Annals of Arid Zone 34(3): 191-207, 1995

Remote Sensing in the Management of Rangelands

Paul T. Tueller
Department of Environmental and Resource Sciences,
University of Nevada Reno, 1000 Valley Road, Reno, Nevada 89512, USA

Abstract : Remote sensing technology is rapidly maturing. Applications for range management continue to develop and are dependent upon three requirements: (1) continued remote sensing technology development; (2) application scientists and managers with optimum knowledge of the rangeland ecosystems to be managed; and (3) a continuing improvement in the arid land/rangeland knowledge base consisting of information on vegetation, soils, climate, water, fauna, etc., for the area to be managed and monitored. In addition, the rapidly developing computer infrastructure and the significant potential contributions of Geographic Information Systems, Global Positioning Systems now place remote sensing in a premier place among the possible techniques or new science available to assist range managers in their work.

Key words : Remote sensing, range management, rangeland, Geographic Information System, vegetation mapping.

Remote sensing along with the related technology of Geographic Information System (GIS) and Global Positioning System (GPS) provide new opportunities for intensive analytical examination of rangelands. Range management can certainly be improved by these new technologies, but will be realized only when range professionals are able to couple this technology to important rangeland resource management problems.

Remote sensing is in itself an art and a science. The science is provided mostly by physicists who along with engineers have increased our abilities to exploit information inherent in various regions or wavebands of the electromagnetic spectrum. The science also involves studies and their interpretation by various rangeland scientists. Aerial photography, in the wake of newer digitally oriented remote sensing and geographic information systems, is in some ways, almost a forgotten resource.

Semi-arid landscapes are found throughout the world. Resources management in arid regions where many rangelands are found, is complicated by characteristics such as sparse vegetation, low biomass, low leaf area indices, little greenness in the vegetation, often bright soils, considerable bare ground, shadows cast by shrubs, various soil and rock colors, often cloud-free weather, high air and surface temperatures, high evaporation rates and generally poor spectral response of the shrubs in the near infrared (Tueller, 1987).

Mapping from either aerial photography or digital images is complicated by the sparsity of the vegetation, the diversity of geomorphic surfaces, water erosion patterns, shadows cast by shrubs and soil and rock color variations common to desert and many range landscapes. The perspective offered by remotely sensed data gives opportunity to look at large land areas where extensive rather than intensive management is often required. This synoptic view or approach offers the possibility of providing data and understanding that will lead to better or, at least, enlightened management of rangeland resources throughout the world.

Research into pixel modelling (a quantitative assessment of the proportion of rock, soil, litter, plant species or species groups inherent in individual pixels) will eventually lead to the ability to routinely assess arid land livestock and wildlife management concerns such as forage and browse productivity, suitability for class of grazer or browser, carrying capacity, forage utilization and the monitoring of vegetation and soil surface changes resulting from the level and kind of management or the lack of management applied to the range landscapes. Successional changes related to the management process can also be measured.

Monitoring rangeland vegetation and soil conditions is an essential requirement. Because of limited funds and personnel for monitoring large expanses of arid landscapes, ground-based monitoring is rarely possible on a regular basis and remote sensing is often thought of as a tool for accomplishing such monitoring. For adequate remote sensing there must be sufficient understanding of the ecology/synecology and spectral characteristics of the natural rangeland vegetation. Below I discuss many of these concepts in greater detail.

Remote Sensing Techniques

Range managers have several sources of image or remote sensing information for resource interpretation, including panchromatic, color and color-infrared (CIR) aerial photographs; satellite images and digital data products and aerial video data, all in various wavelengths, and radar data. Aerial photographs as a form of remote sensing provide the highest resolution and capture the spatial and textural essence of the scene with greater fidelity than any other procedure. Disadvantages include the cost of repeated coverage for change detection, including the costs of film and processing, and the limited spectral sensitivity of conventional photography (Tueller, 1989).

Aerial photography still provides the highest resolution and most detailed information depending upon the scale (ratio between the distance on the photo and the corresponding distance on the ground). Resolution is usually considered in two ways, first as effective ground resolution which can be defined as the size an object must be before it can just be identified on an aerial photograph or image or as the number of line pairs per millimeter that can be differentiated from a ground target. The term image is used in remote sensing to refer both to conventional aerial photographs as well as to photographic products for which the data were gathered by sensing in various wavebands of the spectrum and then combining these wavebands to produce a product similar to an aerial photograph but derived in an altogether different way.

The concepts of stereoscopy and stereo viewing based on stereoscopic parallax allow greater detailed interpretation along with the time honored principles of photo interpretation: color, tone, texture, pattern, shadow, size, shape and convergence of evidence (several different but related characteristics when combined lead to correct interpretations). During photo interpretation the human mind acts as the master manipulator and integrator of information leading to a correct interpretation. For many rangeland uses this approach is still the most useful and cost effective.

Large scale (1:600 - 1:1,500) color and color-infrared photography in 70 and 35 mm formats are useful for arid vegetation analysis, including monitoring. Considerable technology has developed around these small format cameras with either 35 mm or 70 mm format (Carneggie and Reppert, 1969; Reppert and Driscoll, 1970; Carneggie *et al*., 1971; Poulton *et al*., 1975; Heintz *et al*., 1978; Tueller, 1978; Waller *et al*., 1978; Everitt *et al*., 1980; Meyer *et al*., 1982; Everitt, 1985; Tueller, 1987b and Tueller *et al*., 1988). These cameras provide photographic scales from 1:500 to 1:2,000 or smaller and are useful for identifying many species and making detailed measurements. However, since the format is small and the scales large, limited area coverage requires creative sampling to provide adequate data and make valid projections concerning rangeland areas of interest. Species identification procedures using small formats and large scales have been developed along with methods to quantify the vegetation (Tueller, 1978). This technology still has potential usefulness because of the very high resolution of the images.

Among the spacecraft providing remote sensing data are the Landsat Multispectral Scanner (MSS) which has four spectral channels, two in the visible and two in the near infrared; the Landsat Thematic Mapper (TM) which has seven channels, three in the visible part, one in the near infrared, two in the mid infrared or water absorption region and a thermal channel, the SPOT (Systeme Pour l'Observation de la Terre) satellite which has three channels, two in the visible and one in the near infrared; and the AVHRR (Advanced Very High Resolution Radiometer) with five channels, one in the visible, one in the near infrared, one in the mid infrared and two thermal channels. Numerous other satellite systems are coming along.

MSS data has picture elements (pixels) approximately 80 m on a side and the TM pixels are 30 m on a side. SPOT data from the French Satellite has 20 m pixels. In addition, SPOT has a single panchromatic black and white band with 10m resolution. The imagery from these two systems can be co-registered, giving effective 10m resolution of color and color infrared products. Orbital characteristics of the spacecraft result in repeat coverage of the same ground area at regular intervals, thus making such data potentially very useful for monitoring.

The NOAA weather satellites (AVHRR) have an approximate scale of 1:10,000,000 and pixels that vary from 1.1 to 8 km depending upon whether the instrument is in Local Area Coverage (LAC) or Global Area Coverage (GAC) mode. AVHRR data have been used to study desertification in the Sahel (Tucker and Justice, 1983; Tucker *et al*., 1985). An advantage is the daily data, a disadvantage is low resolution. These data are useful where daily synoptic views are required for monitoring over very large land masses. More detailed analysis of pixel details will be useful for determining the speed with which desertification is occurring and just what kind of changes are taking place.

Microwave systems have potential for rangeland monitoring and include both Side Looking Airborne Radar (SLAR) and Synthetic Aperture Radar (SAR). These systems are useful because they are not constrained by either night (darkness) or cloud cover. Green (1986) used Shuttle Imaging Radar-A (SIR-A) data and found that during periods when most of the vegetation in a shrub rangeland in South Australia was non-vigorous and spectrally homogeneous, the SIR-A data, as a surrogate measure of shrub cover, allowed the reflectance due to shrubs in Landsat data to be separated from the reflectance due to the intervening ground. Radar has potential to measure and monitor soil moisture as well as other parameters on arid lands and may be used in conjunction with other forms of remote sensing as supplemental information for rangeland monitoring.

Several valuable instruments have been developed to be flown as multispectral scanners from aircraft. One such instrument is the Thermal Infrared Multispectral Scanner (TIMS), an aircraft-borne scanner providing six-channel spectral capability in the thermal infrared (8.2-11.7 μm) or that portion of the infrared that has thermal or emitted heat sensitivity. The added feature of measuring surface temperature has been used to map soils in arid regions (Miller *et al*., 1986). There appears to be some potential for discriminating soil textural features because of the ability of the system to identify emissivity minima for silicate minerals (Kahle and Goetz, 1983).

Video remote sensing systems have several attractive attributes potentially useful for monitoring, the most prominent of which is the near-real-time availability of imagery and relatively low cost. These factors can be very important whenever the application is very time-sensitive or when film and film processing are not available such as is the case in many developing countries (Everitt and Escobar, 1989). Another advantage is the capability of obtaining imagery in very narrow spectral bands (0.05 - 0.10 μm) and in the near and mid-infrared bands. The main disadvantage is low resolution relative to aerial photographs. New digital video systems are now coming on line. These may well be the remote sensing tool of choice for rangeland applications in the future. Digital airborne multispectral video systems, circumventing the use of a VCR, have considerable potential for rapid data accumulation and analysis, both by image processing systems and by Geographic Information Systems in the future.

High spectral resolution systems (hyperspectral remote sensing) now being evaluated include AIS, AVIRIS and HIRIS developed at NASA's Jet Propulsion Laboratory. AIS (Airborne Imaging Spectrometer) is an instrument that images 32 cross-track pixels simultaneously, each in 128 spectral bands in the 1.2 to 2.4 μm region (Vane *et al*., 1984). No data are acquired in the visible part of the spectrum. Preliminary arid land vegetation studies with AIS indicated that brightness was reduced by the vegetation primarily due to shadowing. At periods of peak growth, saltbush and Great Basin sagebrush communities were found to have unique spectral curves (Ustin *et al*., 1985). The AVIRIS (Airborne Visible and Infrared Imaging Spectrometer) instrument covers the spectral region from 0.41 to 2.45 μm using bands 10-nm wide. This instrument consists of four spectrometers that scan the test site from an aircraft. At any one moment the spectrometers are viewing a 20 metre square pixel. This pixel is viewed simultaneously in 224 spectral bands (Porter and Enmark, 1987).

HIRIS (High-Resolution Imaging Spectrometer), planned for the 1990's will acquire simultaneous images in 192 spectral bands in the dominant wavelengths of the solar spectrum, 0.4 to 2.5 micrometers, at a spectral sampling interval of 10 nanometres. The ground instantaneous field-of-view (GIFOV) will be 30 metres over a 30-kilometre track. In addition a pointing capability will allow image acquisition up to +60 degrees/-30 degrees down-track and plus or minus 24 degrees cross-track (NASA, 1987). This latter feature may someday be very important to range managers interested in evaluating rangeland vegetation for suitability, phenology, carrying capacity and range readiness since the cross-track pointing will also allow multiple viewing opportunities during one orbital revisit cycle, nominally 16 days.

High spectral resolution data from aircraft may potentially be used to measure lignin, nitrogen and both green and non-green (dry leaves, dry reproductive structures, bark, and wood) plant materials (Elvidge, 1990). The future may see high resolution remote sensing systems used to routinely gather spectral data concerning several species on a rangeland site and provide an instant analysis of the quality, quantity and condition of rangeland forage. The utility of certain narrow band widths and their combinations useful for monitoring changes on rangelands are yet to be determined.

Now we must also include GIS and GPS systems as part of the remote sensing technology. Range management is a land based science and requires that we routinely display spatial information. This spatial information must have many dimensions or layers and attribute data concerning the polygons, points and lines must be at the fingertips of the land manager. Thus the need for GIS. In order to always know exactly where the data applies the range manager must know where the features and their attributes are with respect to the rest of the world. Thus the need for GPS where we now have the potential to provide latitude, longitude and elevation at any point on the globe within only a few meters. Use and improvement of these techniques is growing at spectacular rates.

Spectral Characterization of Rangelands

Prior to successful application of remote sensing/GIS for rangeland application there is a requirement to reach a high level of understanding of the spectral characteristics of the components in any given scene. Without such knowledge the interpretations tend to be rather general, even superficial and based on very subjective evaluations. In some cases this is sufficient. However, when there is need for a greater understanding of what the remotely sensed data is telling us about a feature, e.g., during the monitoring process, then an understanding of the spectral characteristics becomes extremely important.

As one examines or analyzes a set of multispectral data, what do specific bands or indices, based on mathematical manipulations of specific band data, tell us about certain important characteristics of the scene? This must be viewed or considered in the context of single pixels one at a time. Would a simple Digital Number (DN) in the near infrared provide us sufficient information about the productivity of the natural vegetation in a rangeland scene? Probably not. Would the modified normalized vegetation index provide the necessary information? Also probably not, although a bit more information would be added. Would some combination of bands evaluated in some other fashion provide the data? Would a complete spectroradiometric trace of the scene from AVIRIS data (Vane, 1987) provide the answer? Can such information be quantified? Can data sets derived in this way provide serious information on range vegetation biomass, productivity, species composition, utilization, plant vigor and other factors for which we require a rapid accumulation of data over large land areas?

Spectral response from any land area (including arid lands) and any sensor depends on numerous variables that must be evaluated alone and in various combinations. These characteristics include such things as: a) vegetation cover by species, b) total vegetation cover, c) species or vegetation structure or geometry, d) leaf geometry, e) bare ground percentage, f) amount of shadow, g) cryptogam cover on the bare soil, h) lichen cover on soils and rocks, i) algal mats, j) microbial desert crusts, k) gravel and/or pavement, l) standing dead vegetation and m) topography (Tueller, 1989). These factors along with such factors as season, time of day, solar zenith angle (Singh, 1988), soil moisture, soil and foliage color, and vegetation maturity all contribute noise to vegetation indices.

To understand these variables there is a recognized need to carefully examine the spectral characteristics of various rangeland scenes and components of those scenes. For example, Asrar *et al.* (1985) found that burned and unburned tallgrass prairie grass canopies showed distinctly different, diurnal and seasonal, spectral reflectance characteristics in the visible and infrared regions of the spectrum. Musick (1984) found that green vegetation indices tended to remove the influence of shrubs in New Mexico mesquite/grass vegetation that was green in June, giving an estimate of grass cover. Tueller and Oleson (1989) described fluctuations in radiance values of pixels in arid shrubland vegetation depending upon differences in ground target, latitude, time of year and time of day. Radiometric corrections based on linear regression models are usually required because of atmospheric variations and must be developed for each region and for the date the imagery was acquired.

An important approach to this problem is the use of what I choose to call pixel modelling - any procedure whereby the spectral mixture inherent in an individual pixel can be separated into various known components (Tueller, 1989). Improved procedures for evaluating individual pixels can lead to improved applications of remote sensing for rangeland management problems. An example is the potential to monitor changes in aridland resource attributes, either in terms of changes in accumulated biomass, level of productivity, degree of use or changes in the composition of dominant species that can be indicative of range trend. We model pixels to determine if the spectral information can give a clear picture of the relative proportions of green woody vegetation, green non-woody vegetation, standing dead vegetation, litter, bare ground, gravel, rock and other parameters that are related to ecological conditions and trend.

The factor analytic model (Huete, 1986) is one promising model for separating vegetation and soil spectra. The model uses factor analysis, a multivariate statistical approach, which hopefully can be further analyzed in combination with a multiple linear regression model to provide reliable estimates of various ground components. Adams *et al.* (1986) and Smith *et al.* (1990) have used spectral mixture analysis to transform radiance data into fractions of a few dominant endmember spectra which correspond to scene components.

Litter/soil mixtures may also influence the soil spectra signature and be an indicator of erosion, an important parameter for rangeland monitoring. Soil/litter targets possess no green phytomass and ideally would not produce a signature. However Huete and Jackson (1987) found that dead grass material reduces the ability to discriminate green vegetation. The presence of litter and senesced grass material significantly altered the spectral behavior of background soils and amplified the range of GVI values not attributed to green grass. Litter influences were minimal with the RVI and NDVI.

Separating vegetation and soil spectra is a vital step in the approach to erosion detection. Vegetation spectral responses can vary with amount of soil exposed, soil color, soil water, and cultural practices. The influence of soil type is critical in many aridland sites where numerous soils are often present in complex spatial patterns and vegetation densities are low. Therefore, there is a need to isolate vegetation from soil background. Most of the variability of bare soil signatures is due to brightness (Huete *et al.*, 1984).

The soil line concept has become widely accepted. Although the soil line may shift with atmospheric conditions and Landsat calibration factors, many have assumed that there exists one unique soil line encompassing a wide range of soil types and soil surface conditions (Kauth and Thomas, 1976). Jackson *et al.* (1980) reported deviations from linearity when a wide spectral range of soils were plotted. Also some have suggested that the soil line is not a plane in the Landsat MSS or TM data space but more a broad band. The soil line location can vary substantially with soil color, making vegetation assessment difficult in scenes with a range of soil colors (Schweyen and Tueller, 1991). It has also been suggested that the soil line is more of a vegetation cover line in the red-infrared data space (Graetz *et al.*, 1988).

Improved procedures for evaluating individual pixels can lead to improved applications of remote sensing for rangeland management problems. An example is the potential to monitor changes in rangeland resource attributes either in terms of changes in accumulated biomass, level of productivity, degree of use or changes in the composition of dominant species that can be indicative of range trend. We model pixels to determine if the spectral information can give a clear picture of the relative proportions of green woody vegetation, green non-woody vegetation, standing dead vegetation, litter, bareground, gravel, rock and other parameters that are related to ecological conditions and trend. When only a few days pass between dates the variations are not significant (Gupta, 1992).

Vegetation Indices

For live vegetation there is a significant differential in reflectance and absorption of electromagnetic radiation when going from visible to near or mid infrared wavelengths (Tucker, 1979). These differences have led to the development of several multispectral band ratios and indices that involve both the red/infrared differences and coefficients derived from several bands. Only certain ones of them now appear to be useful on arid rangeland sites with sparse vegetation. These ratios and indices are indicative of the quantity and quality of green and senescent vegetation. On rangelands, especially arid and semi-arid rangelands, soil background conditions and shadows often influence the signal received by a multispectral scanner which acts to complicate the use of these indices for evaluating vegetation on rangelands (Tueller, 1987a).

An ideal vegetation index for use on arid lands would be highly sensitive to vegetation, insensitive to soil background changes and only slightly influenced by atmospheric path radiance (Jackson *et al.*, 1983). On rangelands the ideal index would have the capability of sorting out the influence of shadow and the influence of the great variety of leaf reflectances among the many species and species groups found as well as the standing dead vegetation and litter. It would also account for the variety of soils found in arid regions (Tueller, 1987a).

The multispectral or n-space indices originated from Kauth and Thomas (1976) who proposed a transformation that used linear combinations of four Landsat MSS bands to produce four indices: brightness, greenness, yellowness, and nonsuch. The soil spectra in four-dimensional Landsat MSS signal space was found to be distributed along a plane, known as the plane of soils. It is sometimes referred to as a soil baseline in two-dimensional digital space. This observation led to the soil brightness index (SBI) which established the data plane for soils. The Soil Brightness Index (SBI) is measured as the vector distance in the direction of the soil baseline. The greenness vegetation index (GVI) is defined as the measured distance perpendicular (orthogonal) to the soil baseline towards a point of all vegetation (Kauth and Thomas, 1976).

The perpendicular vegetation index (PVI) is a combination of infrared and red bands (Richardson and Wiegand, 1977). This two-dimensional n-space equivalent of the GVI has been defined as the orthogonal distance of a given spectral point from the soil baseline. The PVI responds to changes in both the quality and quantity of vegetation. The PVI, unlike ratio-based indices, minimizes the influence of the soil background for the assessment of green biomass (Elvidge and Lyon, 1985). This index is proving to be particularly useful for arid land applications.

Ratio based indices include the ratio vegetation index where, RVI = NIR/red, and the normalized difference vegetation index (NDVI) where, ND = (NIR + red)/(NIR - red). The ND increases as the vegetation becomes greener or more dense. A modified normalized difference (MND) is a ratio based index where, MND = (NIR -(1.2*red))/(NIR + red). Tucker (1979) and Jackson *et al.* (1983) gave thorough descriptions of ratio-based indices. Paltridge and Barber (1988), in a study of arid lands in Australia produced the MND by modifying the NDVI to include the slope of the best-fit line for lands with low vegetation cover. The MND maximizes the contrast in "greenness" while assigning a value of zero for no vegetation or dry vegetation. Huete's (1988) soil-adjusted vegetation index (SAVI) is a similar modification of the NVDI. A constant of 0.5 was recommended for sites with intermediate amounts of vegetation. Ratio-based indices are relatively independent of illumination intensity and eliminate the irradiance measurements required for the calculation of reflectances (Pinter *et al.*, 1983). A constant of 1.2 may be most suitable for arid lands with very sparse vegetation.

Interpretation of Rangeland Soils

Soil scientists, hydrologists, range ecologists and others have been concerned with water, soil and nutrient movement and vegetation changes on arid lands. This concern has been plagued with difficulties in predicting soil erosion, evaluating long term site stability, measuring vegetation succession over large land areas, determination of nutrient flow patterns, measuring vegetation, litter and rock cover, and with associated sampling problems.

Soil spectra vary with water and organic matter content, litter cover, particle size distribution, soil mineralogy, soil structure, surface roughness, and the presence of soil particle coatings and shadows (Huete *et al.*, 1984). Desert varnish is an example of a dark amorphous coating of clays and ferromanganese oxides found on stable surfaces in the desert. It has a dark signature which creates spectral ambiguity. The shade of darkness from the desert varnish or desert pavement and bedrock is a function of physical weathering, the relative age of the surface and soil surface particle size distribution (Shih and Schowengerdt, 1983). Rocks of varying lithologies but with a coating of desert varnish may display the same spectral signature.

Kauth and Thomas (1976) determined that data space distribution of soil reflectance variation in Landsat data was confined to a line in 2-dimensional space or plane in 3-dimensional space. Reflectance variations of developing vegetation grow perpendicular out of this plane of soils. Kauth's plane of soils in bands 5 and 7 consists of overlapping soil brightness levels including clouds and cloud shadows along the best-fit line. The slope of the best-fit line appears relatively constant. Further investigation is necessary to determine whether the plane of soil shifts significantly from one study site to another and from date to date (Richardson and Wiegand, 1977).

Sun angle effects have a profound influence on the soil background line. The greater the sun elevation, the higher a point plots on the soil background line. An increase in vegetation density is displaced furthest from the line. Water points deviate from the line but on the opposite side from the vegetation points. This may be a useful factor for water body monitoring. Ben-Dor and Banin (1994) used a near-infrared analysis to predict soil chemical constituents from soil reflectance curves. Others have used remote sensing data to model daytime average evapotranspiration fluxes from rangeland soil surfaces (Kustas *et al.*, 1994) and the measurement of surface temperatures for monitoring evapotranspiration rates and crop water use (Seguin *et al.*, 1994).

After the soil-vegetation spectral signatures have been separated, several approaches may be applied to isolate erosional components of the land. Robinove *et al.* (1981) studied desertification from albedo images. Degradation, in general, increases light reflectance from land due to exposure of subsoils. However, if the land is covered by annuals with a density greater than the previously existing vegetation, then reflectance may remain constant or decrease.

Ratioing is another possible approach to monitoring erosion. A TM 5/7 ratio will increase with clay content due to a hydroxyl absorption band near 2.2 μm. A ratio of TM 3/1 is a useful indicator of redness. The response to iron oxide is dependent on the soil particle size distribution. The degree of redness increases more slowly with iron oxide content in soils with high clays and will thus change the PVI.

Band ratios are used for ground interpretation because they partially normalize data for factors such as variations in sun angle, haze, topography, and system-generated noise. They also minimize albedo differences between soil and rock surfaces but enhance subtle differences in reflectance between bands that are diagnostic of variations in surface material. Infrared to visible ratios distinguish between vegetation and dry vegetation and soil. The 4/5 ratio separates rock from the most severe erosion.

Combinations of band ratios provide increased differentiation; a 4/6 or 4/7 ratio plotted against the 5/6 or 5/7 ratio separates depositional stable and erosional surfaces. Plotting 4/6 and 5/6 values will indicate extreme erosion. Extreme erosion plots closest to the upper limit and as erosion severity increases, the distribution of points shifts slightly to the right. A mixed soil-vegetation signal has a consequent shift away from the upper line (Pickup and Nelson, 1984).

Monitoring the status of the soil is a very important part of rangeland quality evaluation. The number and distribution of cattle and sheep is a major consideration for allotments with slopes susceptible to degradation. Soil degradation can evolve through several often interacting processes: water erosion, wind erosion, salinization, chemical and biological degradation. Gad and Daels (1986) assessed soil degradation in an arid region in Egypt and found that aerial photographs were useful in determining slope, soil texture, vegetation cover, topographic and human impact. The calculations were then used to evaluate existing and potential degradation caused from the above-stated erosion processes.

Economic Considerations

Many remote sensing costs are reasonable unless there is a need for repeat data which might be required for arid land monitoring. For example, a recent air photo job that I contracted was approximately $4,000 to provide 70 exposed and processed positive infrared transparencies at a scale of 1:12,000. Costs included aircraft mobilization costs, cameraman, pilot, aircraft (including climb and descent times), color film and film processing. These 200 frames could cover a large or small area depending upon the length of the lens and flight altitude.

The cost for digital data is another matter. A single scene for a single date (7 Landsat TM bands) is, as of this writing, $ 4600 which can become costly if multiple dates of imagery are required for a range management application. Even a 512 by 512 pixel portion of a scene downloaded to a floppy disk for use on a PC is remarkably expensive at $600 for the 7 bands if available. One must be careful in sampling and know precisely the areas one needs to study or evaluate before purchasing either digital, photographic image or satellite computer compatible tapes, disks or CDs.

This leaves video as possibly the least costly remotely sensed data for rangeland management. The principal cost for a video system, once the initial capital expenditure for equipment, including camera, recorder, etc., has been met, is for the plane and pilot. A multispectral video camera system can be obtained for twenty to thirty thousand dollars (J.H. Everitt, personal communication). New digital airborne multispectral video systems are now available off-the-shelf for between $ 60 and $ 150 thousand.

Training and Education

The value of remote sensing to the solution of range management problems will have to await the further training of individuals in both remote sensing and range management. It is important to provide continuity of personnel capable in remote sensing for monitoring. Emphasis must be given to range management, vegetation science, plant ecology, soils and vegetation-landform-soil relationships. If understanding of these basic elements is lacking, the monitoring job simply doesn't get done.

An impediment to rapid application of remote sensing science to resource management in arid lands is the lack of individual workers educated in both remote sensing and arid land ecology. For example, very few range management professionals receive training in remote sensing (Tueller, 1983). Those that have such training often do something else rather than remote sensing when employed.

One solution would be to provide in-service education to arid land conservationists or scientists already working in the field. Another approach would be to provide range students with a working knowledge of photo interpretation, remote sensing and GIS while they are still in school although this might entail a program going beyond the traditional 4 years. Those who require the information should use the remote sensing procedures themselves to obtain the data which they will then interpret based on sound ecological and range management experience and familiarity with the field problems and locations involved.

Vegetation Mapping

While remote sensing cannot provide all of the data and management input to these various rangeland activities, in many instances a considerable part of the required information can be provided. The first and perhaps the most important place to begin is by the process of using remote sensing to assist in the classification and mapping of natural rangeland vegetation.

Vegetation mapping using digital image processing has been attempted on rangelands with variable success (Maxwell, 1976; Everitt *et al.*, 1981; Tueller, 1983; Pando *et al.*, 1992). Several researchers have studied the feasibility of using image processing approaches to map rangeland ecosystems, habitat types, plant communities, range sites, ecological sites or whatever classification unit is presently in vogue. There are three basic methods used in creating spectral class statistics for vegetation mapping: supervised, unsupervised and an approach referred to as guided clustering. In a supervised approach, training windows consisting of a group of pixels that are known to represent a range plant community or ecological site, based on field observations, are selected and related to ground data. Statistics describing these windows are generated by the computer (mean and standard deviation) and then extrapolated over the entire area being mapped and a classification and map are derived. This procedure has proved most useful in agricultural areas and for other landscapes where the mapping units are already known and are relatively homogeneous. However, for heterogeneous rangelands there are usually a significant number of pixels that are not classified because it is difficult to locate and identify homogeneous grazing sites for all important rangeland plant communities or ecological sites.

In an unsupervised approach, a clustering algorithm is used to group all pixels into clusters with similar spectral response. Spectral response limits to define classes which can be controlled by setting maximum standard deviations, minimum distance between cluster centres, and specifying a minimum number of pixels allowed in a cluster. This latter idea is similar to specifying a minimal mapping unit. This approach allows most pixels to be included in a class. Then it is up to the range manager to determine exactly what information classes (e.g., plant communities or ecological sites) are represented by one or more spectral classes (Tueller, 1983). Pando *et al.* (1992) constructed a quantitative key to identify community types by their Landsat reflectivities.

Guided clustering is a combination of these two approaches. Training sets can be utilized to define certain homogeneous classes such as meadowlands, seedings and then an unsupervised analysis of the remaining pixels will, in effect, map the area into several interpretable spectral classes. Classification accuracy in most previous attempts has been quite variable. McGraw and Tueller (1983) working in the sagebrush/grass vegetation were able to show approximately 80 percent mapping accuracy. This is similar to other reported attempts to map rangeland vegetation. The problem, however, is that the mapping was accomplished for one scene and one date for one season. Multidate data sets only improve classification accuracy slightly. Even the addition of topographic information does not significantly improve classification accuracy. With the added power of GPS and GIS the value of these procedures will be improved in the future.

The real problem with using remote sensing classification tools to map is that the results are difficult to extrapolate to other cases. Often the signatures used to depict a specific plant community do not hold up when attempts are made to use a similar classification during a different season, year or even moving to a different mountain range or changing latitude. The signatures simply do not give the same information under these different conditions. What can be done to improve extrapolation of results and to allow more refined information requirements to be fulfilled? By more refined data requirements I am referring to a gradient of difficulty of analysis by remote sensing for range management applications. Moving from least to most difficult in such a gradient would be approximately as follows: mapping relatively homogeneous ecological sites, mapping relatively heterogeneous ecological sites, measuring vegetation change or range trend, measuring vegetation utilization or range readiness, measuring species vigor or physiological state. The vegetation map is often one of the first tools used by the range manager as he begins the process of management. Updating of maps and the resources they represent is important. Computer aided mapping of rangeland resource feature such as ecological sites, coupled with use of powerful geographic information systems will be the wave of the future. Geographic information systems will be discussed later in this paper.

Rangeland Monitoring

The management of rangelands must be based on sound vegetation science principles. Without an understanding of the plant species and communities that characterize the world's rangelands we would not be able to manage these vegetation resources. Analysis of the vegetation as a collective resource, consisting of numerous species forming a specific composition, plays a pivotal role in determining the successes and failures of rangeland management. Considerable effort and thoughtful interpretation must go into monitoring this fundamental part of the biomass.

Vegetation succession is a predictable process. Monitoring of the vegetation presupposes that managers can describe and predict series based upon species reactions to specific natural or man-caused disturbances. Many methods have been developed. A large number of them are both conceptually and statistically very sound while others lack soundness. Some are subjective and some are objective. The cost for objectivity is high while the cost for subjectivity is lower. Therefore, vegetation monitoring must be a practical trade off between cost and subjectivity.

Management

Measurements of vegetation must be based on key areas and key species just because of the objectivity Vs. subjectivity and cost question. Repeatability is likewise an important question. Any monitoring method must be repeatable within a reasonable probability of error or variance, since monitoring, of necessity, occurs over time and people with different skills and experience come and go. Rangelands are either monitored over the short-term or long-term. Short term monitoring involves actual use records, interpretation of weather data, utilization, evaluation and use mapping. The purpose of short-term monitoring is to evaluate and alter management on an annual or seasonal basis to improve distribution and obtain proper use over the managed rangeland.

Long-term monitoring is accomplished to measure changes over several years or even decades. Succession (species composition/soil surface) changes are measured. One useful and highly repeatable procedure is sampling for species frequency using appropriate frame sizes. Both the short-term and long-term procedures, including the frequency sampling procedure, may be useful under conditions found in many parts of the world. The challenge is to find an objective, repeatable method of following long-term vegetation change. Procedures should emphasize repeatability and objectivity. Minimum standards can be developed and then supplemented to solve unique site specific monitoring sampling problems.

Many of the ground-based vegetation sampling techniques can provide useful monitoring data. They must be sensitive to changes in parameters of interest to range managers. With respect to remote sensing the ground sampling can and should be used to calibrate the failure or success of various remote sensing techniques to detect these changes. The interpretation of the data, once again, requires trained range ecologists. The second important challenge then is to interpret the data and make decision as to what management changes should be brought to the landscape. The permanent record provided by the remote sensing products becomes an important element in range condition and monitoring studies (Tueller, 1978).

Vegetation productivity and biomass levels are of great interest to range managers. Using Landsat MSS data McDaniel and Haas (1982) found that the GVI was highly correlated with wet green yield, dry green yield and cured vegetation cover on mesquite-grass vegetation. They concluded that quantitative measurements of rangeland vegetation condition can be made from Landsat MSS data. Monitoring vegetation and soil conditions is an essential element of good range management. Because of limited funds and personnel for monitoring large expanses, ground-based monitoring is rarely possible on a regular basis. Multitemporal aerial photographs or processed images can provide an efficient means of recording both long and short-term changes. Monitoring provides a permanent record of the region and may be short-termed (daily or seasonal) or long-termed (such as years) (Carneggie *et al.*, 1983).

The permanent record provided by the photographs becomes an important element in range condition studies (Tueller, 1978). Rangeland condition refers to a set of characteristics defined by ecological site which includes soil type, topography, hydrology and a specific plant species composition. Although remote sensing evaluations of rangeland condition may not be totally successful, photographs or digital products provide a media for mapping the extent and severity of stressed areas. It is possible to determine the extent of many "invader" species, the nature of the dominant vegetation and the amount of bare ground on a site. The extent of severely impacted areas of vegetation, such as in "sacrifice areas" around stock watering facilities or perhaps the level of forage use, soil influence on nomadic grazing sites, can be monitored even with satellite images.

Evaluation of non-forage species can indicate the condition of the range vegetation. For example, open tree stands in savannas may contain large amount of useable forage; denser stands usually contain very little useable understory. On many arid shrub-dominated rangelands the understory is often closely regulated by the overstory. The interpreter can often make accurate assessment of the potential understory without actually viewing the understory on the aerial photograph.

Measurements of changes in biomass accumulation over time (productivity) may be the most desirable procedure to follow. However, this measurement is not often used because of both high cost and high variability expressed from year to year, leading to difficulties in interpretation. Therefore, range scientists and managers often look to other procedures involving cover (either foliar projection, basal cover, canopy cover, areal list procedures or even volumetric or allometric measurements), density (individuals by species per unit area), height and vigor or frequency of occurrence. These kinds of vegetation data then are interpreted by skilled range conservationists and range scientists with the interpretations tempered by ancillary data on animal use, climate, soil, erosion and microtopography, microbiota, actual use data and other factors.

There is no one best answer to the sampling question. The rule should be that it is necessary to obtain some measure of vegetation amount and vigor by species on key or representative areas. The question of vigor is related to seed production, reproduction and growth rates of site species. In addition, the key area concept is not without its pitfalls. Range ecologists often argue long and hard on this subject and then only agree to disagree relative to what a key area really represents. This issue must be resolved before scientifically accurate and useful monitoring can be done.

If a procedure or method is finally agreed upon then repeated measures of the vegetation over time can be documented often with high statistical accuracy and precision. It becomes a matter of interpretation as to what amount of change is important and justifies a management alteration. Questions arise as to what alterations are justified and what will be the influence of an alteration in management on the vegetation, if any, over time.

Vascular plants are usually considered to be the principal component of the range landscape for monitoring purposes. An assessment of gully, rill and interrill erosion is often a close number two in the quest for attributes to monitor in order to determine the health of the rangeland. The microbiota has been generally overlooked in previous rangeland monitoring programs. However, microorganisms are certainly important in the development and sustainability of rangeland ecosystems and therefore should be monitored.

On rangelands the consideration of microbiota is related to the structure and function of microphytic soil crusts. The kinds of organisms that can be involved in microphytic crusts are very diverse and are of two broad groups: 1) those visible with the unaided human eye (mosses, lichens and liverworts), which could be termed "thallophytic" crusts and 2) those parts of crusts whose individuals are visible only microscopically (algae, fungi and bacteria), which would be termed "microscopic" crusts (N.E. West, Personal communication, 1992).

Potential monitoring of these organisms, both as crusts and as they occur in the rhizosphere, is complicated by the fact that the taxonomy of many of these groups is only poorly known; not many researchers have worked on the microbiota, and they are quite difficult to work with. Microbiota in the rangeland ecosystem are related to erosion, interception and infiltration, nutrient cycling and other factors important to continued ecosystem functioning. Both microscopic and thallophytic crusts may have been reduced by intense grazing use on rangelands.

Rangeland Applications

Management suggests that we are working to achieve some sort of a dynamic equilibrium where a balance is reached between disturbance and recovery. This concept is attractive because it provides some sense of stability even in the presence of constant change. Of critical concern for proper interpretation is whether or not there are long-term trends over one or several decades that may be unrelated to many of the attributes that are often measured when monitoring. In other words, is the noise of short-term change capable of masking long-term trends in vegetation equilibrium, particularly as measured by remote sensing techniques? And if this is so, how can these changes be excluded from the changes attributable to management?

Answers to these questions of interpretation will only come over time in an empirical framework. Only experience with specific kinds of vegetation will lead to appropriate answers to management questions based on rangeland vegetation monitoring and analysis. Vegetation monitoring interpretation problems are confounded by questions of climax, equilibrium situations, potential natural vegetation and other real and conceptual considerations. The answer actually lies in the interpretation of vegetation changes based on site potential for producing biomass, either for forage or general ground cover and the creation of a situation which will be interpretable by land users and conservationists alike. Satisfaction of both management goals and conservation/biodiversity issues must be forthcoming, particularly in developed countries.

Now, what about some practical aspects of using remote sensing in range management? Based on field experience we can use aerial photographs to identify features, judge their significance, measure their number or extent (inventory) and determine over time using subsequent photographs whether or not significant changes have taken place (monitoring). Unfortunately, there have been very few examples where aerial photography has been used routinely to assist in ongoing rangeland management operations.

However, very large scale aerial photographs (1:600 - 1:2500) can be used to estimate livestock carrying capacity by identifying characteristics such as vegetation density, grazing or browsing quality of the species, and forage production. Soil surface features such as cattle droppings and rodent disturbance from some species of small mammals can be identified on large scale photographs and related to range utilization, condition, and carrying capacity (Tueller, 1978). For example, counting harvester ant mounds formed partly by removal of surrounding vegetation would provide an estimation of either increased or decreased forage productivity that may result from the activities of these animals. Both scenarios are possible. For many years vertical aerial photography has been available for rangeland interpretation purposes.

After rangeland resources have been mapped and resources inventoried, we must then either analyze and interpret the remote sensing product from which the inventory data was derived or provide new data from one or more remote sensing devices in order to acquire additional information that will be important to management. For example, the manager might select the Perpendicular Vegetation Index (PVI), some other vegetation index or even laser profiling to measure shrub cover for key areas within each allotment. Riparian zone sites may be adaptable to the Normalized Difference Vegetation Index (NDVI), the Modified Normalized Difference Vegetation Index (MODNDVI), the Kauth and Thomas Greenness Index or some other index that has greater sensitivity to bright green highly reflective vegetation such as found in a willow-bank, a stand of aspen or a mountain meadow.

In some cases, real-time information might be desirable (floods and fires for example) wherein the data acquisition and interpretation must go on almost simultaneously. In this situation airborne multispectral video would be the technology of choice. The real-time capability and increasing resolution of new digital video systems may make airborne video systems the remote sensing technology choice for the future (Everitt and Escobar, 1989).

Reference must be continually made to the timeliness of data acquisition (multitemporal), to the use of various band widths (multispectral) and to the use of different scales each with their inherent resolution. Multitemporal, multispectral and multiscale data sets are important in any rangeland management scenario. Spectral information from one band may be most important to describe one parameter, whereas, data from another band may supply the optimum information about another parameter. Or the best course of action will be to examine several different bands and combine the data in various mechanistic or mathematical ways to provide data useful for answering a posed question. And finally, the scale must correspond with the potential or lack of potential to extract the desired information required for the making of specified management decisions.

Many of the parameters of interest can now be obtained from digital data derived from satellite data or from airborne video systems. For example, we have been able to use a linear regression model based on Landsat TM data to extract various range ecosystem cover components. Scheweyen and Tueller (1991) found a high correlation between the PVI and plant cover (R squared = 0.91) for 15 shrub dominated range sites. In another study, bare ground was estimated using the PVI, SAVI, TSAVI indices (R squared = 0.88). Total woody ground cover required both satellite data in the form of the NDVI as well as the shrub ground reflectance in band TM2 and TM4 (R squared = 0.90).

Both new and improved systems will come along that will provide the required management data (e.g., carrying capacity, utilization levels, vegetation trend) in even more timely and useful ways. Along with this will come improved capabilities to remotely measure the parameters of interest to arid land management. Perhaps these will be related to some of the new high spectral resolution systems such as AIS, AVIRIS and HIRIS or to improved space flown scanners, or to new radar systems and other combinations of sensors and data. Also, as one further considers the emerging of ever new technologies range managers may be able to assess and understand rangeland ecosystems within the framework of Computer Aided Design (CAD) technology and the examination of land resources in three dimensions. Together these several methodologies will provide the means of determining what is happening on our rangelands that will in future assist in the process of successful rangeland resources.

Management requirements for rangelands include inventory and classification of rangeland vegetation, the determination of carrying capacity and site productivity, the determination of the condition and trend of rangeland vegetation, evaluations of utilization and range readiness, counts of the kind, class, and breed of livestock or other species of large animals, the protection of soils, the maintenance of wildlife population and habitats, assessment of recreational uses on rangelands, determining improvement potential for rangelands and associated wildlife habitats on rangelands and the development, implementation and evaluation of grazing management systems (Tueller, 1983).

A late 90's view of rangeland remote sensing will almost certainly see a much closer tie between remote sensing and GIS. Data manipulation will be accomplished almost exclusively within a GIS format with queries designed to answer remote sensing management questions. At the same time, GPS will allow range managers to locate field sites and critical areas with unprecedented accuracy. A Remote Sensing/GIS/GPS framework, possibly aided by some form of expert system based on artificial intelligence, will certainly assist range managers as they try to analyze and interpret the extensive and, in some cases, intensive data sets in the future. The beauty of it will be that the considerable data formerly held in scattered field offices or by other agencies and organizations can become almost instantly available and brought to bear on specific management questions. This of course will be a result of the continuing buildup of computer infrastructure by those doing range management.

References

Adams, J.B., Smith, M.O. and Johnson, P.E. 1986. Spectral mixture modelling: a new analysis of rock and soil types at the Viking lander site. *Journal of Geophysical Research* **91**: 8098-8112.

Asrar, G., Myneni, R.B., Li, Y. and Kanemasu, E.T. 1985. Measuring and modelling spectral characteristics of a tall grass prairie. *Remote Sensing of Environment* **21**: 143-155.

Ben-Dor, E. and Banin, A. 1994. Visible and near-infrared (0.4-1.1 μm) analysis of arid and semiarid soils. *Remote Sensing of Environment* **48**: 261-274.

Carneggie, D.M. and Reppert, J.N. 1969. Large scale 70mm aerial color photography. *Photogrammetric Engineering* **35**: 249-257.

Carneggie, D.M., Schrumpf, B.J. and Mouat, D.M. 1983. Rangeland application. In *Manual of Remote Sensing* (Ed. R.N. Colwell), Vol. 2, pp. 2325-2384. American Society of Photogrammetry. Falls Church, Va.

Carneggie, D.M., Wilcox, D.G. and Hacker, R.B. 1971. *The Use of Large Scale Aerial Photographs in the Evaluation of Western Australia Rangelands.* Technical Bulletin No. 10, 37 p. Department of Agriculture of Western Australia, Perth, West Australia.

Elvidge, C.D. 1990. Visible and near infrared reflectance characteristics of dry plant materials. *International Journal of Remote Sensing* (In Press).

Elvidge, C.D. and Lyon, R.J.P. 1985. Influence of rock-soil spectral variation on the assessment of green biomass. *Remote Sensing of Environment* **17**: 265-279.

Everitt, J.H. 1985. Using aerial photography for detecting blackbrush (*Acacia rigidula*) on south Texas rangelands. *Journal of Range Management* **38**(3): 228-231.

Everitt, J. H. and Escobar, D.E. 1989. The status of video systems for remote sensing applications. In *Proceedings of the 12th Biennial Workshop on Color Aerial Photography and Videography in the Plant Sciences and Related Fields*, pp. 6-28. American Society of Photogrammetry and Remote Sensing, Sparks, Nevada.

Everitt, J.H., Gerberman, A.H., Alaniz, M.A. and Bowen, R.L. 1980. Using 70-mm aerial photography to identify rangeland sites. *Photogrammetric Engineering and Remote Sensing* **47**(9): 1357-1362.

Everitt, J.H., Richardson, A.J. and Wiegand, C.L. 1981. Inventory of semi-arid rangelands in South Texas with Landsat data. *Proceedings of 1981 Machine Processing of Remotely Sensed Data Symposium*, Purdue Univ. pp. 404-415.

Gad, A. and Daels, L. 1986. Assessment of soil degradation in an arid region using remote sensing. *Proceedings of IGARSS' 86* Symposium, pp. 1241-1246. Zurich.

Graetz, R.D., Pech, R.P. and Davis, A.W. 1988. The assessment and monitoring of sparsely vegetated rangelands using calibrated Landsat data. *International Journal of Remote Sensing* **9**(7): 1201-1222.

Green, G. M. 1986. Use of SIR-A and Landsat MSS data in mapping shrub and intershrub vegetation at Koonamore, South Australia. *Photogrammetric Engineering and Remote Sensing* **52**(5): 659-670.

Gupta, R. K. 1992. District level NOAA/AVHRR vegetation indices and scan angle effects. *International Journal of Remote Sensing* **13**(4): 715-735.

Heintz, T.W., Lewis, J.K. and Waller, S.S. 1978. Low-level aerial photography as a management and research tool for range inventory. *Journal of Range Management* **32**(4): 247-249.

Huete, A.R. 1986. Separation of soil-plant spectral mixtures by factor analysis. *Remote Sensing of Environment* **19**: 237-251.

Huete, A.R. 1988. A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment* **25**: 295-309.

Huete, A.R. and Jackson, R.D. 1987. Suitability of spectral indices for evaluating vegetation characteristics on arid rangelands. *Remote Sensing of Environment* **23**: 213-232.

Huete, A.R., Post, D.F. and Jackson, R.D. 1984. Soil spectral effects on 4-space vegetation discrimination. *Remote Sensing of Environment* **15**: 155-165.

Jackson, R.D. 1983. Spectral indices in n-space. *Remote Sensing of Environment* **13**: 409-421.

Jackson, R.D. *et al.* 1980. *Hand-held Radiometry*, ARM-W-19, U.S. Dept. of Ag., Science and Education Administration, Oakland, California, 66p.

Jackson, R.D., Slater, P.N. and Pinter Jr., P. 1983. Discrimination of growth and water stress in wheat by various vegetation indices through clear and turbid atmospheres. *Remote Sensing of Environment* **13**: 187-208.

Kahle, A.B. and Goetz, A.F.H. 1983. Mineralogic information from a new airborne thermal infrared multispectral scanner. *Science* **222**: 24-27.

Kauth, R.J. and Thomas, G.S. 1976. The tasselled cap-a graphic description of the spectral temporal development of agricultural crops as seen by LANDSAT. *Proceedings of the Symposium Machine Processing of Remote Sensing Data*, LARS, Purdue.

Kustas, W.P., Perry, E.M., Doraiswamy, P.C. and Moran, M.S. 1994. Using staellite remote sensing to extrapolate evapotranspiration estimates in time and space over a semiarid rangeland basin. *Remote Sensing of Environment* **49**: 275-286.

Maxwell, E.L. 1976. A remote rangeland analysis system. *Journal of Range Management* **29**(1): 66-72.

McDaniel, K.C. and Haas, R.H. 1982. Assessing mesquite-grass vegetation from Landsat. *Photogrammetric Engineering and Remote Sensing* **48**(3): 441-450.

McGraw, J.F. and Tueller, P.T. 1983. Landsat computer-aided analysis techniques for range vegetation mapping. *Journal of Range Management* **36**: 627-631.

Meyer, M., Batson, F. and Whitmer, D. 1982. *Helicopter-borne 35mm Aerial Photography Applications to Range and Riparian Studies*. Remote Sensing Laboratory. University of Minnesota, St. Paul, Minn. IAFHERSL Research Report 82-1. 80 p.

Miller, D.A., Peterson, G.W. and Kahle, A.B. 1986. Soil and geomorphic studies in arid region using the Thermal Infrared Multispectral Scanner (TIMS). *Paper presented at the 3rd Arid Lands Remote Sensing Workshop at the University of Arizona*. Tucson, April, 8 p.

Musick, H.B. 1984. Assessment of Landsat multispectral scanner spectral indexes for monitoring arid rangeland. *IEEE Transactions on Geoscience and Remote Sensing GE* **22**(6): 512-519.

NASA 1987. *HIRIS High-Resolution Imaging Spectrometer:Science Opportunities for the 1990's. Earth Observing System*. Volume IIc. Instrument Panel Report. 74 p.

Paltridge, G.W. and Barber, J. 1988. Monitoring grassland dryness and fire potential in Australia with NOAA/AVHRR data. *Remote Sensing of Environment* **25**: 381-394.

Pando, M., Lange, R.T. and Sparrows, A.D. 1992. Relations between reflectance in Landsat MSS wavebands and floristic composition of Australian chenopod rangelands. *International Journal of Remote Sensing* **13**(10): 1861-1867.

Pickup, G. and Nelson, D.J. 1984. Use of Landsat radiance parameters to distinguish soil erosion, stability, and deposition in arid central Australia. *Remote Sensing of Environment* **16**: 195-209.

Pinter, P.J. Jr., Jackson, R.D., Idso, S.B. and Reginato, R.J. 1983. Diurnal patterns of wheat spectral reflectances. *IEEE Transaction on Geoscience and Remote Sensing GE* **21**: 156-163.

Porter, W.A. and Enmark, H.T. 1987. A system overview of the airborne visible/infrared imaging spectrometer (AVIRIS). *Airborne Visible/Infrared imaging spectrometer (AVIRIS), A Description of the Sensor, Ground Data Processing Facility, Laboratory Calibration, and First Results* (Ed. G. Vane), pp. 3-12. NASA Jet Propulsion Laboratory. JPL Publication 87-38.

Poulton, C.E., Carneggie, D.M., Day, J.H., Driscoll, R.S., Parker, H.D., Philpotts, L.E., Psuty, N.B., Roberts, E.H., Schrumpf. B.J. and Tueller, P.T., 1975. Range resources: inventory, evaluation and monitoring. In *Manual of Remote Sensing* (Ed. R.G. Reeves), Vol II. pp. 1427-1478. American Society of Photogrammetry, Falls Church, Virginia.

Reppert, J. N. and Driscoll, R. S. 1970. 70-mm aerial photgraphy - A remote sensing tool for wildland research and management. In *Range and Wildlife Habitat Evaluation, a Research Symposium*. pp. 190-193. USDA Forest Service Misc. Publ. No. 1147, 220 p.

Richardson, A.J. and Wiegand, C.L. 1977. Distinguishing vegetation from soil background information. *Photogrammetric Engineering and Remote Sensing* **43**: 1541-1552.

Robinove, C.J., Chavez, P.S., Gehring, D. and Holmgren, R. 1981. Arid land monitoring using Landsat albedo difference images. *Remote Sensing of Environment* **11**: 133-156.

Schweyen, N. and Tueller, P.T. 1991. Estimating desert shrub vegetation cover using Landsat Thematic Mapper derived vegetation indices. *Remote Sensing of Environment*, submitted.

Seguin, B, Courault, .D. and Guerif, M. 1994. Surface temperature and evapotranspiration: applications of local scale methods to regional scales using satellite data. *Remote Sensing of Environment* **49**: 287-295.

Shih, E.H.H. and Schowengerdt, R.A. 1983. Classification of arid geomorphic surfaces using Landsat spectral and textural features. *Photogrammetric Engineering and Remote Sensing* **49**: 337-347.

Singh, S. M. 1988. Lowest order correction for solar zenith angle to Global Vegetation Index (GVI) data. *International Journal of Remote Sensing* **9**(10 & 11): 1565-1572.

Smith, M.O., Ustin, S.L., Adams, J.B. and Gillespie, A.R. 1990. Vegetation in deserts: 1. A regional measure of abundance from multispectral images. *Remote Sensing of Environment* **31**: 1-26.

Tucker, C.J. 1979. *Radiometric resolution for monitoring vegetation, how many bits are needed?* NASA Technical Memorandum 80293. 25 p.

Tucker, C.J. and Justice, C.O. 1983. Satellite remote sensing of desert spatial extent. *Desertification Control Bulletin* **9**: 2-5.

Tucker, C.J., Praet, C.L., van Sharman, M.J. and Ittersum, G. van 1985. Satellite remote sensing of total herbaceous biomass production in the Senegalese Sahel: 1980-1984. *Remote Sensing of Envrironment* **17**: 233-249.

Tueller, P.T. 1978. Large scale 70 mm photography for range resources analysis in the western United States. *Proceedings 11th International Symposium on Remote Sensing of Environment*. Ann Arbor. pp. 1057-1514.

Tueller, P.T. 1983. Rangeland remote sensing: an approach. *Proceedings RNRF Symposium on the Application of Remote Sensing to Resource Management*. American Society of Photogrammetry. pp. 42-45. Seattle, WA.

Tueller, P.T. 1987a. Remote sensing science application arid environments. *Remote Sensing of Environment* 143-154.

Tueller, P.T. 1987b. Large-scale color aerial photograp for monitoring shrub dominated rangelands. *Proceedings 11th Biennial Workshop on Color Aerial Photography* *and Videography in the Plant Sciences and Related Fields.* pp. 84-95. Weslaco, TX.

Tueller, P.T. 1989. Remote sensing technology for rangeland management. *Journal of Range Management* **42**(6): 442-453.

Tueller, P.T., Lent, P.C., Stager, R.D., Jacobsen, E.A and Platou, K.A. 1988. Rangeland vegetation changes measured from helicopter-borne 35 mm aerial photography. *Photogrammetric Engineering and Remote Sensing* **54**(5): 609-614.

Tueller, P.T. and Oleson, S.G. 1989. Diurnal radiance and shadow fluctuations in a cold desert shrub plant community. *Remote Sensing of Environment* **27**: 1-13.

Ustin, S.L., Rock, B.N. and Woodward, R. A. 1985. Analysis of substrate and plant spectral features of semi-arid shrub communities in the Owens Valley, California. *Proceedings of the Fourth Thematic Conference: Remote Sensing for Exploration Geology.* pp. 347-360. San Francisco, CA April.

Vane, G. 1987. First results from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). In *Airborne Visible/Infrared Imaging Spectrometer (AVIRIS). A Description of the Sensor, Ground Data Processing Facility, Laboratory Calibration, and First Results.* (Ed. Gregg Vane). pp. 89-97. JPL Publication 87-38.

Vane, G., Goetz, A.F.H. and Wellman, J.B. 1984. Airborne imaging spectrometer: a new tool for remote sensing. *IEEE Transactions on Geoscience and Remote Sensing.* Vol. GE-**22**(6): 546-549.

Waller, S.S., Lewis, J.K., Brown, M.A., Heintz, T.W., Butterfield, R.I. and Gartner, F.R. 1978. Use of 35mm photography in vegetation sampling. *Proceedings 1st International Rangeland Con*gress. Denver, CO. pp. 517-520.