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MACHINE PROCESSING OF REMOTELY SENSED DATA
W. LAFAYETTE, INDIANA, JUNE 23-26, 1981

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16. Abstract

This paper will attempt to identify the need for, and the current capability of, a technology which could aid in monitoring the Earth's vegetation resource on a global scale. Vegetation is one of our most critical natural resources, and accurate timely information on its current status and temporal dynamics is essential as we attempt to understand many of the basic and applied environmental interrelationships which exist on our small but complex planet.

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PREPARED BY
EARTH RESOURCES RESEARCH DIVISION
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Monitoring Global Vegetation

by

R. B. MacDonald, A. G. Houston, and R. P. Heydorn
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lyndon B. Johnson Space Center
Houston, Texas

D. B. Botkin, J. E. Estes, and A. H. Strahler
UNIVERSITY OF CALIFORNIA, SANTA BARBARA

I. INTRODUCTION

As the world's population base broadens and expands in the coming years, the need will increase for accurate data concerning the extent and use of the vegetated areas of the Earth. Farsighted resource planning and utilization will require improved assessments of the current and changing status and usage of vegetated lands as influenced by shifting agriculture, wildfire, large-scale cattle ranching, fuel wood gathering, commercial logging, construction of roadways and utility corridors, and urban expansion. Such assessments are essential for determining whether vegetated lands are to support single or multiple uses, and what degree of conservation reestablishment practices should be applied to the land to ensure continued productivity.

Beyond the planning perspective, inventory and monitoring of the world's vegetation is vital for a fundamental understanding of global ecology. The areas and extents of the world's biomes are presently known only with great uncertainty, in spite of the importance of this information for modeling natural ecosystem and man's impact upon them.

An estimation of the worldwide land area covered by each vegetation type is fundamental to our understanding of the relative size and role of the biosphere in the surface chemistry of the Earth. Area by categories multiplied by vegetation biomass and soil carbon measured in carefully selected sample plots representative of the universe within each category allows estimation of the size of the biotic pool of living and dead material in each category, and ultimately the world. By monitoring changes in land cover types through time, we can perhaps gain improved insights on the environmental effects of these changes. More accurate estimates of rates and locations of deforestation, conversions of prime agricultural lands, and increases in surface albedo due to overgrazing or the clearing of vegetation can, when integrated on a global scale, give both ecologists and resource managers richer insights into global cause and effect mechanisms.

Leading scientists and research groups in a number of disciplines have recognized the need for accurate baseline data on the nature and status of land cover, including native vegetation. The need is real and is rapidly growing. In the area of climatology, the first two recommendations of Working Group 6 (Geographical, Land Use, and Assessment Data) at the National Climate Data Base Workshop held at Harpers Ferry, West Virginia, May 8-11, 1979, were to:

1. Explore the feasibility of preparing generalized land use and land cover maps and digital data for the world from Landsat data for use in climatic modeling and impact assessments.

2. Initiate a project to examine the practicality of digitizing data from existing global and national thematic maps such as the FAO global soil survey and the UNESCO vegetation type maps.

The report of the Working Group goes on to state that global land use/land cover data will be important as we attempt to gain insights into a variety of climatological problems which have profound ecological implications.

In the area of ecology, a recent report of a weeklong NASA-supported workshop entitled "Life From a Planetary Perspective: Fundamental Issues in Global Ecology" recommended the establishment of a research program to provide quantitative information on a global scale about the biota of the Earth.[1] The program is designed to answer three very basic questions about the biosphere: (1) What is the area of the Earth's surface occupied by various vegetation types? (2) What is the

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distribution pattern of these vegetation types? (3) What is the spatial and temporal variation in important ecological characteristics such as canopy leaf area and biogenic molecules?

The need for better data on agricultural lands became better recognized during the decade of the 1970's. The supporting paper by Study Team 8 on information systems on the National Academy of Sciences' "World Food and Nutrition Study" recommended that "a system be developed and implemented to monitor the world's critical food producing regions and to provide early warning of possible production shortages."[2]

For these global information requirements, a technology with a global perspective is needed. Remote sensing, incorporating data from both orbital and airborne platforms, provides such a perspective. The primary purpose of this paper is (1) to document the potential of remote sensing to inventory and monitor vegetation resources, and (2) to discuss the research issues involved in developing an operational vegetation monitoring capability. Our assessment of the potential of remote sensing technology to monitor global vegetation goes a step beyond those in the current literature with which the authors are familiar. This is not to imply that in this paper all the answers are given. What is attempted herein is to: bring into focus clearly the need for information on the status and location of major vegetation types on a continuing basis or a global scale (section 2); discuss the capabilities and limitations of existing systems, in terms of research needed to aid in this endeavor (section 3); and to present, for the sake of discussion, an outline of a research program which, if initiated, would begin to demonstrate the potential of satellite remote sensing for assisting in the monitoring of vegetation on a global basis (section 4). A final brief section presents our summary and conclusion (section 5).

This paper does not attempt to provide an exhaustive discussion or even a well-drafted research plan for global vegetation monitoring. Its true purpose is to stimulate thought, provoke discussion, create dialog, and, hopefully, stimulate movement towards action. If any of these occur, this paper will have served its purpose. The need to attack the problem is clear; for as Charles Mathews, retired NASA Associate Administrator, said: "Man can live in harmony with the physical world only by balancing his growing needs against his understanding of the long-term ability of the Earth, and his own capability to use the Earth, to satisfy them."

II. BACKGROUND

As man's technological potential has expanded, so too has his responsibility to employ the fruits of his technological labors wisely. To many scientists and resource managers, it has become quite apparent that in the twentieth century, man has achieved the capability to significantly alter his environment on a global scale within the lifespan of a single individual. What is less apparent to many of these same scientists and resource managers is that technological research and development has also been producing tools which offer the potential for man to observe, gauge, and perhaps control the effects of his actions on our global environment.

To date, mankind's actions with regard to environment have been haphazard, for the most part. To a very real extent, mankind has acted and typically only later recognized and attempted to assess the consequences of what has been done. We extract organic carbon from the Earth which has been deposited by natural processes over millions of years. We utilize energy stored in fossil reserves, depositing vast quantities of carbon (estimated to be on the order of four billion tons per year) in the atmosphere without, until recently, regard for the consequences for climate. We have only recently come to realize that the chlorofluorocarbon propellants used in aerosol sprays and refrigeration equipment can greatly influence the ozone concentration of the stratosphere, driving ozone to new levels of equilibrium with uncertain effects for the biosphere.[1]

The effects of man's actions may be subtle. Agricultural practices favoring the cultivation of legumes enhances the rate of which nitrogen is fixed by natural processes. In combination with nitrogen fixed inadvertently by combustion, or deliberately during manufacture of fertilizer, this nitrogen may drive the biosphere to new domains, with as yet unpredictable consequences for air, sea, soil, and biota. Man's actions may also be direct. The greatest feat of global engineering, conversion of an estimated 10 percent of total planetary land area from natural vegetation to agriculture, has been carried out without regard for the large-scale consequences. Early farmers did not file environmental impact statements — and even if they had, their documents would probably have provided little insight into the long-range consequences of agricultural land conversion. The scientific basis for assessment was lacking then, and to a very real extent, it still is.

Several examples illustrating the magnitude of changes occurring in our environment at global and national levels point up the need for the implementation of a program of global vegetation monitoring. At a global scale, we have the deforestation question, while at the national level we have the issue of the conversion of prime agricultural lands.

A recent report to the President by a U.S. Interagency Task Force on Tropical Forest states that the closed forest cover in the world's tropics is decreasing by some 10 to 20 million hectares a year, "according to the best available estimates."[3] This means that of the currently estimated 1.15 billion hectares of closed forests in the world today, between 1 and 2 percent are being cleared each year. A recent article in Science 81 summarized this report by noting that in less than 50 years the tropical forests of the world will be devastated.[4] Forty-two percent of the tropics are still wooded, but between 25 and 50 million acres are cleared every year. Since 1970, one-fourth of the forests in Thailand have been cut; one-third in Costa Rica; one-third in the Ivory Coast; Haiti's woodlands will be completely cleared within four years; Latin America and Southeast Asia have lost two-thirds of their woodland; in Africa, only half of the forest areas remain. Yet how accurate are even these estimates? We can only speculate.

The principal direct causes of the loss of tropical forest can be generalized into three categories: (1) conversion and use for agriculture; (2) fuel wood gathering; and (3) exploitative logging practices. Behind these direct causes lie the more basic problems of increasing populations, inequality in land tenure, lack of employment opportunities on proven agricultural lands or in other sectors of tropical economies, among others. Yet, as the Science 81 article makes clear, once the terrestrial vegetation has been removed from these tropical lands, they are much more vulnerable to erosion by rainfall. In addition, certain kinds of soil such as the lateritic soils of the American tropics can become converted to forms that no longer are capable of supporting forests and are lost as resources for an indefinitely long period of time.

For many developing nations, wood is the primary fuel resource. Three-fourths of the world depends on wood as its chief source of fuel, and there is now a well-known worldwide firewood crisis.[4,5] However, how much wood is available for timber, for firewood, and for all other uses is unknown for any of these regions. Clearly the three most important forest types are the boreal, the tropical rain forests, and the tropical savannas. The tropical savanna woodlands are important because they are intensely inhabited, are sites of much of the natural wildlife resources of the world, and are subject now to rapid depletion. Not only do we lack an estimate of current storage, but we have no good way of estimating the actual rate of change. In this case, the advantages of remote sensing for both the present abundance and time changes are obvious.

With respect to the conversion of agricultural lands in the United States, in 1972 the U.S. Department of Agriculture (USDA) estimated that during the 1960's some 295,000 hectares of land were urbanized each year; recreational uses increased annually by some 410,000 hectares, while transportation related uses increased at an annual rate of 55,000 hectares.[6] Much of this change came at the expense of agricultural uses. Recent figures indicate that this trend has continued and has even intensified in some areas. The figures indicate that each year some 1.3 million hectares of U.S. farmland are changed to uses other than agriculture. About one-third of this total is considered prime agricultural lands. At the current rate, farmland is being converted to other urban, industrial, and recreational uses; estimates are that Florida _ which currently produces the most U.S. grapefruit and a large share of other citrus fruit _ will lose 100 percent of its prime agricultural land by the year 2000. So too will New Hampshire and Rhode Island, while Virginia will lose 73 percent; Connecticut, 70 percent; Massachusetts, 51 percent; and Maryland, 44 percent. Unless legislation is passed to slow or halt these conversions, we can expect that the corn belt will lose approximately 13.3 million hectares of prime land in the next 20 years. The current yield from that land would be on the order of 480 million bushels of corn per year; at a current price of $2.00 per bushel, that loss would spell a 960 million dollar per year loss. And, once agricultural land is plowed under or paved over, there is little chance that it will revert to agricultural use. Since agriculture consistently adds large trade surpluses to our balance of payments and affects gross national product (GNP), the problems here are not trivial. This is true even if we assume that some portion of the converted lands would be used in areas which could also add the the U.S. balance of payments.

Yet life on Earth depends in large measure on the foods and fibers from our croplands, grasslands, and forestlands. As our populations increase, more and more pressures are brought to bear on these portions of our vegetative lands. Varying climatic conditions, changing energy availability, and economic factors influence the daily decisions that determine the usage of these areas throughout the world. Global and regional information that is adequate to support an assessment of the extent and/or condition of these lands, let alone an assessment of changes in a timely manner, is virtually nonexistent outside the U.S.A.

In addition, to direct utilization of land resources, inventory and monitoring of vegetation will provide information essential to the understanding of many ecological problems. The movement of carbon through the biosphere is an example. Recent analyses of the global carbon dioxide cycle suggest that the fate of the carbon produced by the burning of fossil fuels is not known completely. More carbon dioxide is being added by burning fossil fuels than can be accounted for as accumulating in the atmosphere or being transferred by presently understood mechanisms to the oceans or land. A controversy has ensued among terrestrial and oceanic biologists as to the possible fate of this excess carbon. Some believe that the land vegetation must be the sink for the carbons. Others have argued that because forests are being cut faster than they are growing, the terrestrial vegetation could not possibly be a sink for carbon dioxide and in fact there is a strong possibility that the Earth's terrestrial vegetation is an additional source not included in estimates of the annual addition of carbon dioxide to the atmosphere. It is also possible that carbon dioxide is entering the ocean at a faster rate by mechanisms not yet understood.

The global carbon dioxide cycle cannot be understood without a basic knowledge of the size of the compartments that store the carbon. The largest storage of carbon as living tissue is on the land in terrestrial woody vegetation. It is therefore a basic part of the understanding of the global carbon dioxide cycle to estimate this storage pool. Current estimates are based on a very small sample and in general involve a considerable intuitive estimation by field biologists. With such estimates, it is essentially impossible to attach a reasonable measure of error, but the estimates vary considerably and it is our belief that the knowledge of the total amount of carbon stored in terrestrial vegetation is not within 50 percent accurate.

What can we do to correct this situation? The following section deals with the potential of remote sensing to assist in the acquisition of data/information which can aid in giving both researchers and resource managers an improved understanding of our current global vegetation base in terms of types, amounts, and dynamic status.

III. SATELLITE REMOTE SENSING AS A MAJOR TOOL FOR GLOBAL VEGETATIVE LANDS MONITORING

With the dawning of the space age in 1957, as evidenced by the first successful launch of an Earth orbiting satellite, a new and powerful vantage point for viewing Earth came into existence. Over 20 years of research since then has produced a rudimentary but unique tool for repetitively observing our vegetative lands at a global, regional, and local level.

Land observing satellites currently provide a cost-effective platform for global monitoring of vegetative lands. Sensor data from on-board the spacecraft are telemetered to ground stations for recording. These raw data from the sensors as well as supporting spacecraft ephemeris data are then transmitted to a central processing facility for conversion to computer compatible digital formats. This conversion process includes calculating and applying the necessary corrections for spacecraft orbit, sensor calibrations, and true positioning of the sensor image with respect to known locations on the ground. Throughout this process, the data are manipulated in a totally digital computerized environment. The format of the data is carefully controlled so that individual users can reconstruct in their own facilities the sensor data and conduct analyses ranging from simple photographic interpretations to complex digital manipulations of the information content in each of the sensor bands.

Existing mechanisms for receipt of the spacecraft data rely on a combination of receiving sites in the U.S. plus on-board telemetry recorders for temporarily storing sensor data when the spacecraft is out of communications range of the ground station. Practical limitations in the scheduling of data record/playback on board the spacecraft plus finite lifespans of the recorders themselves have tended to limit coverage from the existing Landsat series of satellites. Commencing with Landsat D, a new system of global satellite communications [Tracking and Data Relay Satellite System (TDRSS)] will be in place. This satellite network is capable of providing virtually worldwide coverage for Landsat-D.

Further, the communications satellites are capable of handling the very high data rates from the Thematic Mapper generation of sensors. The geosynchronous orbit of the TDRSS satellites will permit the entire data stream to be received real time at a single ground station without regard to the dictates of managing on-board tape recorder budgets and life cycles, or the costs of upgrading a network of ground stations to accommodate TM data. Along with the advent of improved communications facilities, a new generation of high speed, relatively low cost digital processing and analysis systems is emerging in the market place. Because of recent price reductions in computer mainframes as well as in ancillary high volume devices such as array processors used in performing many of the repetitious digital manipulations, the cost of installing an image analysis processing capability is significantly lower than it was 5 years ago. As a consequence, there has been a corresponding growth of digital analysis capabilities often tied to the so-called minicomputers in both the public and private sectors. For investigators with small projects and a limited budget, these mini-analysis systems can provide a powerful analysis tool in evaluating vegetative lands at relatively low cost. Moreover, by careful planning, these systems can be made upgradeable to support high orders of data processing and data rates by the addition of such devices as array processors. Price reductions in the mid-size computer bracket will enable large users to develop extensive research capabilities at costs unheard of a few years ago. Such a system has been installed at JSC and supports not only local researchers but also those at a number of universities throughout the country. Through the use of networking techniques and remote job entry (RJE) terminals, a computational facility that affords not only digital image manipulation, but also a general purpose research computer, can be made available. By providing the networked computational capability to outside users, the funds they receive can be more productively spent on research and not on the purchase of computer support, thus providing a greater return on the research dollar.

Even with improvements and efficiences gained with high throughput digital computers, it isn't cost effective or even technically preferrable to collect and process all the data potentially available over the Earth's entire land surface. Sound sampling approaches significantly reduce the data load while at the same time retaining, or even improving, the accuracy of estimates that could conceivably be achieved if data were collected over the entire surface and accurately reduced. As a result of cloud cover and the tendency to see a reduction in accuracy with increasing data loads, better results can often be achieved with sound sampling procedures. Moreover, reduced data loads cost less to analyze and can be analyzed in shorter time intervals. In the LACIE, the sample of data processed to make crop area estimates for the U.S. Great Plains covered approximately 2 percent of the total area of the sampling frame. At the U.S. Great Plains level, this resulted in a sampling error on the order of 2 percent.[8] Sampling error refers to the difference between the estimate based on the sample and the true value which would be obtained by taking a census. Note that this does not include error due to misclassification or mislabeling of the remotely sensed data, which is commonly referred to as classification error.

As a result of research and development conducted during the LACIE and the AgRISTARS Project, techniques have been developed for utilizing remotely sensed data to estimate large area crop acreage and production while keeping the cost of the survey to a minimum by utilizing statistical sampling methodology. Sampling techniques, suitable for use with satellite acquired remotely sensed data that have been developed, include sample frame development, multipurpose allocation, estimation in the presence of nonresponse, and aggregation to large area levels.[8-14] Sampling efficiency has been achieved through the use of Landsat and agromet data to stratify regions along natural boundaries (figs. 1 and 2) as opposed to political (e.g., state in U.S. or oblast in USSR) boundaries.[12] The use of these natural strata has also led to reduced bias in large area crop acreage estimates due to nonresponse (usually caused by cloud cover).[15,16] These sampling techniques are applicable for surveying any vegetative class that can be identified using remotely sensed data.

Transformations of Landsat MSS data have been and are being developed that are particularly well suited to monitoring vegetation classes and their biophysical characteristics in the presence of varying soil backgrounds. Kauth and Thomas demonstrated that the four-channel MSS data are essentially two-dimensional for agricultural applications.[17] These two orthogonal linear transformations of the four MSS bands are called brightness and greenness. The brightness establishes the data space of soils and greenness is a measure of green vegetation. Thompson and Wehmanen, among others, have found that greenness is relatively constant for various soil

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backgrounds in a given geographic region.[18] Badhwar has found that the temporal behavior of greenness for an annual crop is sigmoidal, a characteristic shape for many biological systems.[19] Badhwar has also found that planting date variations can be accounted for by a simple shift in the time axis of greenness and other derived parameters.[19] This suggested that a crop has a unique greenness profile which is shifted by changes in planting date. Figure 3 illustrates the sigmoidal behavior of greenness for spring wheat when the values are adjusted by an emergence date, also estimated from the spectral data.

Based on the above empirical findings and properties of light scattering through crop canopies, a mathematical model for greenness has been developed to describe the temporal trajectories of various vegetative classes.[19-21] The suggested model form is:

$$\rho(t) = \rho_o, \; t < t_o$$

$$\rho(t) = \rho_o (t/t_o)^{\alpha} \exp[\beta(t_o^2 - t^2)], \; t > t_o \tag{1}$$

where ρ_o is the soil greenness at day of the year $t = t_o$, t_o is the spectral emergence date, $\rho(t)$ is the greenness at time t, and α and β are parameters describing the rate of increase and decrease, respectively, of greenness values before and after peak greenness. The curve in figure 4 is a fit of observed greenness values to this model for a field of corn. The spectral emergence date is the point, t_o, at which the bare soil greenness, ρ_o, intersects the crop development temporal profile as indicated in the figure. The parameters t_o, α, and β can be determined for each field (or pixel) in a scene from a sequence of congruent MSS acquisitions which include a bare soil acquisition and acquisitions prior to and following peak greenness. If these parameters are unique within a vegetative type, they provide the basis for a highly automated vegetation identification procedure. Figure 5 is a histogram of α values for a segment in Iowa illustrating the separability of corn, soybeans, and other vegetation using this parameter.

Another parameter that shows promise for monitoring vegetative classes is the ratio of greenness to brightness. Figure 6, provided by Badhwar, compares this parameter to the brightness parameter for several grains, pasture, and hay.[22] The brightness parameter is highly variable from crop to crop, whereas the ratio tends to be parabolic for each crop with the width of the parabola varying from crop to crop. Figure 7 illustrates that the parabolic fit of the ratio of greenness to brightness also holds well for winter wheat plot data taken on consecutive days. This suggests that the parabolic width parameter may be useful in identifying vegetative classes.

The above modeling techniques are very cost effective in making use of multiple acquisitions of congruent MSS data. Figure 8 illustrates the data compression that results when applying these techniques, while at the same time preserving the information required to identify the vegetative classes of interest. In this figure, four acquisitions are considered to have been obtained throughout the growing season of crops of interest. Initially, these are 16 dimensional data, 4 channels of data for each of the 4 acquisitions. The Kauth-Thomas transformation reduces this to 8 dimensions, greenness and brightness for each of the 4 acquisition dates. Finally, the Badhwar temporal profile models reduce the dimensionality to 2. This could also be 3 or 4 depending on which of the 4 parameters (t_o, α, β, and the parabolic width parameter, σ) are deemed suitable for identifying the vegetative classes of interest. A key point to be made here is that increasing the number of available satellite acquisitions does not increase the dimensionality of the data when using these temporal profile models, but instead increases the precision of the estimates of the temporal profile parameters.

To apply scene analysis techniques which utilize multitemporal data, it is generally essential to render multiple look data from satellite imaging sensors to be congruent. This process, in which one digital image is mapped or made congruent with another digital image, is known as registration. The related process of rectification results if the image or images are mapped to an Earth coordinate system. Both registration and rectification (particularly registration) have undergone considerable investigation.[23-25] In general, to register two scenes, identifiable points (tie points) are located in both images or enhanced versions (e.g., edge) of these images. Based on these tie points, the coordinates of one image are distorted or warped to fit the other image. The warping

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may be constrained in accordance with prior knowledge regarding the possible distortions between the images.

To enable reasonable throughput in rectification or registration, locating tie points in the imagery should be automatic. Automation is usually achieved by using similarity seeking methods (such as correlation) to identify tie points in the two images. To keep processing times reasonable, it is customary to allow only two degrees of freedom in the search. This means images must be rendered to approximately the same scale and orientation from prior knowledge before automatically locating tie points. Using current automated techniques, it is possible to locate tie points with sufficient accuracy in Landsat data to permit registration to subpixel accuracy at least for scenes whose extent is of the order of 10's of kilometers.[26]

Various clustering algorithms have been developed for sorting MSS data into spectral groups. One such algorithm, called CLASSY, decomposes the probability density function of the data into class conditional probability densities.[27] These class conditional densities can then be used to assign points to clusters. CLASSY, at the present time, does not account for any spatial structures in the MSS data. However, another algorithm which is somewhat similar to CLASSY, called HISSE, does use the fact that in agricultural scenes the pixels are often arranged in fields.[28] By detecting data groupings which resemble fields and using these groupings in the estimation of the class conditional densities, this algorithm uses some of the spatial information in the data. Other clustering algorithms which are based on principles different from those of CLASSY and HISSE have also been developed. These are Ameoba, Blob, and ECHO.[29-31] Each of these algorithms also uses the spatial information in the data related to the groupings of points in agricultural fields.

Methods for estimating proportions of crop acreages in an area are being developed which may have superior statistical properties over previously used methods. The usual approaches apply some form of classification, whether it be of a manual or machine variety, to assign a crop name to selected pixels. All the pixels grouped into one crop class are then counted to obtain the estimate. These approaches tend to produce biased estimates, a consequence of classification error. The methods under development do not use a classification approach, but estimate crop proportions using a mixture model approach. In this approach, the probability that a pixel is a member of a class is estimated by the actual assignment to a class, as is done in classification methods, is never made. By working with these probabilities, as opposed to the actual class assignments, the classification error problem is avoided. A test version of this approach is being implemented using the CLASSY algorithm.[27]

Classification methods are being developed which depend upon transformations of the Landsat MSS channel variables to variables which tend to respond to discriminating growth properties of crops; for example, the previously mentioned greenness to brightness parabolic width parameter. These variables are parameters of certain growth models, called profile models, that are fit to a time sequence of Landsat observations. In the space of these new variables, crop signatures are more stable over large regions and in general less sensitive to extraneous--noncrop growth related--effects. This stability means that only a small number of training observations are needed to calibrate a classifier of this kind, and this implies a cost-effective advantage over other classification approaches. An example of such a classifier is provided in reference 32. This classifier uses the t_o, α and β parameters from equation (1) for labeling pixels. In this approach, an image analyst provides a single field of the vegetative class of interest to be identified in the scene of interest. The temporal profile in each MSS band is fitted to the model in equation 1; every pixel in the scene is then compared to the fitted model forms (one for each MSS band) to decide whether or not it is of the same class as the training field.

While the results of current studies which demonstrate the potential of satellite remote sensing are encouraging, research in a variety of areas will still be required to meet the information/accuracy requirements of a variety of users of vegetation information at global, national, regional, and even local scales. First and foremost is the need to improve our understanding of the relationship between Landsat-derived data and the biophysical characteristics of the vegetation data under investigation. This will necessitate the development of improved sampling procedures. Such improvements are of interest not only to remote sensing technologists, but to basic and applied scientists involved in vegetation research as well.

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For example, Botkin conducted an ecosystem study of Isle Royale National Park, a large island in Lake Superior, prior to his having been introduced to the concepts and potentials of remote sensing. On a global scale, this is a relatively small area, occupying only 550 km^2. However, the island contains eight major forest types and is an excellent site for studying ecological interrelationships. Working under a grant from the National Science Foundation, an attempt was made to estimate the biomass in each of these forest types. Two crews of two men were hired for a summer. Because this was a wilderness area without roads, all travel was by foot and small boat and all sampling equipment had to be hand carried. In an entire summer's work, these two crews were only able to sample approximately 80 small plots of a 100 square meters each. While one could argue that a massive labor effort could accomplish the task as well as remote sensing, the damage and disruption to a major recreational area like this national park by such a labor force would be unacceptable to the National Park Service. Clearly, the informed application of remote sensing techniques could have supplied important information in a more expeditious manner. This is not to say that a complete census of every tree or every square meter of forest was necessary. Rather, simple and highly stratified sampling, combined with straightforward ground truth measures, would have vastly improved the estimate of forest biomass over what was obtained in the example just quoted. Problems as just described could be repeated again and again.

As another example, it is suspected that greenness probably reaches saturation for certain vegetative classes under select conditions. In this case, the sigmoidal model would not be representative. If saturation does present a problem, data may be required in the larger wavelengths of the electromagnetic spectrum where saturation is not a problem, or the temporal trajectory models using current parameters may require more sophistication.

In the area of registration, there remains a number of open-issues to be resolved. In fact, Mikhail lists 14 such issues in the area of registration and rectification.[33] They are presented in table 1. As has already been suggested, the basic requirement is to routinely register and rectify to subpixel accuracy scenes from a variety of sensors such as Landsat MSS and RBV, Thematic Mapper, radar and other satellite and airborne sensors. These types of registration and rectification are confronted with basic problems such as differences in resolution and kinds of features that can serve as tie points. New and improved techniques are required to account for these differences as well as improve the accuracy, success rate, and throughput of existing systems.

Clustering has been used to sort spectral measurements into groups for purposes of obtaining an unsupervised classification or for obtaining a stratification to be part of a stratified area estimation approach. In both applications, mixed clusters are a problem. A mixed cluster is defined as a grouping which contains more than one class of measurements. For example, when clustering an agricultural area, one cluster may have grouped spectral measurements from both wheat fields and barley fields. If the purpose of the clustering is to separate these classes, then clearly errors result. If the purpose of the clustering is to produce a stratification for use with a sampling approach which attempts to estimate the given class proportions, then mixed clusters simply reduce the sampling efficiency. In general, the more mixed the clusters are, the lower the sampling efficiency afforded by the stratification.

Classification of Landsat data into preselected categories is accomplished by a rule which partitions the spectral observations into subsets in such a way so that each subset, as well as possible, corresponds to one and only one category. These rules are generally selected from a parameterized family of rules: for example, the family of all linear discriminants, and the one discriminant within that family which best fits the given classification problem, is determined by estimating values of the parameters. This parameter estimation is based on example observations, called training samples, from each of the given classes.

Many problems associated with the classification of Landsat data are related to classification error and selection of an appropriate training sample. Classification error, of course, depends upon the selection of the classification rule. A poor selection can lead to high classification error. Generally, though, the major problem is simply the spectral separation of the Landsat data, which is measured by the frequency with which observations from different classes fall within the same small spectral neighborhood. High error rates mean that the classes of interest cannot be well separated by the chosen classifier. However, often a coarser classification can be done fairly accurately. For example, in agricultural applications, the classification of wheat and barley observations into two separate classes has led to high error rates. On the other hand, by grouping those classes into a larger class called small grains, the classification into small grains versus non-small grains has been done with reasonably low error rates.

The proper selection of a training sample is often a major problem. For those classifiers that are designed on statistical principles, training is selected through a random process. If the size of this sample is too small, then the classification results can be erratic. In situations where the classifier is being used as part of a vegetation inventory process, then this erratic behavior generally shows up as a variance in the inventory estimates. On the other hand, if a large number of training samples are selected, then the use of a classifier may be questioned since the training sample itself may supply the required answers. That is, the training sample can often be used to acquire an inventory estimate, and if the sample is large, the variance of the estimate may be sufficiently small.

There is also a spatial aspect to the selection of a training sample. Classification of Landsat data is generally a 'region dependent' process. This is due to background difference (e.g., soils), mixing of vegetative classes that are spectrally confused, and other factors. Hence, the training sample must be selected to "capture" these effects. Often this implies that the region of interest should be first stratified such that these factors are relatively homogeneous within the strata.

The resolution element (a pixel) of Landsat is about 1.1 acres in size. This implies that the pixel may contain more than one class type. For this reason mixed pixels are a major source of error in many uses of Landsat data. Mixed pixels, for example, do not have a "logical" classification and therefore cannot be treated within the theoretical framework of classification theory. In many applications, this fact is ignored with the effect that an error component of the classification results is due to mixed pixels. Since the pixels surrounding a mixed pixel may indicate the material types contained within the mixed pixel, some form of spatial processing is suggested to deal with this problem. In crop inventory applications the mixed pixel problem often introduces a bias in the crop acreage estimate. While the exact nature of this bias is not well understood it is apparently related to field sizes of the crops of interest. It has been found, for example, that in the U.S. Great Plains, the bias introduced in estimating small grains using classification methods with Landsat is not nearly as severe as the bias introduced in estimates of corn and soybeans in the U.S. Corn Belt. The problem of how to deal with mixed pixels when estimating acreages of vegetative classes of interest with Landsat data is being studied and, to the best of the author's knowledge, is still in the early stages of research.

We anticipate that some improvements in the use of computerized pattern recognition analysis will flow from the improved application of data base technology into mainline image processing. These improvements include the implementation of improved methodologies for both integrating diverse data sets and developing new logical structures which more closely mimic qualified interpreters with extensive backgrounds in image analysis through modeling procedures. We feel this area of expert systems development has important implications for both global vegetation classification and monitoring as well.

With specific respect to the detection of change, again a number of lines of research must continue to be pursued. Techniques which must continue to be examined and improved upon include the following.

- Image Differencing - where the raw data from two images are registered and normalized (to remove sensor and local area variations) and then a pixel-by-pixel comparison is made. The product of this type of comparison is a "change image" which identifies areas in which further analysis should be concentrated. Research to date has demonstrated a 97 percent reduction in the amount of raw data needed to be analyzed.

- Principal Components Differencing - where information contained within the spectral data is reduced in dimensionality and then compared for two or more dates.

- Spectral/Temporal Change Classification - this technique is based upon a single analysis of a multidate data set to identify change.

- Post-Classification Change Detection Differencing - where two or more classifications are compared and the differences noted. This procedure is extremely sensitive to within scene classification errors, errors in registration of the data sets, differences in classification criteria, and differences in minimum map size unit.

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Further discussion of these techniques can be found in Estes and Stow.[34]

A number of other factors greatly affect our ability to employ the change detection techniques referenced above. These factors require further definition and research if we are to accomplish our long-range goal of developing a global vegetation monitoring capability which provides resource managers with both accurate and timely information. These areas include: (1) the development of regional change detection calendars which will provide guidelines for the seasonal selection of remotely sensed data for the detection and classification of vegetative cover changes which may vary from region to region and from one type of change to another; and (2) the development of temporal guidelines for detecting regionally related type changes which would greatly enhance the potential for success in future studies. An example of the latter process in monitoring citrus acreage in central Florida. In the 1950's, acreage was expanding rapidly, and annual changes were watched closely. In the 1960's, the area in citrus stabilized and a longer time between updating became acceptable.

Yet, in the final analysis, the ability to detect changes in any important natural resource parameters cannot be viewed in a void. Research in many areas is needed, and improved techniques are required before natural resource managers can exploit the full potential of satellite remote sensing. We must: (1) improve our ability to provide consistently accurate vegetation cover maps; (2) if this can be achieved, we will then be better able to assess the magnitude and direction of changes in resource parameters; (3) as we become more accurate in this capability, we can then begin to employ this "historical" record to model and predict potential future resource scenarios; and (4) to accomplish all of the above in an expeditious fashion, we need more research directed at the application of geobased information systems (GIS) technology within the context of a remote sensing based natural resource survey.

GIS technology is itself a developing technology as is remote sensing — neither is widely familiar or well understood with the research and user communities at large. A thorough literature review turns up little substantive work on the philosophical and conceptual linkages between information systems and remote sensing. This lack of work on models of the potential interactions between the two technologies has served to insulate the work on design of remote sensing techniques, hardware, and software applications, from concepts of GIS design. As remote sensing and geographic information systems technologies move into new states of maturity — as we believe they are moving now — many of the current problems of intergration for natural resource management applications will dissolve. Integration is not a matter of fundamental incompatibility of the technologies nor of the reluctance of the technologies to collaborate. Integration of the technologies is dependent on realization that the potential of each technology cannot and will not be achieved until they are integrated.[34]

Satellite remote sensing blended together with other data can be effectively utilized to monitor our vegetative resources.

One of the major problems faced in the compilation of vegetation information on a scale larger than regional has been that the mapping units vary greatly from one map to the next. No consistent vegetation classification system has been employed to date in the compilation of most small scale vegetation maps. Existing vegetation maps at country, continental, or global scales are typically compiled from ground observation and local knowledge. In some maps and atlases, remotely sensed data play an important role; however, this includes satellite imagery, air photos, and side-looking airborne radar in a few experimental applications. Often the imagery is not fully current, and ground observations can be limited and anecdotal. Still, these are the best available sources and are used in policy setting and decision making, hopefully with allowances by decision makers for known areas of change. Yet, at a most general level, the current Landsat series satellite systems offer the potential for providing for the first time a globally consistent data source from which information concerning the current type, status, and temporal dynamic of world vegetation can be extracted.

Forest inventory provides an example of the current capability of remote sensing technology to provide vegetation resource information. Professional land managers have learned that much of the information which they desire concerning forest lands, in particular, can be readily seen on various types of aerial imagery. For those conditions which cannot be discerned directly, information can often be acquired about them on the ground more efficiently with the aid of imagery. Thus, systems have evolved for rapidly and accurately classifying forestlands in terms of variables which can be estimated or directly measured on the images themselves. For example, timber stands usually can be classified employing conventional aerial photography according to types, species composition, size class, and height class.[35] The work of Strahler has extended the capability to extract this information from Landsat series satellite digital data in combination with digital elevation data and ecological modeling.[36,37]

Thus, research to date has demonstrated a capability for vegetation category mapping at both general and specific levels, and while there are some problems with mixed forest categories, it would appear feasible from our knowledge of the literature and systems capabilities to accomplish a global mapping of generalized world vegetation units based on Landsat data. Such a capability could provide researchers with the most consistent, accurate world vegetation base maps in existence. This task, we feel, is practical and achievable.

The LACIE is a second example of the current capability to monitor crop lands on a global level.[38] LACIE was a proof-of-concept experiment focused on utilizing Landsat together with weather data to monitor wheatlands around the world and quantitatively estimate their production. This experiment concentrated on not utilizing within-year ground truth in the analysis of Landsat data. LACIE clearly demonstrated the potential utility of satellite remote sensing to monitor an important crop distributed over the world in a timely manner.

IV. AN OPERATIONAL GLOBAL VEGETATION WATCH PROGRAM

The particular concept discussed in this paper calls for a partitioning of the vegetative land areas of the world into meaningful regions and subregions. An organized administrative structure of scientists and technical personnel within each region would design and operate a system to produce a standardized vegetation data and information at the regional and subregional level. Selected standards and procedures would be utilized to produce data that could be pooled from each region at the global level. It is conceivable that such a distributed Global Vegetation Watch could be producing several types of rudimentary but important vegetation information by the end of this decade at local, regional, and global levels, and could be upgraded to produce what might be categorized as essential vegetation information at such levels by the beginning of the 21st Century. It is thought that the rudimentary data that could be produced initially would include: Level I small-scale vegetation cover type maps for the large areas of our globe of critical concern to scientists and resource managers, improved estimates of the hectares of certain important vegetative classes, and estimates of certain biophysical characteristics such as leaf area index or biomass. More sophisticated data such as estimates of evapotranspiration rates, or even refined estimates of biomass by species suitable to support such issues as the CO_2 sink-source question, will in all likelihood require a more sophisticated capability that conceivably could be developed over time through additional research and application experience.

In this particular approach, the important vegetative classes of interest in regions and subregions of critical concern together with their biophysical characteristics and those of the life support systems that constitute important vegetative information would need to be decided upon initially. In addition, appropriate scales, minimum mapping, and statistical estimation procedures, as well as initial functional categorizations and update sequences, will also need to be addressed. In order to initiate a program and provoke discussion of critical issues, we would propose that the above tasks be undertaken through a series of highly directed workshops over no more than a one-year period and that the results of these workshops be widely distributed both within the national and international research and vegetative source management communities. The overall comments of both scholars and operational managers will need to be carefully weighed in the development of mapping and monitoring criteria.

An analysis of the requirements presented by these individuals would then be conducted. This analysis would focus on the tradeoffs in the relative importance of requirements against the capabilities of remote sensing technologies that currently exist, as well as projected future advances to meet those requirements. Important vegetation information would then be ordered on a basis of relative importance and the capability of satellite remote sensor systems to provide them. Exploratory experiments would then be designed, evaluated, and conducted in selected regions employing the most stable of the technological elements to ascertain through direct experience how well each of the initial requirements under investigation are being satisfactorily met. These studies would also serve to demonstrate what, if any, improvements are required to satisfy the need for the acquisition of this first order vegetation information.

If acceptable performance is proven feasible in these tests with only modest technological research and development required, the next step would be the design and implementation of a quasi-operational system of vegetation mapping and monitoring for the selected regions. This program would be implemented with the support of a parallel research and development effort directed at bringing about an improved capability over time. The approach taken would be firmed up through the experience gained operating this first rudimentary system. In addition, plans for incremental upgrades would then emerge based on need, research, and continuing operational experience. The procedures and experiences gained in this evolutionary approach would support the implementation of similar approaches in other regions by scientists and resource managers with common interests.

A logical technical approach based on what we know today could involve the following steps:

- Landsat multispectral measurements acquired at selected periods over the course of several years would be acquired, preprocessed, and merged together with other selected environmental data into a georeferenced data base. The region would be initially stratified into relatively homogeneous subregions. Existing sampling approaches would be applied to identify sample units suitable for the application of automated processing of remotely sensed data. These remotely sensed data would be integrated and interact with other data sources for mapping and monitoring of the selected vegetation classes and certain of their biophysical characteristics.

- Temporal trajectory profiles of the different vegetative classes would then be developed and analyzed to determine which are separable and uniquely identifiable and which of their biophysical characteristics can be determined based on an analysis of spectral trajectory profile data when integrated with other collateral/ancillary data in a modeling format.

Two types of analyses could then be applied to the temporal trajectory profiles for the sample data points selected. Proportion estimation techniques would provide an initial estimate of the proportions of the classes within the regions/subregions. Per pixel classification analysis techniques would then be employed to provide a pixel-by-pixel identification of the relevant information. Following these initial estimates, Landsat data together with selected ground observations would be acquired at a given frequency related to within-class variance. These sample data would then be reestimated and reevaluated at periodic intervals. Where significant changes are detected, pixel-by-pixel reclassification would be performed to identify the location and spatial magnitude of the change. These data would then be used to update a georeferenced data base which would be developed as an integral part of this resource monitoring program. Data base parameters would be defined early on and information stored therein would be in an easily accessible "user friendly" format.

V. SUMMARY AND CONCLUSIONS

In summary, this paper has attempted to identify the need for, and the current capability of, a technology which could aid in monitoring the Earth's vegetation resource on a global scale. Vegetation is one of our most critical natural resources, and accurate timely information on its current status and temporal dynamics is essential as we attempt to understand many of the basic and applied environmental interrelationships which exist on our small but complex planet.

The authors herein assert that for the first time, the critical components of a technology exist to permit mankind to monitor our global vegetation resource in an affordable manner. The authors further assert that a proper mix of satellite, sensors, communications, computers, analysis techniques and ancillary data, together with distributed, coordinated implementation approaches, can be effectively brought to bear on this task and indeed could evolve into a capability that could perhaps keep pace with the ever-increasing, complex information requirements of scientists and resource managers for the rest of the century and beyond.

It has been stated that "of all the factors that determine the quality of our environment, the most fundamental is the use we make of the land."[39] The manner in which the land is managed has become a crucial issue, succinctly expressed by Cook. "The nations of the world have reached the place in time when the management of their land and environment for the benefit of their people is essential for their survival. The choice is between mismanagement with its waste of limited resources such as soil, water, air, minerals, oil, and timber, and wise management to obtain full benefits from the expenditure of public funds and to prolong indefinitely limited resources."[40] Vegetation then, is one of our most critical natural resources. We strongly urge the beginning of a coordinated integrated Global Vegetation Watch.

VI. ACKNOWLEDGEMENTS

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TABLE 1. REGISTRATION ISSUES

1. How to register images with differing spatial resolution.

2. Definition of measures of accuracy for registration.

3. Effects of intensity quatization on registration accuracy.

4. Radiometric transformation due to registration (Resampling problem).

5. Definition of corresponding reference points and objects for registration and rectification.

6. How to register images with different wavelengths.

7. Order on registration and rectification in multi-imagery.

8. Recovery of elevation from overlapping images

9. Production of orthophotos.

10. Use of elevation data in rectification.

11. Identify ancillary data.

12. How to use such data.

13. Merging data into data base (e.g., mean high water).

14. How to register ancillary spatial data to other images.

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Figure 1. Agrophysical units (APU's) mapped on a June 1976 Landsat image (Texas-Oklahoma panhandle).

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Figure 2. Landsat color infrared image showing degrees of agricultural density: A - low, B - high, C - moderate (pivot irrigation).

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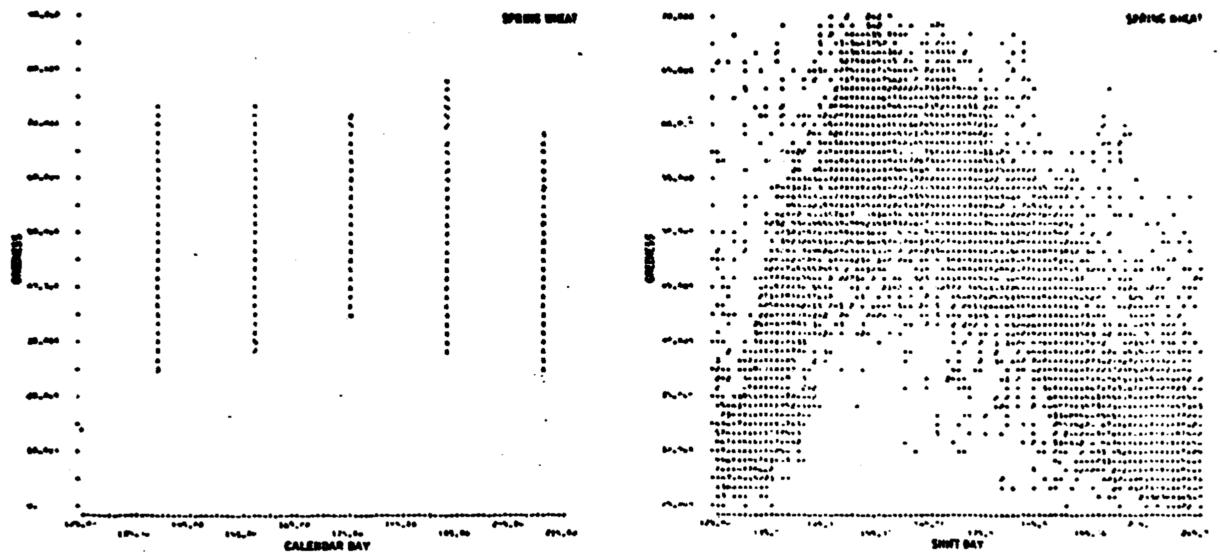

Figure 3. A plot of greenness for wheat. The graph on the left contains the raw data, and the graph on the right contains the data adjusted for the emergence date. (* = one pixel; x = >10 pixels; each graph contains ≈5000 pixels.)

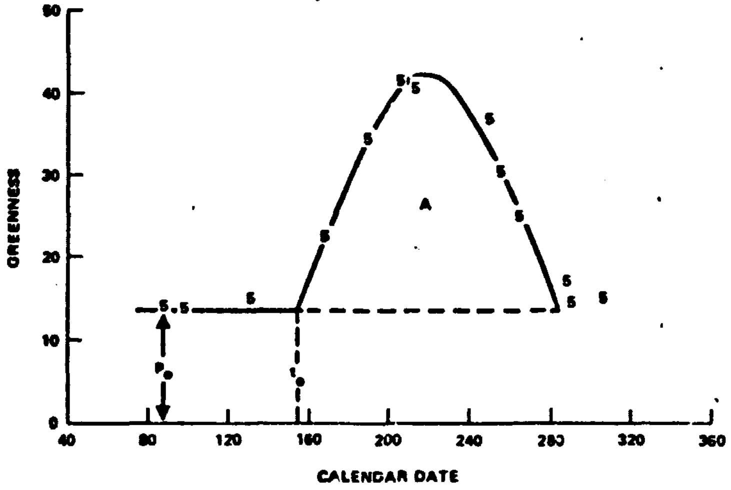

Figure 4. Temporal profile of a cornfield in Iowa, 1978.

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HISTOGRAM OF THE VALUES a FOR CORN AND SOYBEAN PIXELS IN SEGMENT 882, IOWA, 1978

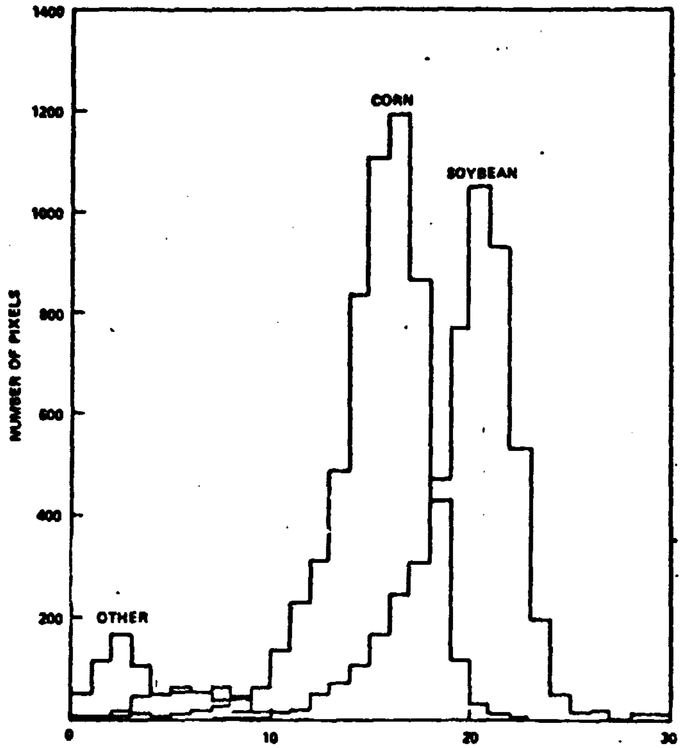

Figure 5. Histogram of the α values for pixels in segment 882, Iowa, 1978.

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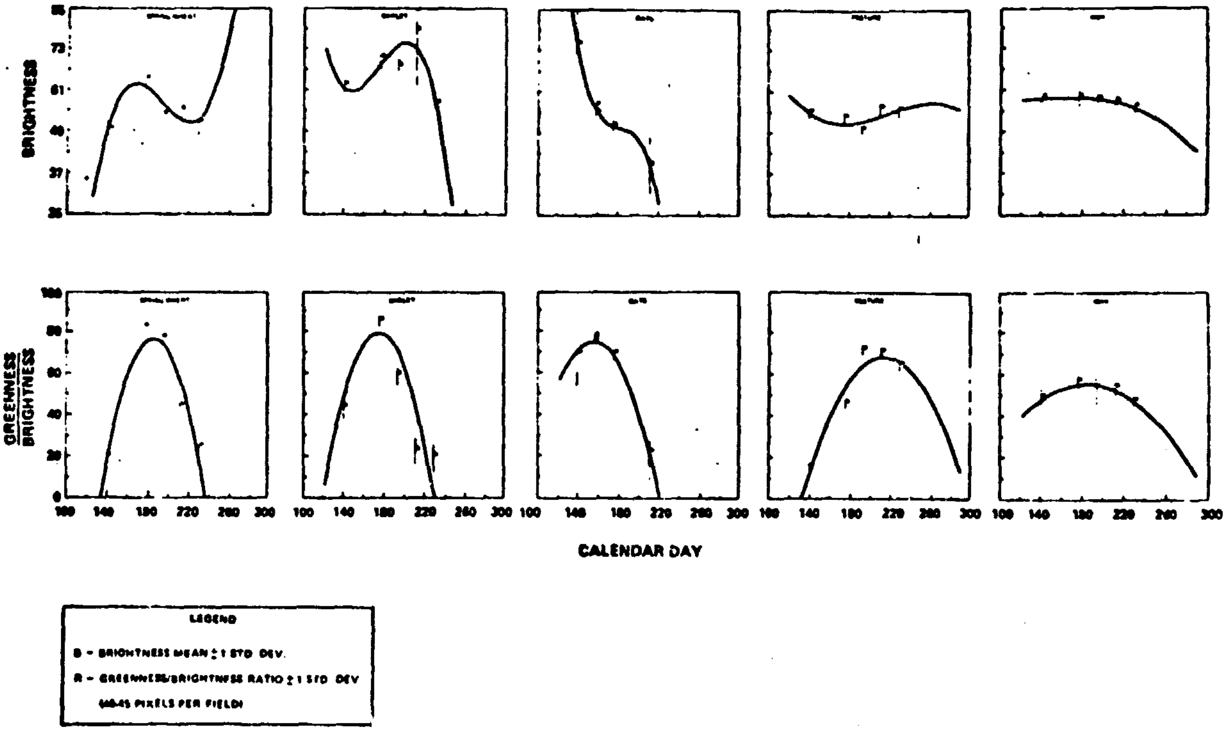

Figure 6. Comparison of brightness profiles and greenness-to-brightness ratio profiles for several grains and grasses.

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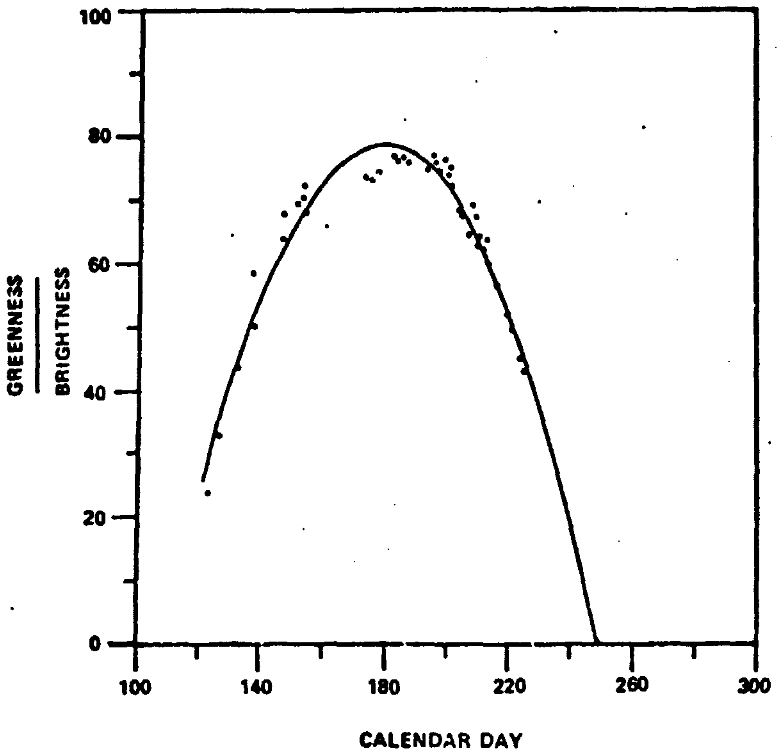

Figure 7. Parabolic fit to Arizona winter wheat plot data for crop year 1976.

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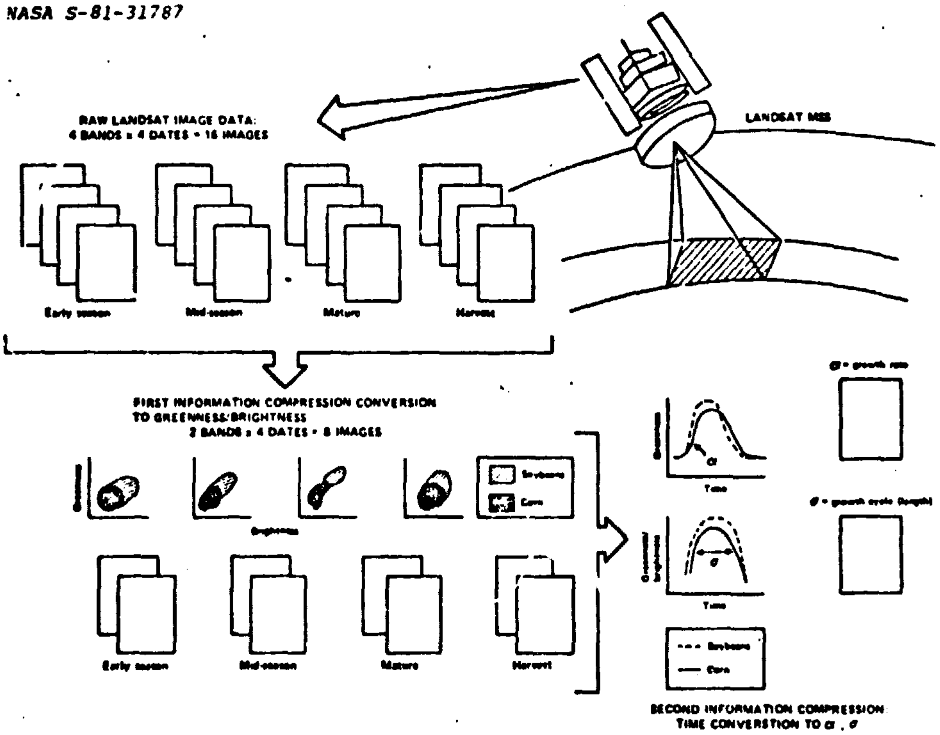

Figure 8. Physical transformation of Landsat data to its information-bearing components.