mw cm^{-2}-sr^{-1}-μm^{-1}.

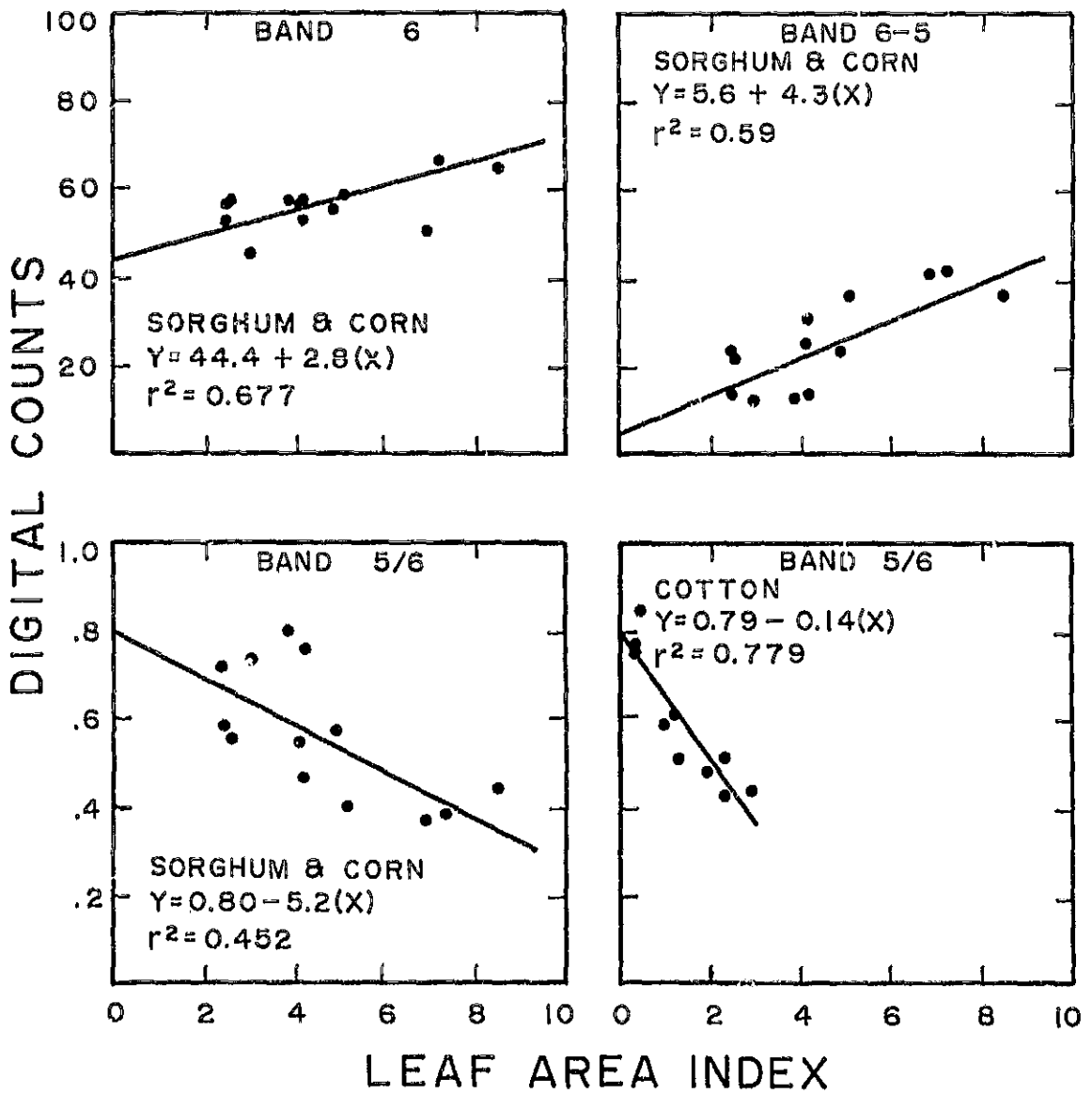

Fig. 3a. Combinations of CCT digital counts (band 6), digital count differences (band 6 minus band 5), and digital count ratios (band 5/band 6) for sorghum and corn combined into one crop type and for cotton versus LAI.

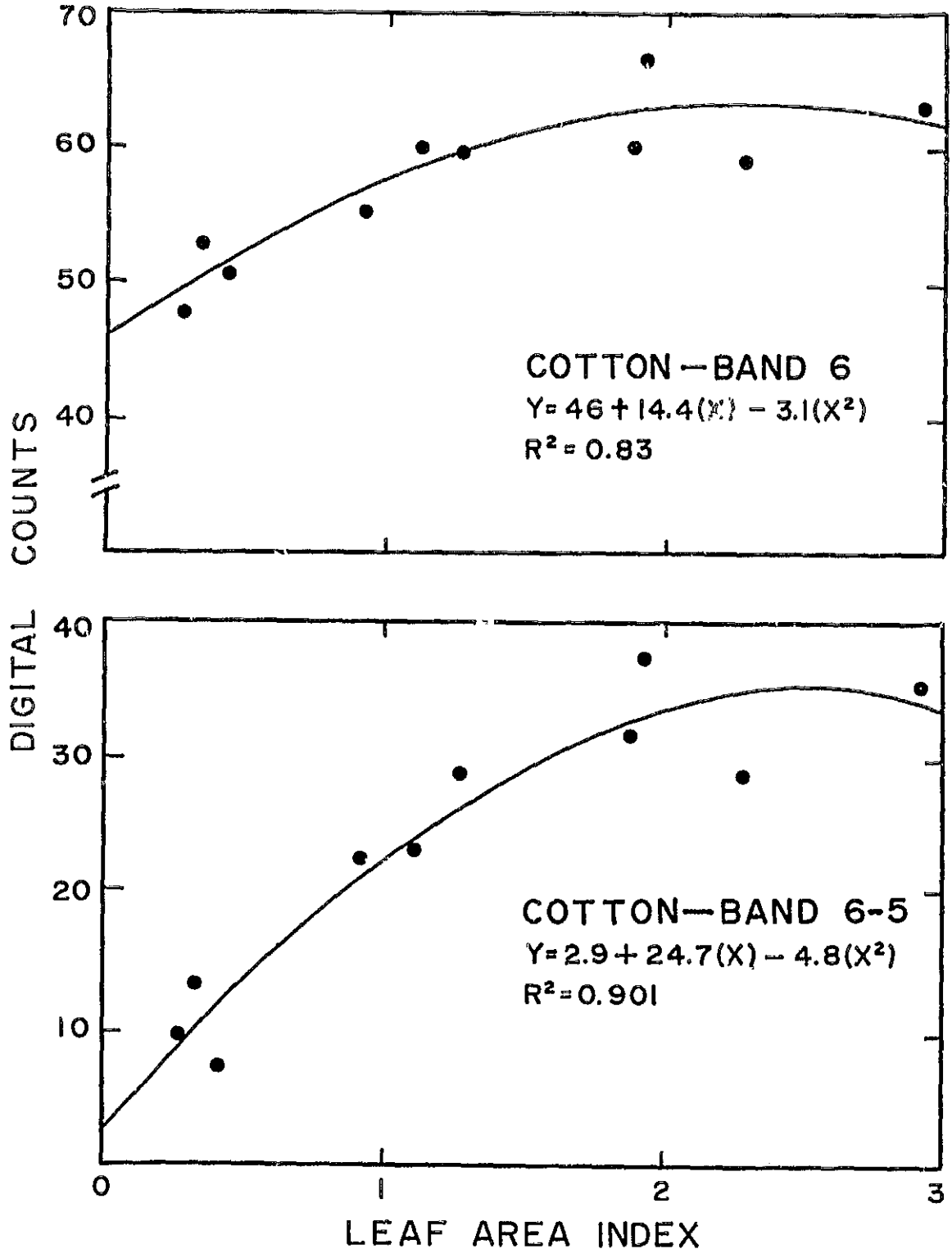

Fig. 3b. LAI of 10 cotton fields versus band 6 digital counts and band 6 minus band 5 count differences. In the regression equations Y symbolizes digital counts and X symbolizes LAI. $R^2 \times 100$ is the percent of variation attributable to the relation between LAI and digital counts.

APPENDIX C

Comprehensive Summary

LAND USE CLASSIFICATION AND GROUND TRUTH CORRELATIONS FROM SIMULTANEOUSLY ACQUIRED AIRCRAFT AND ERTS-1 MSS DATA[1]

A. J. Richardson, M. R. Gautreaux, R. J. Torline,

and C. L. Wiegand[2]

INTRODUCTION

Data simultaneously collected by the NASA 24-channel multispectral scanner (MSS) on board the NASA NC130B aircraft (flown at 10,000 feet altitude) and by the first Earth Resource Technology Satellite (ERTS-1) on January 21, 1973 were compared in an area where detailed ground truth was available. Specific objectives were to: (1) determine the optimum MSS channels for both aircraft and spacecraft data for agricultural land use discrimination, (2) determine the degree of correlation between aircraft and spacecraft MSS sensor signals for a set of common agricultural fields, and (3) measure the recognition performance of aircraft and spacecraft data for a common set of agricultural fields.

PROCEDURES

All four of the spacecraft channels and 10 aircraft channels were used for this study. All aircraft and spacecraft MSS resolution elements were collected from a flight line covering 94 agricultural fields (15 out of 197 sample segments in Hidalgo County, Texas). Seven of these fields and a portion of the Rio Grande were used to determine classification training statistics. All 94 fields were used as test fields to evaluate classification accuracy. Recognition accuracies for both aircraft and spacecraft data were determined on per pixel and per field bases.

The MSS data within each field were averaged for each of the 10 aircraft channels, and each of the four spacecraft channels. These averages were used to study the relation among the aircraft, spacecraft, and ground truth data.

RESULTS

Channel 3 yielded the highest recognition results (71.4%) using the aircraft training data, and channel 7 yielded the highest recognition

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results (87.9%) using the spacecraft training data. The overall recognition results for the aircraft training data reached the point of diminishing returns (94.1%) for channels in excess of the best three (3, 8, and 5; 0.466-0.495 μ, 0.770-0.810 μ, and 0.588-0.643 μ). The best three ERTS channels (4, 7, 5; 0.5-0.6 μ, 0.8-1.1 μ, and 0.6-0.7 μ) yielded 95.3% overall correct recognition for the spacecraft training data. Channel 6 for the spacecraft MSS data was bad every sixth scan line and was not used for this study.

The 94 fields studied totalled 2,244 acres, and consisted of 177,414 aircraft pixels (0.0127 acre/pixel), and 1,942 spacecraft pixels (1.155 acres/pixel). Classification categories were: vegetables; immature crops and mixed shrubs; and bare soil. On a per pixel basis, recognition for vegetables was 40.6 and 40.4% for aircraft and spacecraft data, respectively. Recognition results for bare soil was 77.9 and 77.0% for aircraft and spacecraft data, respectively. The recognition of the immature crop and mixed shrub category was 53.5 and 28.8% for aircraft and spacecraft, respectively. The low recognition in the last category was expected because of the great variability within this spectral classification category; it consisted of vegetable crops that were young and had low percentage ground cover, low density mixed shurbs, and a few weedy fallow fields. Overall recognition results were 64.5 and 59.6% for aircraft and spacecraft, respectively.

The per field recognition results indicated an even closer association between the aircraft and spacecraft MSS data. The 28 vegetable fields were discriminated almost exactly the same (50.0% recognition for aircraft and spacecraft data); the number of vegetable fields classified into each category was 14, 4, and 10 for the aircraft data, and 14, 5, and 9 for the spacecraft data, respectively. The discrimination results for aircraft and spacecraft field classifications did not correspond as closely for the other two categories, but the overall recognition results did at 61.8 and 62.8%, respectively.

Aircraft channels 8 and 9 (0.770-0.880 μ) had the highest simple correlation coefficients (0.704** and 0.695**, respectively) with spacecraft channel 7 (0.80-1.10 μ); they cover similar spectral intervals. Aircraft channel 5 (0.588-0.643 μ) had the second highest simple correlation (0.477 and 0.517)** with spacecraft channels 4 (0.50-0.60 μ) and 5 (0.60-0.70 μ); they cover similar spectral intervals. Spacecraft channel 6 for these data had defective data every sixth scan line and correlation coefficients with aircraft channels were generally lower than with the other three spacecraft channels.

The multiple correlation coefficients of spacecraft channels 4, 5, and 7 with all aircraft channels were high (0.762**, 0.847**, and 0.927**, respectively).