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A REVIEW OF REMOTE SENSING AND GRASSLANDS LITERATURE

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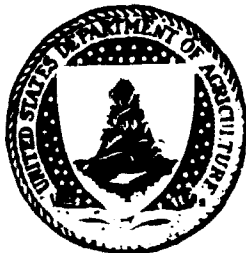(E82-10277) A REVIEW OF REMOTE SENSING AND
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A REVIEW OF

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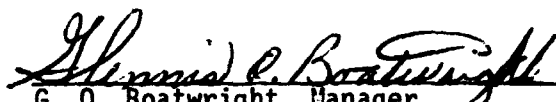
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PREFACE

The Agriculture and Resources Inventory Surveys Through Aerospace Remote Sensing is a program of research, development, evaluation, and application of aerospace remote sensing for agricultural resources, which began in fiscal year 1980. This program is a cooperative effort of the National Aeronautics and Space Administration, the U. S. Department of Agriculture, the Department of Commerce, and the Interior, and the U. S. Agency for International Development.

CONTENTS

1. INTRODUCTION

Grasslands, a natural resource, comprise approximately 24 percent of the earth's vegetated area. Of all the earth's plants, grasses are the most useful to man since the; include both grain and forage crops. Confronted with a global situation of increasing food demand, monitoring and management of this natural resource is crucial if conservation, rejuvenation and optimum production are to be attained. Both activities require timely information regarding the quantity and condition of grasslands over large areas.

Traditional techniques for estimating the productivity and condition of grasslands are based on detailed field data collection. These techniques are often time consuming and costly and are not applicable in the evaluation of large geographic areas. Remote sensing is an alternative which permits large area inventory and evaluation.

This literature review is a summary of significant studies dealing with remote sensing of rangelands.* The information derived will become the basis for additional research in the remote sensing of rangelands within AgRISTARS/Early Warning.

*The terms rangeland and grasslands will be used interchangeable in this paper.

2. GENERAL SPECTRAL PROPERTIES OF RANGELANDS

A brief description of vegetation and soil reflectance properties is included in this section to review the basic principles used in monitoring rangelands through remote sensing. Studies reviewed concentrate on multi-spectral scanner bands (0.4 to 1.1 um); other wavelengths were not considered.

Electromagnetic radiation from vegetation cover is a combination of the reflectance from various parts of the plants, the soil background and the illumination conditions. The actual reflectance of vegetation cover is highly complex since the spatial configuration of vegetation is extremely heterogeneous. However, light reflectance from vegetation surfaces does have some general properties which characterize the ways in which various wavelengths of solar energy interact with plants.

The reflectances of typical living herbaceous vegetation, dead or dormant herbaceous vegetation, and soil in the wavelength range of 0.4 um to 1.1 um are composed in Figure 1. The visible portion of this wavelength interval lies between 0.40 and 0.75 um. Pigments in the chlorophyll of vegetation characteristically absorb high levels and reflect low levels of solar energy. (Reeves et al; 1975). A slight peak in reflectance occurs at about 0.55 um, which explains why healthy vegetation is seen as predominently green. The 0.75 to 1.1 um wavelength interval, or part of the near-infrared region, is characterized by high reflectance from plant surfaces influenced by the internal structure of the leaves. These reflectance curves vary somewhat from species to species and also vary with the age of the plant, the pheno-logical stage, vigor of growth, and plant health. These variables make it difficult to distinguish between different plant species solely on the basis of their spectral reflectance characteristics. Discrimination using characteristic spectral curves or spectral signatures are not impossible, but they are typically confined to general plant communities rather than to individual species.

Dead or dormant vegetation exhibits markedly different spectroreflectance properties from those of green or living vegetation. The dead or dormant grass has a higher reflectance than living grass in the visible part of the spectrum (0.4 to 0.75 um) and a lower reflectance in the near-infrared (see Figure 1). As indicated by the graph, the difference in reflectance between the two is maximized in the red portion of the spectrum at approximately 0.68 um. Theoretically, the wavelength of 0.68 um is the best single wavelength (between 0.4 and 1.1 um) for discriminating between these two conditions of vegetation cover.

As with vegetation, the spectroreflectance properties of soil are complex and extremely varied. Many types of soil and soil conditions exist and an attempt to attach a particular spectral reflectance signature to soil would result in a gross generalization. Nevertheless, most soils share some basic reflectance properties, and general spectroreflectance characteristics can be plotted. Figure 1 also illustrates the relationship of spectroreflectance among soil, living grass, and dead or dormant grass. In the visible portion of the spectrum, the soil has a higher reflectance value than the green vegetation and a lower value than the dead or dormant vegetation; while in the near-infrared, its reflectance is lower than green and dead vegetation. Here, soil/green grass reflectance contrasts are also maximized in the red portion of the spectrum.

Rangeland spectroreflectance is composed of the sum of the reflectance from the ground components. Many additive and subtractive factors contribute to the resulting total reflectance, such as the amount of vegetation present; the spatial configuration of the vegetation canopy; the reflectance from the various surfaces of the vegetation; the condition and phenology of the vegetation; the amount of shadow, soil background and soil brightness; soil structure; the angle of incident solar radiation; view angle of the sensor; and extraneous effects such as atmospheric haze, sensor noise, etc. Remote sensing devices generally do not measure reflectance of specific ground components within their field of view but rather add the varying amounts of reflectance from the various components to produce a total reflectance value

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of the scene. Naturally if a green cover of rangeland vegetation dominates
a sensor's field of view, the total amount of reflectance received by the
sensor will be determined mainly by the reflectance characteristics of the
vegetation while other scene components will have a lesser effect on total
reflectance. In most of the studies considered here, the primary concern is
the effect of the reflectance of green rangeland vegetation on the reflectance
from the total scene.

3. REVIEW OF LITERATURE

Numerous study results were identified for comprehensive review. The authors of these publications are:

a. Pearson and Miller (1971, 1972, 1973)

b. Tucker, et al. (1973, 1975)

c. Seevers, et al. (1973)

d. Rouse, et al. (1973, 1974)

e. Deering, et al. (1975)

f. Deering and Haas (1977)

g. Colwell (1974)

h. Maxwell and Johnson (1974)

i. Maxwell (1975)

. Carneggie, et al. (1973, 1975)

k. Conn, et al. (1975)

l. Everitt, et al. (1975, 1979, 1980)

m. Tucker (1976, 77, 78, 79)

n. Tucker and Miller (1977)

o. Richardson and Wiegand (1977)

p. Wiegand, et al. (1977)

q. Tueller (1979)

r. Harlan and Deering (1979)

s. Harlan, et al. (1979)

t. Thompson and Wehmanen (1979)

u. Tappan (1980)

v. Tucker and Deering (1980)

This section presents a summary of each review. Generally, the literature is presented in chronological order with the exception of common authors and/or topics.

Pearson and Miller (1971, 1972, 1973) were among the first investigators to develop a technique for mapping rangeland biomass from remote sensors and initially worked with spectral measurements of small plots in the Colorado

shortgrass prairie region. A simple spectroradiometer was used to establish relationships between components of the sample plots (soil, green vegetation and dead vegetation) and their respective spectral responses. This information was used to develop a rapid, non-destructive method for estimating the amount of vegetation cover The in situ spectroreflectance curves obtained by the spectroradiometer varied with the amount of green vegetation in a predictable manner. By correlating dry green biomass on a plot with that plot's reflectance at various wavelengths in the visible and near-infrared portion of the spectrum, Pearson and Miller identified two wavelengths (.68 and .78um) which exhibited high correlations between the variables. Reflectance at the .68um wavelength showed a strong inverse relationship with varying amounts of biomass because this wavelength lies within one of the chlorophyll absorption bands. Reflectance at the .78um wavelength showed a strong positive relationship because of the reflective nature of green vegetation in the near-infrared.

Combinations of these two wavelengths were then investigated to determine if the sensitivity to vegetation cover could be improved. Two combinations were tried: (1) the difference in reflectance at .68um and at .78um and (2) a simple ratio of the two reflectances. Results indicated high correlations (over 95 percent) between the values of the combined reflectance and green vegetation cover.

Many of the vegetation indices used today are based on the principles investigated by Pearson and Miller. Their methods could easily be applied to aircraft and satellite remote sensing systems.

Tucker, et al. (1973) investigated the relationships between plots of short-grass prairie vegetaion and the reflectance of the plots at 91 wavelength intervals. Three green vegetation measurements were made: (1) green biomass, (2) chlorophyll and (3) leaf water content. Because of the interrelationship in these three plant characteristics, the simple linear spectro-correlation curves for each measurement were similar.

Correlations between these parameters and the 91 individual wavelengths yielded the following results:

(1) The two chlorophyll bands of the visible spectrum (approximately .40-.50um and .60 - .70um) resulted in high negative correlations for the sample parameters. These spectral regions remained fairly constant for green functioning vegetation and were unaffected by increasing amounts of standing dead vegetation on the plot.

(2) High spectro-correlations were observed between the green functioning vegetation and the near-infrared portion of the spectrum. These values were also unaffected by varying amounts of standing dead vegetation.

(3) Spectroreflectance relationships were successfully used to map grassland biomass over large areas from aircraft scanners. The authors also expressed optimism regarding the potential of using Landsat data for monitoring rangelands.

In 1973, Seevers, et al. made optical density measurements from Landsat transparencies using reflectance in red wavelengths, and found them useful for determining vegetative biomass in the Sand Hills of Nebraska. Comparisons of biomass could be made easily within one Landsat frame, but correction factors were needed for comparison between acquisitions.

The Great Plains Corridor rangeland project, conducted at Texas A&M University, used natural vegetation systems as phenological indicators of seasonal development and climatic effects on regional growth conditions. In 1973, Rouse, et al. determined the feasibility of using ERTS (renamed Landsat) to monitor the vernal advancement and retrogradation of vegetation throughout the high plains.

They developed the Band Ratio Parameter (BRP) for measuring native vegetation conditions from Landsat. The BRP can be defined as the difference in the Landsat radiance values of bands 5 and 7, divided by their sum. This normalization of bands was used to eliminate seasonal sun angle differences and to minimize the effects of haze. They also used the Transformed Vegetation Index (TVI) which is equal to the square-root of the BRP, plus an arbitrary constant; this being done to avoid working with negative BRP values and to eliminate the chance of a variance of the ratio proportional to the mean values.

Comparison of the TVI values to ground-based measurements at a test site indicated that green biomass accounted for 89 percent of the variation in TVI, and interactions of vegetation moisture content measurements with green biomass exhibited an even stronger relationship with TVI. A threshold was found to exist below which TVI is insensitive to biomass. Indications were that sparse vegetation cover might not be measured accurately by TVI, and further analysis would be necessary to confirm this. In general, TVI was found to be suitable for monitoring the green-up and senescence of vegetation in the Great Plains and for measuring most amounts of green biomass.

In 1974 Rouse, et al. reported their continued work on using Landsat to monitor the advancement and retrogradation of rangeland vegetation in the Great Plains. They successfully corrected for variations in solar elevation angle. Testing of the TVI continued and it was found to be useful for detection and monitoring of biomass levels on a regional basis. Attention was also given to the influence of weather on the TVI parameter. A number of weather-related, independent variables was isolated and correlations were found between them and TVI (the dependent variable). Analysis indicated that weather data should be used, if possible, as input to a prediction model for green biomass determination.

Using the same regional approach, Deering, et al. (1975) reported findings on the use of Landsat data for monitoring the phenological stages of rangeland growth from south Texas to North Dakota. They correlated ground observations of the vegetation cover with data from the Landsat overpasses and demonstrated the use of waveband ratios to normalize the effects of soil variations. They also used TVI and a model discussed above for correcting data for effects of varying solar elevation angles from one Landsat pass to another.

In a later study, Deering and Haas (1977) used the TVI parameter to monitor green forage biomass in Great Plains areas of near-continuous vegetation with insignificant amounts of brush cover. Results showed that Landsat digital data could provide a useful estimate of green biomass quantities to within 250 kg per hectare and that at least five levels of forage conditions could be mapped for extended regions.

Colwell (1974) investigated many important factors contributing to the
complicated pattern of grass canopy reflectance and showed that several
factors can play major roles in influencing the canopy reflectance: (1) leaf
hemispherical reflectance and transmittance, (2) leaf area, (3) leaf orienta-
tion, (4) hemispherical reflectance and transmittance of supporting structures
(stalks, limbs, etc.), (5) effective background reflectance (soil, rock, leaf
litter), (6) solar zenith angle, (7) look angle, and (8) azimuth angle. In
order to understand the causes for canopy reflectance values obtained at any
given location, each of these factors should be measured to determine their
respective contributions.

Having identified these factors, Colwell undertook a study to assess the
feasibility of using remote sensing techniques to measure biomass on range-
lands (Colwell, 1974b). Detailed investigations were performed on these
variables and some of the significant findings include: (1) The red spectral
region is often most sensitive to percent cover and biomass for green canopies
having low-to-intermediate amounts of vegetative cover. (2) The near-infrared
spectral region is especially sensitive to high values of percent cover for
green canopies. (3) The relationship between biomass and canopy reflectance
is usually curvilinear for the full range of biomass. (4) Soil reflectance
variations can cause large variations in canopy reflectance, especially when
accompanied by low amounts of vegetation cover. The use of reflectances from
a single spectral band for estimating biomass is sensitive to changes in soil
reflectance and, hence, are less suitable for establishing significant estimates
of biomass. The infrared/red reflectance ratio, however, is effective in
normalizing the influences of soil background of a canopy. Leaf litter effects
are also normalized by this ratio. (5) Reflectances from a canopy received
from different view angles yield different values, and different spectral bands
may have different trends.

Maxwell and Johnson (1974) spent considerable effort defining and describing
a remote rangeland analysis system. They attempted to identify characteristics
of rangelands measurable by satellite sensors. Computers were used to develop
techniques for extracting meaningful information from Landsat digital data for

monitoring rangeland biomass. The most significant results included the use of computers for recognition and separation of green biomass classes and the successful use of Landsat band ratios for this purpose. This system did need validation on other grassland environments, however.

In 1976 Maxwell tested a simplified version of the remote rangeland analysis using a supervised classification algorithm with Landsat data. Ground-based training samples were identified and were used as a basis for classifying and mapping 10 vegetation association classes over the test site. The statistical separation between the classes was good, with an average error of 7.5 percent. The best separation between classes was achieved by using Landsat band 5 and the band ratio 5/7, in that order. The other Landsat bands were also used individually, but no other band combinations were tried.

In addition to vegetation association classes, biomass classes were mapped. These were first identified in the field and used to train the computer to separate seven biomass levels. Spectral data from three Landsat passes were combined in the classification. The fairly high classification error that was found (24.6 percent) was attributed to limited biomass samplings in the field and to natural variation of biomass within the test fields. The biomass classes were best separated using the 7/5 band ratio, followed by band 5 above.

Carnegie, et al. (1973, 1975) used Landsat data to determine their utility for monitoring and assessing range condition within an annual grassland in California. Vegetation samples were collected for biomass measurement and ground spectral reflectance data. A simple wavelength ratio of the near-infrared at .800 um to the red at .675 um was used, and the ground reflectance data was correlated with green biomass yielding a close correspondence between variables. Landsat data was used both visually and digitally. Landsat color composite images provided a visual picture of range condition, and repetitive images allowed changes in range conditions to be monitored qualitatively over time. Digital analysis of the Landsat spectral data provided quantitative determination of the occurrence of germination, the peak of foliage development, and senescence. The ratio of bands 5 and 7 indicated changes in growth stages and relative differences in forage production between range area.

Conn, et al. (1975) reported on the spectral signatures of native vegetation communities in an arid environment. Data was obtained on ground spectral signature components using ground-based and airborne radiometers and wavebands comparable to Landsat MSS bands 5 and 7. By plotting the spectral data of the ground components on graphs (red versus near-infrared reflectance), they found that the soil, rock, and litter components of the desert floor dominate heavily the spectral signature of desert plant communities. Vegetation had only a small effect on the spectral signature. A direct relationship was found to exist between the amount of plant cover and the influence of vegetation on the overall signature. Native arid plant communities having low biomass density were difficult to detect; whereas those having more foliage had a stronger influence on the signature of the desert floor.

Landsat-1 data was used by Everitt, et al. (1975) to determine the extent and distribution of rangelands in Hidalgo County, Texas. The data was used to perform a supervised classification of the major cover types in the county. Classification was performed on MSS bands 4, 5, and 7 using a maximum likelihood classifier. Rangeland areas were grouped into either grass or mixed shrub associations and acreage estimates were computed for the various cover types. The computer recognition of rangeland versus ground truth figures compared well (470,000 acres compared with 453,000).

Tucker, et. al. (1975) found a strong correlation between spectroreflectance and green biomass in two pigment absorption bands of the visible spectrum and one in the near-infrared region. These results were found to be based upon the chlorophyll content, the internal structure of the leaves, and the geometrical arrangement of the plant canopy. Further, functioning blue grama grasses were found to maintain proportional amounts of green biomass, chlorophyll and leaf-water. Spectrocorrelation curves were calculated for each of these constituents, and results indicated that they were identical in character but slightly different in magnitude.

Tucker (1976) conducted a study to determine optimum sensor wavelengths and bandwidths for monitoring rangeland vegetation canopies. Sensor characteristics

were simulated by integration of spectral data between wavelengths of 0.35 to 1.00 um and regressed against sample plot reflectances of blue grama grass. Three spectral regions were found to be statistically significant for measurement of canopy variables: 0.37 - 0.50 um, 0.63 - 0.69 um, and 0.75 - 0.80 um. Inclusion of noisy bands which are simultaneously sensitive to green vegetative absorption (red wavelength) and enhanced reflectance (near-infrared wavelengths) resulted in extremely poor correlations between reflectance and canopy variables. Theoretically, Landsat band 6 (0.70 - 0.80 um) is inferior to band 7 (0.80 - 1.10 um) since it covers the noisy transition zone between vegetative reflectance and absorptance. However, many investigators have found band 6 to be potentially significant (Rouse, et. al., 1974; Tucker and Miller, 1977).

Bands 5 and 7 were found to be well situated for remote sensing of vegetation. Greater spectral sensitivity was found earlier in the growing season between reflectance and the grass canopy variables. Grass canopy biomass estimates were made by Pearson et al. (1976) on a shortgrass prairie using an airborne multispectral scanner and a single hand-held radiometer. They found that these instruments could provide accurate estimates of biomass as long as the grass canopies consisted of at least 30 percent vegetation cover. They used a red to near-infrared reflectance ratio (.68 and .80 um) and found that a simple linear model was best for explaining the relationship between the ratio values and the dry biomass.

Tucker (1977a) identified spectral regions (0.35 um and 0.80 um) where the total wet biomass, total dry biomass, and leaf water content of a blue grama grass canopy can be spectrally estimated. He found that "the regression significance existing between leaf water content and reflectance in the 0.45 to 0.50, 0.63 to 0.69, and 0.74 to 0.80 um regions was highly correlated to the amount of photosynthetically active or live functioning vegetation present in the canopy."

In another study, Tucker (1977b) addressed the question of which single wavebands, between 0.35 and 0.80 um, perform best for resolving differences between various amounts of biomass. Results indicated that the best single

narrow band for biomass class discrimination was the photographic infrared region. The study also determined the number of discrete biomass classes that could be resolved by a single narrow band. Three classes of total wet biomass were distinguished by their spectral reflectances taken from in situ plots, and four and five total wet biomass classes were not spectrally resolved at higher amounts of total wet biomass.

In another study, Tucker (1977c), made a valuable contribution toward the better understanding of near-infrared/red reflectance combinations for the estimation of vegetative biomass and condition. He compared several of the existing vegetation indices based on these reflectances (RVI, DVI, VI and TVI) and concluded that only slight differences existed between them. No advantage was found in transforming the VI into the TVI. These band combinations were more sensitive to varying amounts of green biomass than the red or near-infrared radiances taken separately.

Three bandwidths in the near-infrared were evaluated (0.75 - 0.80, 0.80 - 0.90, and 0.75 - 0.90 um) for their correlations against green biomass, and all three were found to be very similar when ratioed with the red radiance.

Finally, Tucker found that the more green vegetation present in the grass canopy, the more nonlinear the relationship between the amount of green vegetation and the various vegetative indices. The presence of standing dead vegetation in the canopy had a linearizing effect upon these relationships.

Tucker (1979) continued his analyses of red and near-infrared linear combinations for monitoring herbaceous vegetation cover. In this study, relationships were evaluated between various vegetation indices and experimental biomass plots, leaf water content, and chlorophyll content. While most of the indices tested were based on the near-infrared/red reflectance combinations, various green/red reflectance combinations were also examined. The findings confirmed that near-infrared/red linear combinations were more significant than the corresponding green/red linear combinations when regressed against six canopy variables. The near-infrared/red combinations were primarily sensitive to the green leaf

material on the photosynthetically active biomass in the canopy and not to the dead or dormant vegetation. Therefore, the vegetation indices do not apply to dead or dormant vegetation, and chlorophyll absorption is needed before these linear transformations will work. However, standing dead vegetation in the grass canopy did have a linearizing effect upon the various green measurements. Other tests indicated that the RVI, NDI, DVI, the VI and the TVI are all very similar for estimating the photosynthetically active biomass.

Tucker and Miller (1977) investigated the contributions of soil reflectance to the grass canopy reflectance and found that in many cases the effects of soil on canopy reflectance can be measured. The influence of soil reflectance to the composite canopy reflectance was found to be inversely related to the amount of biomass (at a given wavelength). Therefore, when the vegetative canopy approaches 100 percent cover, the soil spectral contribution becomes insignificant or non-existent.

The spectral discrimination of vegetation from soil was strongly dependent on the soil/vegetation spectral reflectance contrast, indicating that some wavelengths are better than others for measuring green biomass (supported by Colwell, 1974a, 1946b; Pearson and Miller, 1971, 1972, 1973; Rouse et al., 1974; Tucker, 1976, 1977a, 1977b, 1977c, 1978; and Tucker et al., 1973). A regression analysis was used to quantify the optimum wavelengths for soil/ green vegetation reflectance contrasts, and the 0.67 to 0.69 um and 0.75 to 0.80 um spectral regions exhibited the highest contrasts. The near-infrared soil/green vegetation reflectance contrasts (0.75 to 0.80 um) may explain why Landsat MSS band 6 (0.70 to 0.80 um) has often been found to be better situated than band 7 (0.80 to 1.10 um) for measuring biomass.

Richardson and Wiegand (1977) completed a noteworthy study which also addresses procedures for estimating the contribution of soil background spectral reflectance on reflectances from other components such as vegetation cover. While their study does not examine native rangeland vegetation, the techniques and conclusions derived are applicable to rangeland remote sensing.

Briefly, they discovered that using Landsat bands 5 versus 7 and 5 versus 6 to generate scatter plots of radiance values, features such as clouds, cloud shadows, and various intensities of soil reflectance fell along a highly predictable line called the soil background line. The darkest feature (cloud shadows, dark soils, etc.) clustered near the origin of the axes, and the lighter features fell higher on the line. Landsat digital counts representing vegetation were displaced perpendicularly away from the soil line. The distance of the vegetation values from the soil line was found to vary as a function of vegetation density, where increasing density resulted in further displacement from the soil line. This served as the basis for development of the Perpendicular Vegetation Index (PVI). It was demonstrated that the PVI can be used to determine the soil background reflectance of pixels containing both vegetation cover and soil. Other vegetation indices do not provide this capability.

Eight vegetation indices (TVI, TVI6, RVI, PVI, PVI6, DVI, SBI, and GVI) were compared with four ground truth variables: crop cover, shadow cover, plant height and leaf area index. In general, the TVI6 and the PVI6 indices performed best leading to the conclusion that individual Landsat bands may sometimes correlate better with vegetation parameters, but the vegetation indices are better suited to temporal comparisons of vegetation conditions.

Wiegand, et al. (1977) conducted a study in southern Texas to relate Landsat data to a variety of cover types and conditions. One of the objectives was to identify range sites botanically and then to determine periodically herbacious biomass over these sites. Biomass estimates were made using the perpendicular distance of pixels from the background soil line in MSS bands 5 and 7 feature space. This technique, developed by Richardson and Wiegand as the PVI, was found to be accurate for estimating biomass on native grasslands. Problems were encountered when estimating biomass in a "mixed brush" area where woody vegetation ground cover ranged from 15 to 85 percent.

The contribution of dead or senescent biomass to grass canopy response was investigated by Tucker (1978). Recently senesced vegetation was spectrally

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detected in the 0.36 to 0.45 um and 0.75 to 0.80 um regions. A direct relationship was found between reflectance and senesced vegetation at 0.58 um and at 0.72 um (red wavelengths). This is the converse of the relationship existing between reflectance and green vegetation in the red wavelengths. The relationship at 0.80 um (near-infrared) was also found to have a direct relationship to senesced vegetation. Further, this relationship is similar to that of functioning green vegetation. Therefore, the spectral contrast between senesced vegetation and functioning green vegetation is poorer in the near-infrared.

Tueller (1979) identified some of the interpretation problems involved in conducting inventories on rangelands and range conditions. He pointed out the need for the systematic use of several scales and varying resolution levels, and listed problems and noise sources encountered when quantifying vegetation spectral signatures. He found that automated classification of spectral data for arid rangelands was much more efficient when using an unsupervised clustering algorithm. Supervised techniques were considered too time-consuming because of the extreme heterogeneity of rangelands throughout the world.

Harlan and Deering (1979) conducted a study to investigate the effectiveness of Landsat data for "measuring and monitoring the arid and semi-arid rangeland vegetation biomass and growth conditions which are of direct concern to rangeland managers." In areas of west Texas, they tested the normalized difference parameter (ND6) for estimating biomass, and found that relationships between ND6 and green biomass under low brush canopy cover conditions were strong, but local variations in cover required a calibration to determine the best fit for the ecosystem. They also verified that brush cover had a detrimental effect on the relationship of ND6 versus herbaceous green biomass. Further research was recommended to account for the effects of brush cover.

In another study, Harlan, et al. (1979) looked at procedures for assessing levels of grassland standing biomass in the Pawnee National Grassland of eastern Colorado. Using five vegetation indices (ND6, ND7, and the RVI's: 7/5, 6/5, and 5/4), they successfully achieved useful Landsat biomass estimates

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for low biomass, semi-arid sites. They supported the need to counteract adverse atmospheric conditions since these were found to affect biomass estimates and urged that effective ground sampling instrumentation be developed for relating ground conditions to Landsat data.

ND6 explained 75 percent of the variation in green biomass on acquisitions with a relatively clear atmosphere. Certain cloud conditions were found to shift the ND6 values causing overestimation of biomass. They pointed out that several other problems required solution before Landsat herbaceous biomass monitoring could be applied on a universal scale: accounting for woody species contamination of the spectral data; the high reflectance of some exposed soils; and the effects of high relief tension. In areas of low brush cover, including large portions of the western United States, a capability exists to determine biomass and canopy ground cover.

Everitt, et al. (1979) tested the effectiveness of using Landsat-2 MSS data for inventorying rangelands in south Texas. Two dates of satellite data were used; one in October representing late-season vegetation growth and one in December when the vegetation was dormant. Using a training-field classi- fication approach and a maximum-likelihood clas-ifier, a land cover map of the study area was produced. Comparing the map with ground truth, they found that the near-infrared bands provided most of the separability between various vegetation categories (grassland, mixed brush rangeland, live oak rangeland). Level I land use categories (rangeland, wetland, agricultural land, water, and barren land) were spectrally distinctive on both dates. Level II range- lands (grassland, mixed brush, live oak rangeland) were best identified in October. This indicated that living vegetation is a prerequisite to dis- crimination between Level II categories.

Various studies appear in the published literature concerning the identification and mapping of rangeland from aerial photography. A study undertaken by Everitt, et al. (1980) investigated the use of microdensitometry on 70 mm black-and-white and color-infrared aerial photographs to distinguish quanti- tatively certain characteristics of 11 range sites in southern Texas at

different seasons. Using a variety of films, they found that color-infrared photographs taken during the summer were best for identifying the range sites. The best separation between the various range types was made when the vegetation was at its peak in foliar development. Attempts were also made to relate herbaceous biomass and ground cover to film optional density counts. They were unsuccessful in finding any significant relationship between these two variables.

A technique to detect moisture stress in vegetation using transformed Landsat digital data was developed by Thompson and Wehmanen (1979). This technique used the Green Index Number (GIN), an estimate of the percentage of pixels in a Landsat scene having green numbers high enough (>15) to indicate full cover of green vegetation. GIN values versus time were plotted for a Landsat LACIE segment dominated by wheat, and the resulting curves were compared to a predetermined curve of normal wheat growth. If an observed point for a segment fell into an empirically defined region below the curve, it was classified as stressed by drought. This classification was compared to weekly crop moisture indices, and a high degree of agreement was found between the remote sensing technique and the ground-based data. Extensions of this technique towards more arid or humid environments require more study.

Tappan (1980) examined nine of the common vegetation indices used with Landsat data. The indices were tested throughout the 1980 growing season for a rangeland site in the Kansas Flint Hills. Field data was collected to determine percent green vegetation cover and green biomass during the Landsat overpasses. These measurements were correlated with the Landsat MSS band values and with the vegetation index values. In most cases, strong relationships were found. The ratio of bands 6/5 and the TVI6 parameter exhibited the strongest correlations (values of .989 and .963) to the field-derived measurements. These strong relationships support other studies which indicate that vegetation indices can be related to specific amounts of biomass, ground cover, or other field measurements with high degrees of confidence.

The effect of the mid-summer drought of 1980, which reduced considerably the green vegetation cover in the Kansas Flint Hills, was reflected clearly by sharp decreases in the vegetation index values which support the use of vegetation indices for monitoring drought stress on rangeland vegetation.

Tucker and Deering (1980) conducted a study to determine the effectiveness of Landsat data for monitoring drought impact in Colorado. They determined that the "condition" of natural rangelands was one of the best indicators of drought, since moisture deficits result in reduced primary production in the grasslands. Preliminary results from optical and digital analyses of Landsat MSS data showed the effects of the 1976 drought on rangeland biomass production. Production dropped significantly during the drought, and recovered after the drought.

Monitoring drought impact by measuring the primary production of standing crop and range biomass was done using vegetation indices. Of six indices analyzed, 7/5 and the ND7 performed best. A single set of universal values for relating index values to biomass was found to yield acceptable results for a statewide monitoring of drought impact.

4. CONCLUSIONS

As evidenced from a review of the literature, considerable progress has been made toward obtaining rangeland information through remote sensing. The availability of Landsat data has unquestionably played an important role in design and implementation of much of the research. Future remote sensing systems such as the Thematic Mapper (TM) and the French-made Satellite Probatoire pour l' Observation de la Terre (SPOT) will likely provide additional insight into estimating the productivity and condition of rangeland vegetation.

Some of the main accomplishments related to remote sensing of rangelands, especially within the published literature of the last decade, can be summarized as follows:

a. Progress has been made in the identification and basic understanding of the major variables which contribute to grass canopy reflectance.

b. A number of studies have aided in the definition of optimum wavelengths in the visible and near-infrared portions of the spectrum for green and brown biomass estimation and for discrimination between vegetation and soil cover. These optimums have been found to vary somewhat from one environment to another but, in general, certain spectral regions are more suitable than others. In addition, certain wavelengths have been shown to be more sensitive to monitoring low amounts of vegetative biomass while others were better related to high amounts.

c. The use of wavelengths and waveband ratios, particularly in red and near-infrared spectral regions, has become a highly reliable method of estimating conditions and quantity of vegetation cover.

d. The basic wavelength and waveband ratios have inspired the development of a number of vegetation indices. Most of the indices measure the same characteristics of vegetation and appear to be highly correlated with one another. The indices are computationally straightforward, are readily applicable to Landsat data, are well related to known vegetation cover conditions, are fairly effective for normalization of spectral data with

respect to varying illumination and atmospheric conditions, and reduce spectral data from several wavelengths or wavebands to a single value.

e. Many advances have been made in mapping biomass levels and conditions over large areas using Landsat MSS data. Monitoring seasonal growth and determining the phenological stage of rangeland has also been successful from Landsat data.

f. Techniques for the detection and surveillance of drought impact on rangeland vegetation have been implemented with success. These techniques represent an improvement over conventional methods of assessing drought impact over large areas.

A number of topics can be identified in the literature requiring further research. Some of these are:

a. Investigations are needed in order to extend the reliability and usefulness of the vegetation indices over large geographical areas and time so that biomass levels and conditions can be estimated with confidence without a heavy dependence on field data.

b. More work is needed regarding the resolution of biomass levels as detected by the various indices. Further research should examine the variability of these biomass resolution levels over time (phenological stage) and space.

c. The lower and upper limits of percent vegetation cover, biomass, and other variables measurable by vegetation indices have not been adequately defined. A better understanding of the variability of these limits from one environment to another is needed.

d. Calibration studies are needed to account for the effects of brush cover on the spectral responses of rangeland grasses.

e. Additional commitment is needed regarding the use of remote sensing to monitor the effects of drought on rangelands. Specific problems such as the discrimination of stressed vegetation from natural senescence should be examined.

f. The utility of remote sensing systems which offer very frequent coverage over large areas at lower resolution levels should be investigated with respect to range studies. This type of coverage is presently available from the NOAA and TIROS satellite series.

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