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Rangeland Monitoring Using Remote Sensing

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Monitoring vast landscapes has, from the beginning of rangeland management, depended on people's judgements. This is no longer tenable, but a more effective method has yet to be devised. The problem is how to do an economical inventory that will detect ecologically important change over extensive land areas with acceptable error rates. The error risk is a function of adequate sample numbers and distribution for each indicator monitored. Of all of the indicators identified for monitoring, ground cover and its inverse, bare ground, may be the most discussed. Ground-cover measurements address soil stability and watershed function which are first-priority ecological concerns; are well adapted to remote sensing frameworks thus allowing extensive, unbiased, economical sampling; and, the measurements, especially when done by computer image analysis, have the potential to reduce or avoid the human-judgement factor. Data collection through remote sensing appears the most logical approach to acquiring appropriately distributed information over large areas in short time periods and on random sites far removed from easy ground access. The value of satellite and high-altitude sensors for landscape-level evaluations, such as plant community distribution, is well established but these tools are inadequate for inventory and measurement of details needed for valid conclusions about range condition. New advances in low-altitude remote sensing may give us the ability to accurately measure bare ground and perhaps other indicators. Combining information from high and low-altitude sensors appears to offer an optimal path for developing a practical system for cost-effective, data-based, rangeland monitoring and management.

Keywords bare ground, cover, ecological indicator, image analysis, platforms, upscaling

Monitoring is fundamental to legitimate management. Since the beginning of range management as a discipline, evaluation and monitoring of expansive landscapes have relied on judgement and experience (the art) more than science. This is no longer acceptable. People on both sides of management issues are calling for objective monitoring (NRC, 1994; Donahue, 1999). The challenge is to develop economical methods that will detect important vegetation change within acceptable error rates

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(Brady et al., 1995). Here we review fundamental monitoring issues and the remote sensing tools and technology available for accomplishing monitoring objectives.

Detecting Change

Has ecologically important change occurred or not? Brady et al. (1995) state that, "Monitoring designs should be stable, powerful, robust, and cost-effective if they are to detect... vegetation changes with acceptable error." "Stable" and "powerful" refer to the risk of error, of concluding there is a change when there is not or there is no change when there is. The error risk is a function of adequate sample size and an adequate distribution of samples. It requires that sampling not be limited or influenced by site accessibility, personal bias, or other situations compromising the basic assumptions of statistical science.

"Robust" monitoring means acquired data are not influenced by other factors. Plant frequency, for example, is not a robust measurement because frequency is influenced by the arrangement of vegetation clumps and by plant size (Whysong & Miller, 1987). Walker (1970) evaluated eight methods of vegetation sampling (including three nonimaging methods for measuring plant cover) and concluded that "Every method is entirely dependent on the integrity and attitude of the operator"; also that, "Human stress is a significant factor in most botanical analyses techniques and may easily invalidate the results obtained." Similar findings and related concerns have been stated by a number of authors (Friedel & Shaw, 1987; NRC, 1994; Donahue, 1999). The human factor is a concern because traditional methods use personal judgement. Attitude, bias, experience, integrity, and stress affect judgement. The human factor affects the "robustness" of many—if not most—nonimaging vegetation sampling methods.

Appropriate Indicators

Some have promoted a suite of indicators for assessing rangeland health (Pellant et al., 2000). Karr (1992) noted "the multivariate nature" of ecosystems and commented that such "systems require evaluations based on a number of relevant biological attributes." But he further noted a diversity of approaches to assessing ecological integrity "may be more an impediment than a solution to the problem of defining and measuring ecological health." He argued for consideration of all possible approaches to assessment but clearly stated, "Selection of attributes must balance the need for information with the cost and time involved in collecting that information." Recently the Sustainable Rangeland Roundtable identified over 60 important indicators of rangeland sustainability (Rowe et al., 2002). Optimum management will consider all indicators, but not all indicators need be used in an extensive assessment.

Of all of the indicators identified for monitoring, ground cover and its inverse, bare ground, may be the most discussed. The foremost justification is its direct relationship to soil conservation—the first-priority ecological concern (NRC, 1994; Society for Range Management, Task Group on Unity in Concepts and Terminology, 1995). Cover has also been promoted as the best single measure of a plant species' importance in a community (Taylor, 1986; citing Lindsey, 1956 and Daubenmire, 1959).

Ground Cover Correlated with Soil Stability, Watershed Function, and Grazing Management

Bare ground has been consistently correlated with runoff in studies of aspen, salt desert shrub, and southwest deserts (Branson et al., 1972: citing Marston, 1952, Branson & Owen, 1970; Kincaid & Williams, 1966; and Schreiber & Kincaid, 1967). Similarly, increasing runoff has been correlated with increased grazing in studies on the Manitou Experimental Forest near Colorado Springs, Colorado, on mixed and shortgrass prairie near Cottonwood, South Dakota, and on salt desert shrub in western Colorado (Branson et al., 1972: citing Dunford, 1949; Hanson et al., 1970; and Lusby, 1970). Rostagno (1989) reported that on arid Patagonia, Argentine rangelands, eroded and uneroded soil surfaces and the relative infiltration rates correlated with significant differences in visually-estimated plant and litter cover. Of particular interest is a report by Abel & Stocking (1987), who estimated ground cover, "... the proportion of the ground covered by the aerial parts of grasses and forbs in vertical projection," using low-level aerial photography (35 mm camera, 55 mm lens, 120 m altitude) and correlated their estimates with cover measured on the ground using the step-point method of Evans & Love (1957). Their aerial ground-cover estimates were used with a simple computer model to estimate sediment yield from southeastern Botswana rangelands. They report their methods were easy, inexpensive, and gave results in line with field experience.

Cover measurements have detected differences among grazing treatments on blue-grama rangelands (White et al., 1991), Utah desert (Yorks et al., 1992), sagebrush steppe (Bork et al., 1998), and north central Colorado riparian vegetation (Popolizio et al., 1994). We are unaware of any article disputing the correlation between ground cover and soil stability and note the agreement among the studies for a cover/soil-stability, or cover/management correlation regardless of the year, environments, or researchers involved. We infer that soil-stability-protecting land management can be legitimately supported by accurate cover and bare ground measurements.

Ground Cover by Image Analysis

Cooper (1924) reported the first use of vertical photography for cover analysis. Between 1924 and 1967, photography was used to reduce the two to three hours required to chart (pantograph) quadrats (Table 1). Measurements of plant cover were made from vertical images using a transparent dot-grid overlay (Claveran, 1966) as described by Avery (1968). Wells (1971) used a zoom stereoscopic microscope containing cross hairs to measure plant cover from stereophotographs of quadrats by systematically moving the image and recording cross-hair "hits" on vegetation, litter, or bare ground. Measuring cover from stereophotography was, he felt, "faster, more convenient and, because of the much greater number of points which can be assessed, more accurate" than the standard point-quadrat methods. Bennett et al. (2000) used computer-image analysis methods to measure cover from vertical photographs. Although there have been earlier attempts to do this (Booth, 1974), the development of modern image-analysis software has made it practical.

There are a number of software packages capable of measuring cover and bare ground from an image (Louhaichi & Johnson, 2001; Richardson et al., 2001; Hansen & Ostler, 2002). Cover measurement by image analysis has some inherent errors. Bennett et al. (2000) reported error due to camera perspective averaged 4% for a camera (35 mm camera and 35 mm lens), 2 m above ground level (AGL). However, perspective error was consistent across cover classes. A more important source of error occurs where dissimilar characteristics have similar spectral reflectance, as within shadowed areas of images. The latter error source is a long-standing problem but its importance has, and will continue, to diminish as improvements are made in image-analysis software. Current studies suggest that for many cover types, cover-measurement by computer image analysis is more precise (Richardson et al., 2001) or not different from manual measurements and can be done in minutes versus hours or days (Bennett et al., 2000, Louhaichi & Johnson, 2001; Hansen & Ostler, 2002; Booth et al., 2003). Cover measurement by image analysis appears faster and more objective than standard point-sampling methods, but there remains the need to

TABLE 1 Summary of Methods for Measuring Plant Cover Using Vertical Ground Photography

Author	Year	Journal	AGL[1](m)	Fld.(m^2)	Veg./Loc.	Comment
Cooper	1924	J. Ecol.[2]	1.8	1	Dune, Minnesota, USA	5×7 inch format
Rowland & Hector	1934	Nature	ND[5]	ND	Tufted sward, S. Africa	None
Winkworth et al.	1962	JRM[3]	ND	2.5	Australian grassland	rejected photo method
Claveran	1966	JRM	1.7	1	Sonoran Desert, USA	crown graphic; polaroid film
Wimbush et al.	1967	Ecology	1.2	0.9	Snowy Mts., Australia	35 mm; stereo
Pierce & Eddleman	1970	JRM	1.5	1	Montana, USA	70 mm/55 mm lens
Wells	1971	JRM	1.3	1×1.5	New S. Wales, Australia	35 mm; stereo
Tueller et al.	1972	Exp. St. Rpt.[4]	2.5	2.3	Nevada, USA	35 mm; stereo
Ratliff & Westfall	1973	JRM	1.2	0.09	Meadow, California, USA	stereo adapter; print scale = 1:7
Pierce & Eddleman	1973	JRM	1.5	1	Montana, USA	70 mm superior to 35 mm
Owens et al.	1985	JRM	≤ 7	$\leq 6 \times 9$	Tintic, Utah, USA	70 mm superior to 35 mm
Roshier et al.	1997	JRM	Variable	4×3	New S. Wales, Australia	video; framegrabber; software
Bennett et al.	2000	JRM	2	1	NW Australia	digital image analysis; est. error

[1]Camera altitude above ground level
[2]*Journal of Ecology*
[3]*Journal of Range Management*
[4]Experiment station report
[5]Not determined

acquire an appropriate number and distribution of photographic samples over large areas in short-time periods and on random sites far removed from easy ground access (Tueller, 1996).

Cover Measurements Fit a Remote Sensing Framework

Small-scale image pixels are a mix of the spectral reflectances among cover components, making it difficult to define the proportion of the ground that is exposed soil at risk for erosion (Tueller, 1989). However, at the larger scales, ground cover is among the variables most dependably measured by remote sensing methods (Booth, 1974; Abel & Stocking, 1987; Ritchie et al., 1992; Paruelo & Golluscio, 1994; Pickup et al., 1994; Tueller, 1989; Tueller, 1996; Everitt et al., 1994; 1995a, 1995b; Booth et al., 2003). Bork et al. (1998) justified the use of cover to measure range condition "because this variable best relates the abundance of plant growth to spectrometer data . . . ." West (1999) stated the feelings of many land managers and rangeland scientists when he wrote, "I see no hope that traditional methods of monitoring, *via point sampling on the ground* [emphasis added], will be able to accomplish those [monitoring] needs . . . especially when landscape and regional perspectives are required. There are simply not enough adequately trained people and that approach would not be affordable, even if the necessary professionals existed." The futility of economical ground sampling has been demonstrated by the (U.S.) National Resource Inventory, Colorado Test (a prototype inventory procedure), where random sampling and ground data collection and judgements were used (Pellant et al., 1999). Pellant et al. (1999) reported an average 2.5 hours travel time for 3-person teams to reach sample sites. This included the use of helicopters to reach sites that were not accessible to wheeled vehicles. Field data collection costs (not including cost of data analysis) was $893 per sampled site and field crews sampled 448 locations for a total cost of $400,000 (Pellant et al., 1999). Such costs are not likely to promote the use of adequate sample numbers or adequate sample distribution.

Traditional rangeland assessments have incorporated forage quality as provided by the mix of plant species in the community ("increasers" versus "decreasers") (Stoddart & Smith, 1955). Species composition changes are strongly related to range condition, and good land managers should be alert to these kinds of changes. However, cover and bare ground appear to have greater utility than species composition for extensive, low-cost monitoring using remote sensing methods. If we accept that unbiased, economical monitoring must incorporate remote sensing technology, then it is ". . .necessary to examine what remote sensing is able to accomplish and to reformulate components (of a range assessment procedure) within that framework" (Pickup et al., 1994). The measurement of ground cover from aerial images may be a primary means of "reformulating" range assessment procedures to fit a remote sensing framework.

Altitude and Platforms: The Value of Multiple-Scale Data in Defining a Practical and an Effective Remote Sensing Framework to Monitor Rangelands

> There are two levels of observation in range inspection: one extensive and the other intensive. . . . Intensive observations on small areas are necessary to secure the detailed facts from which the only valid conclusions of range condition can be made. L. Ellison & A.R. Croft, 1944

High-Altitude Remote Sensing

The launch of Landsat in 1972 produced a high level of optimism and several objective studies were initiated to evaluate these data and their rangeland applications. Almost immediately it became obvious that Landsat images were inadequate for identification, inventory, and measurement of detailed rangeland features. The value of Landsat and similar small-scale imagery is for landscape-level evaluations such as plant community distribution and patch dynamics. There are a number of satellite sensors addressing our need for extensive views. These include:

- LandSat 7 TM, providing 30 m, multispectral imagery and a single panchromatic band with 15 m pixels. A multispectral scene covers 31,000 km^2 (photo scale is 1:144,000). (The "photo scale" or representative fraction is defined as the photographic distance between two points divided by the ground distance between the same points).
- Indian Remote Sensing, providing 5.8 m-pixel imagery, is useful in mapping vegetation and showing changes where intense use has caused landscape degradation.
- IKONOS and QuickBird, are providing very high quality imagery at 1 and 0.6 m resolution. Unfortunately, the cost makes this imagery impractical for most rangeland users.
- Hyperion, is a hyperspectral system with 220 spectral bands between 0.4 and 2.5 μm giving 30 m ground resolution. There are a number of new satellites with this or similar systems that might prove useful for measuring rangeland vegetation and soils changes. An image from the EO-1 satellite covers a 7.5×100 km area with detailed spectral mapping across all 220 bands.
- MODIS, or Moderate Resolution Imaging Spectroradiometer, is the key instrument aboard the Terra (EOS AM-1) satellite and provides images of the entire Earth's surface every one to two days in 36 spectral bands. The Terra MODIS 250 m resolution imagery may be sufficient to examine rangeland changes over relatively large land areas.
- National Aerial Photography Program (NAPP). The program is a jointly funded federal and state effort to acquire 1:40,000-scale aerial photography of the United States on a 5-year cycle. NAPP photography is taken from 6100 m above mean terrain using large-format aerial cameras loaded with black-and-white or color-infrared film and using a 150 mm focal-length lens. The ground resolution is approximately 1 m, making it equivalent to the more expensive IKONOS and Quickbird data. Flight lines are north and south with 60% forward overlap, providing full stereoscopic coverage, and with 27% or greater sidelap (Light, 1995). This is excellent imagery for delineating plant communities and relevant topographic features.

Large-Scale Imagery

The development and application of large-scale aerial photography have been promoted almost exclusively by plant scientists—those concerned with the vegetation quality or characteristics in their management areas, be these agricultural crops, forests, or rangelands. The first uses of large-scale photography were to identify plant diseases and calculate timber-stand volumes (Lossee, 1953; Colwell, 1956; Avery, 1958; Pope, 1958; Aldrich et al., 1959; Heller et al., 1964; Murtha, 1972; Hamilton, 1981). Scales employed varied from 1:7,200 (Lossee, 1953) to as large as 1:600, based upon reported flying heights (Colwell, 1956; Avery, 1958) or actual photo distance measurement (Pope, 1958; Aldrich et al., 1959). This large-scale work identified several key components of successful application, including reduction of image blur through improvements to photographic equipment and film, development of dichotomous keys for surface feature identification, and the use of stereo photography that allowed measurement of heights. Aldrich et al. (1959) introduced both the fast-shutter Hulcher (Model 102) 70-mm camera to reduce motion blur, and the use of Anscochrome and Superanscochrome film. The Model 102 had shutter speeds up to 1/2000 sec and remained the preferred camera for large-scale photography to about 1986. The use of Kodak Ektachrome (Heller et al., 1967; Carneggie & Reppert, 1969) and Kodak black and white films (Lyons, 1967) further enhanced image clarity and statistically improved the detection of differences in vegetation type and quality. These improvements led to reductions in errors in timber stand volume calculations (Lossee, 1953; Lyons, 1967). After 1960, the cost per ha (or, per acre) appears to have further highlighted large-scale imagery as an accurate and cost-effective alternative to ground-collected forest data (Lyons, 1967).

The introduction of large-scale aerial photography to rangeland resource inventories began with the work of Carneggie & Reppert (1969) and Carneggie et al. (1971). Carneggie and his colleagues brought to light the importance of obtaining repeat aerial images for plant species identification due to phenological differences. Their use of both color and color infrared film was repeated in subsequent studies of the film's ability to detect range vegetation characteristics (density, cover, and community types) (Tueller et al., 1972; Tueller & Booth, 1975; Heintz et al., 1978; Everitt et al., 1980; Tueller et al., 1988). Hayes (1976) used scales between 1:2000 and 1:8000 to assess grazing on stream-meadow ecosystems. Booth (1974) used a intervalometer to trigger cameras for large-scale, stereo photographic samples of rangeland watersheds along aerial transects as a means of evaluating the erosion condition class in major plant communities of western Nevada watersheds. Systematic, intermittent aerial sampling, as opposed to continuous photographic coverage, was subsequently used by Abel and Stocking (1987) to estimate sediment yield from South African rangelands.

Helicopters can be effective platforms for obtaining large-scale imagery. Tueller et al. (1988) used a Bell B-1 helicopter and 35 mm camera equipped with 120 mm lens to obtain large-scale images for measuring changes in species cover, density, and frequency, and for detecting other ground cover attributes in sagebrush/grass communities of northern Nevada. Most shrub species were successfully identified and measured but this could not be done for bunch grasses and forbs. The authors reported no difference in their ability to detect vegetation trends using 1:960 (107 m AGL) versus 1:1650 (198 m AGL) imagery. The authors felt the helicopter provided a means of quickly getting to key sampling sites with high maneuverability and reasonable safety, and judged the platform ideal for low level photography although the cost exceeds that of any fixed wing aircraft.

Hansen and Ostler (2002) also used a helicopter (and balloons, blimps, and fixed-wing aircraft) to obtain aerial imagery at a variety of scales. They concluded scales of 1:1000 to 1:4000 yielded the best estimates of Mojave Desert shrub cover and fixed-wing aircraft were recommended over other platforms for efficiently photographing large areas.

Very-Large Scale Aerial (VLSA) Imagery

The success achieved in monitoring shrubland ecosystems at 1:1000- to 1:2000-scale imagery is noteworthy. However, even large-scale images may not provide the detail needed to assess herbaceous vegetation or allow the measurement precision obtained by the authors listed in Table 1; a point emphasized by the finding of Hansen & Ostler (2001) that their shrub-cover-measurement accuracy decreased exponentially among larger to smaller-scale images. Thus, methods for acquiring low-altitude, VLSA imagery (scale $\geq$1:500) are of interest (Hinckley & Walker, 1993; Walker & De Vore, 1995; Harris et al., 1996; Quilter & Anderson, 2001; Hansen & Ostler, 2001; Louhaichi & Johnson, 2001; Aerosonde, 2002; Hansen & Ostler, 2002). [VLSA imagery is also referred to as low-altitude/large-scale (LA/LS), near-earth, or close-range vertical imagery].

Platforms for acquiring VLSA imagery have included stationary, but portable, camera supports (Table 1), poles, balloons, dirigibles, kites, radio and computer-controlled unmanned aircraft, ultralight aircraft and ultralight-type fixed-wing airplanes, and helicopters (Tueller et al., 1988; Hinckley & Walker, 1993; Hansen & Ostler, 2001; Aerosonde, 2002; Booth et al., 2003). Helicopters and long-range unmanned aircraft (Aerosonde) are high cost. Among the remaining platforms, the ultralight-type, 3-axis, fixed-wing airplane appears to be the most practical for low and slow flight over extensive areas ($\geq$100 km^2). For that reason it has been the platform of choice for ongoing research undertaken in a cooperative project between the USDA-ARS, Cheyenne, Wyoming, and the Wyoming State Office of the Bureau of Land Management (Booth et al., 2003).

Nadir aerial images (1:200) taken over two public-land grazing allotments in south-central Wyoming were made with a modified Hulcher Model 123, 70 mm camera equipped with a 500 mm lens (Charles Hulcher Co., Hampton, Virginia) and mounted in a Rans S12XL, 2-seat, ultralight-type, 3-axis airplane. The airplane flew at 72 km h^{-1} (ground speed, straight and level flight), 100 m above 1520 m elevation rangelands. Altitude above ground level was continuously monitored with a laser altimeter (range finder) and the camera was automatically triggered for systematic, intermittent, aerial sampling (Booth, 1974; Abel & Stocking, 1987) by computer using preprogrammed coordinates and an interfaced geographic positioning system. The photography was developed, scanned at 1 pixel per 25 μm of negative, and bare ground measured using manual methods (digital grid overlay) and Vegmeasurement software (Louhaichi & Johnson, 2001). Bare-ground measurements from the Hulcher images were compared with measurements from ground photography (2 m AGL) and with standard on-the-ground point-sampling methods. Bare ground was not significantly different among measurement methods (Booth et al., 2003). Although the results appear promising, much testing remains to ascertain the consistency with which the measurements can be made using these methods in this and other rangeland systems. The results do suggest progress toward a technology for inexpensive acquisition of statistically adequate, unbiased, high-resolution, aerial samples (images) from which to make accurate ground-cover measurements.

Upscaling

As used in remote sensing,"upscaling" is technical slang meaning to make inferences about small-scale data based on larger-scaled (greater detail) data. Upscaling has two contexts. One context is image manipulation, say the merging of Kodak 0.26 m data to the IRS 5 m data and the Landsat 7 TM data (Tueller et al., unpublished data). The goal is image processed data for both the extensive and intensive levels by expanding more detailed information to large-area MODIS and Landsat-type views which often have frequent repeat data collection capability (high temporal resolution). A hypothetical application might use large-scale data to identify a dominant species across a landscape, then upscaling might allow phenological changes taking place over days, weeks, and seasons to be detected and accurately described with each overpass of the monitoring satellite. The second context is simple inferential statistical science and sample adequacy. A group of observations obtained by random or systematic sampling are used to make conclusions about a larger area (or population) and the uncertainty associated with that case of specific-to-general reasoning is evaluated and quantified. Geographic Information Systems (GIS) will likely prove useful in this type of upscaling by facilitating evaluation of sample adequacy, distribution, and frequency over a given landscape. For example, GIS might be used to overlay low-altitude, VLSA-obtained cover values by year of acquisition onto a photo mosaic or satellite image, thus providing information about sample distribution within a plant community for a given year and management unit. [In other words, evaluate the "stability" and "power" (Brady et al., 1995)—the error risk—associated with sample numbers and distribution in a particular monitoring effort. A GIS system might also provide ready access to the large-scale imagery, thus allowing a person studying small-scale imagery to have periodic, earth-coordinate-linked, close-up views]. Whether used in the sense of image manipulation or statistical science, upscaling refers to methods for using intensive and extensive data together in a way that supports science-based conclusions about resource conditions.

Summary and Conclusions

Traditional rangeland management dealt with the hugeness of resource monitoring by relying on professional judgement based on observations, or observations accompanied by limited measurements. However, the need for objective monitoring is clear. The problem is in defining economical means for collecting objective measurements in a manner consistent with good statistical science. The questions include what to measure, how to measure, and how data should be interpreted. We have argued that obtaining repeatable, statistically-adequate measurements for a single characteristic is preferable to a less scrupulous evaluation of multiple characteristics. We have reviewed the literature on ground-cover in relation to first-priority, rangeland-health objectives (soil stability/watershed function), and have also reviewed reports that ground-cover is an indicator easily measured using remote sensing methods. The tools are available for obtaining both extensive and intensive views, and we advocate using both for cost-effective, science-based monitoring. We need further research refining the application of these tools to our science. We recommend that research be coordinated among land managers and researchers to more fully exercise our remote-sensing capability and to better facilitate research evaluation and feedback for a diversity of rangeland resources.

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