Arid Land Research and Management 17: 369–388, 2003

ISSN: 1532-4982 print/1532-4990 online
DOI: 10.1080/15324980390229292

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Ecological Sustainability of Rangelands

MARK A. WELTZ
GALE DUNN

USDA-ARS-Great Plains System Research
Fort Collins, Colorado, USA

JEAN REEDER
GARY FRASIER

USDA-ARS-Rangeland Resources Research
Fort Collins, Colorado, USA

Rangelands and pastures are found in every state and cover 55% of the land surface of the United States. Taken as a whole, from Western deserts and grasslands to meadows and woodlands, rangelands comprise some 364 million ha or 80% of the land in the 17 Western states. The vast expanses and remoteness of rangelands make assessing economic and ecological sustainability a difficult task. Currently, there is no national monitoring framework in place to collect data on long-term or episodic processes and agents of change over time. There are no defined methods for summarizing the health of rangelands. Thus individual conclusions about the health or sustainability of the nation's rangelands vary from person to person and organization to organization. Over one million people derive some portion of their income from farm and ranch activities on rangelands and pastures in the western United States. These individuals own and operate over 406,000 farms and ranches with revenues from selling beef cattle exceeding $13 billion in the 17 Western states. Their continued economic survival is dependent on the environmental sustainability of rangelands. Moreover, organizations and individuals charged with selection of best management systems on rangelands are under increasing pressure to consider not only livestock production issues, but also sustainability and health under multiple land use. As a result, ranchers, government agencies, and other organizations have a critical need for improved methods to balance the economic viability of ranchers, the well being of rural America, and the health and sustainability of the nation's range- and grazinglands. Therefore, a coordinated national research and technology transfer effort is required to successfully develop and transfer to ranchers and rangeland managers a science-based, monitoring system to determine the effect of management practices on sustainability of rangeland ecosystems.

Keywords decision support systems, monitoring, rangeland health

Rangeland ecosystems are an interconnected community of living things, including humans, interacting with the physical environment. The goal of rangeland ecosystem management is to maintain or restore the health, sustainability, and biological diversity of ecosystems while supporting sustainable economies and communities

Address correspondence to Dr. Mark A. Weltz, USDA-ARS-Great Plains System Research, 301 S. Howes Street, Fort Collins, CO 80522, USA. E-mail: weltzL,@gpsr.colostate.edu

(McGinty, 1995). Terms like ecological and biological integrity, ecosystem or rangeland health, and ecologically sustainable development have been increasingly used in recent years. While these terms are not synonyms, they have two common features; they involve long-term ecosystem management, and humans must be considered a part of the system. Whether we are concerned with sustaining economic growth, conserving natural resources for future growth, or preserving natural resources for their social, aesthetic, or recreational value, the integrity of ecosystems and their viability is a major challenge facing society today.

In this article, we examine many of the components involved in defining ecological sustainability of rangelands and we evaluate the current procedures and approaches available for measuring ecological sustainability at the scale of an individual landowner/lessee. For our purposes here, we define economic sustainability as the ability of a rangeland operator to remain economically viable over a period of at least 10 years. Ecological sustainability refers to the ability of the rangeland site safely to capture, store, and release water, to provide protection from soil erosion, to maintain biological diversity and integrity, and to maintain the ability to self regulate its processes.

Whether the scale is global, national, or individual landowner, designing and implementing management systems for ecological and economic sustainability should consider issues and questions in Figure 1 and Table 1. Some of the reasons that we have not been more successful in the past in developing or implementing ecologically and economically sustainable management practices on rangelands are:

1. poorly defining the goal or objective to be achieved;
2. not defining the temporal and spatial scale of interest;
3. incomplete understanding of the complex nature of rangelands;
4. reconciling differing goals or values from different sectors of our society that do not converge in a common viewpoint;
5. lack of cost efficient tools and techniques for collecting, analyzing, and disseminating necessary information; and
6. failure to recognize that exogenous forces (i.e., climate or wildfire) may dominate the response.

With a systems approach we can determine the techniques to use, time period the analysis should span, information required, and frequency of repeating the process to maximize the probability of achieving ecologically and economically sustainable management systems. The first step required in developing economic and ecologically sustainable management systems for rangelands is defining the goal of the operator or landowner. The second task is assessing the financial status of the enterprise. The third task is identifying the natural and cultural resources available to the operator. The fourth step is determining the approach or tools required to perform the assessment at the desired level of resolution, accuracy, and frequency to achieve the objective.

Monitoring systems must be more comprehensive than traditional rangeland trend and condition assessments that relied on vegetation composition. Monitoring systems need to be cost effective, rapid, quantitative, repeatable, unbiased, and applicable at a variety of scales. They also should function in diverse ecosystems, integrate new knowledge and tools as they become available, be simple to understand and implement, and permit users to select from a range of tools, depending on their objectives, the ecosystem, and resources. Monitoring systems must be able to distinguish natural fluctuations and change in ecosystems process from anthropogenic directional trends. Finally, monitoring systems need to address the complex abiotic-biotic feedback mechanisms controlling sustainability and distributed measures describing watershed function and soil erosion processes impacting water

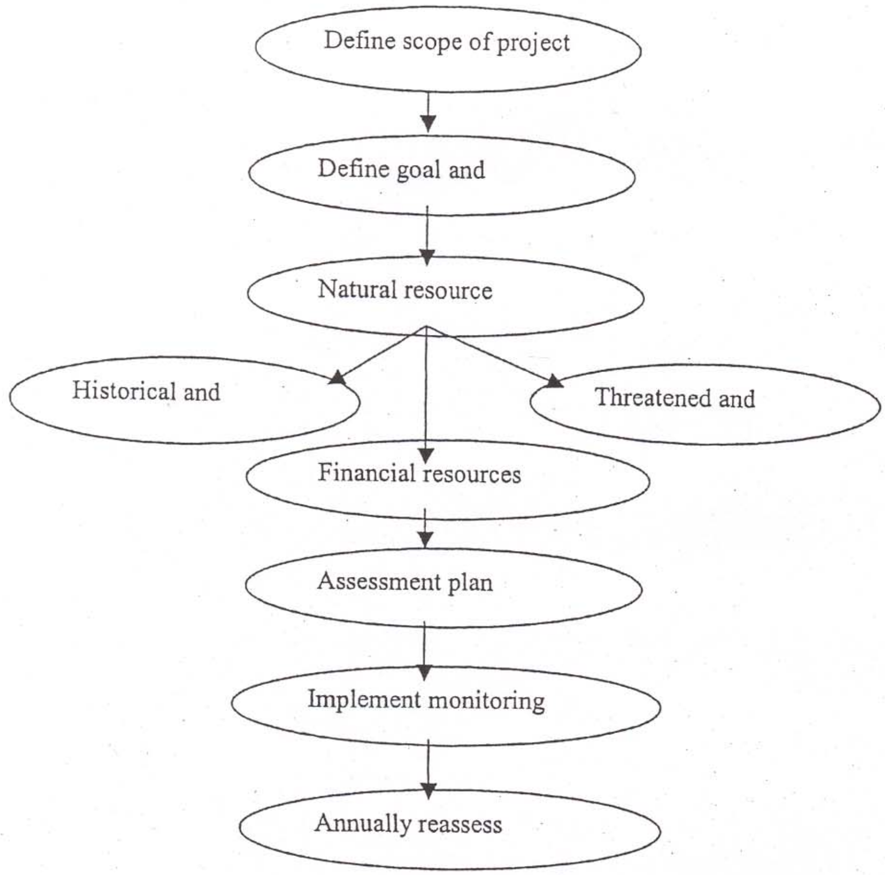

FIGURE 1 Planning steps necessary to achieve economic and ecological sustainability.

quality and quantity, soil quality, wildlife habitat, invasive and noxious weeds, wildfire fuel loads, and biological diversity. This effort must incorporate and address social and economic factors if we expect voluntary adoption of monitoring tools as they become available.

Much of the confusion and debate over condition and health of our rangelands is due to an absence of knowledge and agreement on:

1. science-based quantitative monitoring tools which give an objective status or an overall rating of sustainability;
2. clear procedures for determining sampling numbers, points, and locations;
3. clear identification of parameters to be measured;
4. clear methodology on how to scale information from a point to a pasture to a watershed;
5. a standard procedure for interpreting the data; and
6. a functional data analysis, storage, and retrieval system.

There is no national monitoring framework in place to collect data on long-term or episodic processes and agents of change over time. There are no defined methods for summarizing the health of rangelands. Available approaches are limited because they are based on qualitative data collected at individual points, ignoring interactions and feedbacks among different parts of the landscape. Thus, individual

TABLE 1 Process Necessary to Define, Design, Implement, and Monitor Ecological and Economical Sustainable Management Practices

Define scope of project	Who, why, and how often do they need the information? What level of precision and accuracy is required? What is their level of risk tolerance or risk aversion to failure? Who is going to provide and pay for the information?
Define goal and approach	Define financial and ecological goal of person or agency Define approach needed to achieve goal (tactical or strategic tool) Define type of assessment desire (qualitative or quantitative)
Acquire resource information	Size and number of pastures What ecological sites occur in the pastures Status of ecological sites (both abiotic and biotic components) What are current grazing practices Number and type of livestock and wildlife Acquire climatic information What soil series occur in the pastures Status of fences, livestock facilities, water development, roads, availability of required labor, etc.
Threatened and endangered species	Address appropriate rule and regulation
Historical or archaeological sites	Address appropriate rule and regulation
Acquire financial resource information	What is financial goal (i.e., what net profit would define success)? What is current debt load? What are current liquid and nonliquid assets?
Develop assessment plan	Select appropriate monitoring techniques, sample numbers, and frequency of sampling to achieve objectives
Implement abiotic, biotic, and financial resource monitoring	Establish a monitoring program to track status of ranch resources
Annually reassess	Revisit goals and assess status of ranch resources and make adjustments in operations as necessary

conclusions about the health or sustainability of the nation's rangelands vary from person to person and organization to organization (Mitchell, 2000).

Difference in Assessing Rangeland Health and Ecological Sustainability

The National Research Council (1994, p. 4) stated, "Rangeland health should be defined as the degree to which the integrity of the soil and the ecological processes of rangeland ecosystems are sustained." The sustainability of a site should be based on an objective evaluation which should be independent of the suitability of the site or vegetation to provide any individual or suite of goods and services. The determination of whether a site is sustainable (healthy), at risk, or degraded (unhealthy) should be based on the evaluation of three criteria: degree of soil stability and watershed function, integrity of nutrient cycles and energy flows, and presence of functioning recovery mechanisms (National Resource Council, 1994, p. 97).

To achieve ecological sustainability, one must addresses the concepts of equilibrium, state-and-transition model of plant community change, and the processes of resistance to degradation and resilience after disturbance. Rangeland plant communities are never static and constantly change as a function of climate and management. These concepts are fully discussed by Holling (1973), Walker (1980), Walker et al. (1981), Noy-Meir & Walker (1986), Westoby et al. (1989), Laycock (1991), Friedel (1991), Milton & Hoffman (1994), Tongway (1994), Herrick et al. (1998), and Safriel (1999). Degradation of rangeland health causes a loss of capacity to produce resources and satisfy values. However, rangeland health is not synonymous with ecological and economical sustainability. Rangeland health is not an estimate of the kinds and amounts of resources that a rangeland produces. It is not an evaluation of the different potential uses of a site or the sustainability of a given use for that site.

In contrast, economic and ecological sustainability is based on the amounts and types of good, services, and resources that a rangeland site produces for a particular use. The particular mix of commodities and values produced by a rangeland depends on how it is used and managed under a particular climatic sequence. Managing a desired plant community for ecological and economic sustainability depends on the relative utility of the plant community for its intended uses and values desired for the site. It also depends on the feasibility of implementing the required management to prevent degradation of the site or the feasibility (ecological, economic, or legal) to change the present vegetation to a more desirable type. Different types of data and evaluation techniques are required to determine which uses and management practices are ecologically and economically sustainable from those used to determine the health of the system.

Qualitative Assessments of Rangeland Health

There are four general approaches, derived in part from the rangeland health literature, that can be employed to assess ecological sustainability of a site: (1) qualitative visual assessment techniques, (2) quantitative monitoring techniques, (3) computer simulation modeling of the processes, and (4) a combination of the approaches listed above. Two qualitative approaches have recently been developed. The first was proposed by the National Research Council (1994) and uses three subjective categories to define the status of the 12 different indicators of rangeland health (Table 2). The attributes and indicators used in this qualitative assessment are

TABLE 2 An Example of Descriptions Used to Subjectively Evaluate Rangeland Health using the Indicator Evaluation Matrix of the National Research Council (1994)

Indicator	Healthy	At Risk	Unhealthy
Rills & Gullies	No visible scouring or sheet erosion	Patches of bare soil or scours	Bare areas and scours well developed and contiguous

poorly defined and rely heavily on the expertise of the person performing the evaluation. Most attributes have not been sufficiently validated with field data and lack a sound scientific basis for inclusion in a monitoring system.

In response to the National Research Council call for a technique to evaluate the health of rangelands, the Natural Resource Conservation Service (NRCS), Bureau of Land Management (BLM), and Agricultural Research Service (ARS) jointly developed a qualitative guide called Interpreting Indicators of Rangeland Health (Pellant et al., 2000). The recently released interagency qualitative approach for assessing rangeland health

> is to be used only by knowledgeable, experienced people and it is not to be used to: identify the cause(s) of resource problems; make grazing and other management decisions; monitor land or determine trend; and independently generate national or regional assessments of rangeland health. It is not intended that this assessment procedure be used by individuals who do not have experience or knowledge of rangeland ecological sites they are evaluating. (Pellant, 2000, p. 1)

This approach uses five subjective categories (Table 3) to define the status of an indicator of rangeland health. They recommend that the site is independently evaluated for soil/site stability, biotic integrity, and hydrologic function as a departure from a reference area with no overall assessment of the health of the site.

Weltz et al. (1999) proposed a technique to aggregate the scores quantitatively and produce a single rating of health of the site for an earlier version of the rangeland health assessment technique (NRCS, 1997). This approach links a spreadsheet-based, multi-objective, decision support system to the indicators of rangeland health assessment technique (Yakowitz et al., 1998; and Yakowitz & Weltz, 1998). A decision hierarchy representing the rangeland health worksheet was developed, and orders of importance were assigned to the decision criteria. This approach was tested on four watersheds in southern Arizona whereby four conceptual zones were defined that might exist within watersheds based on hydrologic processes. The zones were gullies (deeply incised channels, definite side cutting), rills (depth > 5 cm), concentrated flow paths (depth $< 5 \times 5$ cm, more transitory), and diffuse uplands (overland flow). Rangeland Health assessments were performed within each zone at each of the four watersheds using the techniques presented in the NRCS Range Handbook (1997).

TABLE 3 An Example of Descriptions Used to Subjectively Evaluate Rangeland Health Using the Indicator Evaluation Matrix of the Interagency Team (Pellant et al., 2000)

Indicator	Extreme	Moderate to extreme	Moderate	Slight to moderate	None to slight
Rills	Rill formation is severe and well defined throughout most of the area.	Rill formation is moderately active and well defined throughout most of the area.	Active rill formation is slight at infrequent intervals; mostly in exposed areas.	No recent formation of rills; old rills have blunted or muted features.	Current or past formation of rills as expected for the site.

Weltz et al. (1999) found that all four watersheds in the study were healthier today than they were at the inception of the watershed study in the mid-1970s due to the increase in the introduced grass Lehmann lovegrass (*Eragrostis lehmanniana* Nees). They reported extreme temporal variability in the rating of health of the system, due to climatic conditions that can confound interpreting the long-term health of a site, if normal variability of the site is not addressed. It is recommended that these ratings to estimate health of the site be performed at the same phenological time of the year and when the system is most vulnerable to degradation.

Quantitative Monitoring of Rangeland Health and Sustainability

Management for sustainability of rangelands depends upon knowledge of the flora, fauna, abiotic characteristics of the site, and an understanding of the variability of climate for the area. Unless these are known, describing the type, level of use, and time of year for use that is appropriate for a specific site is impossible (Bonham, 1989). It is also important to understand that no two sites are exactly the same nor is the site exactly the same at different times within or across years (Heady & Child, 1994). Sustainable rangeland management practices require careful inventory and continued monitoring of the resource to ensure that the goal of sustainability is being achieved. The objective, vegetation type, current vegetation composition, soil, landform characteristics to be measured, and the availability of financial and technical resources dictate the design of the monitoring program. Monitoring systems should be designed to be proactive. They should alert the managers of changes in the state of the system. If the site is in eminent danger, the monitoring system should provide clear indicators to signal the need for a change in management.

Designs of most field based monitoring systems use a subsampling approach whereby only a portion of the area is actually evaluated (Mayne & West, 2001). These areas are called indicator areas or key areas and should be placed where the site will respond rapidly to perturbation. The location of the key area(s) depends on the type of perturbation and requires a great deal of skill for correct selection and placement of the monitoring site(s). The key questions in defining a monitoring system are: what is measured? how do we measure the attribute? how many samples are required? and what is the time interval between measurements to be able to have an early warning system that the site is vulnerable to shifts across a sustainability threshold?

The SRM (1991) proposed a site conservation rating to assess the degree of protection from erosion afforded to a site. The major recommendation of the SRM (1991) was:

> The effectiveness of present vegetation in protecting the site against accelerated erosion by water and/or wind should be assessed independently of the actual or proposed use of the site. This assessment should be called a Site Conservation Rating. The Site Conservation Rating at which accelerated erosion begins should be called the Site Conservation Threshold. Any site rated below the Site Conservation Threshold would be considered in unsatisfactory condition and those above it, satisfactory.

The difficulty in rating an area arises in identifying the thresholds that allow an area to move from one category to another (USDI-BLM, 1993).

Watters et al. (1996) proposed a method to establish Site Conservation Thresholds for rangelands. They defined rangelands that rill with a 10-year return period precipitation event as unsustainable. Rangelands that initiate rilling with the 25-year return period precipitation event are currently functioning but at risk to degradation, and rangelands that do not initiate rilling until the 50-year return period precipitation event are potentially sustainable. They utilized the Water

Erosion Prediction Project (WEPP) model (Lane & Nearing, 1989; Tiscareno-Lopez et al., 1995) as an objective index of soil stability to assess the degree of site protection. The Natural Resource Conservation Service soil loss tolerance value (T) was used with the sediment yield predicted by the WEPP model to establish a threshold value for the Site Stability Rating. The objective measures of standing biomass, basal cover, average distance to the nearest perennial plant, and frequency of quadrats with no rooted perennial plant showed strong relationships to the subjective Site Stability Rating. Site Conservation Thresholds were identified for standing biomass (750 kg ha^{-1}), basal cover (8%), average distance to the nearest perennial plant (15 cm), and frequency of quadrats (20 × 20 cm) with no rooted perennial plant (13%).

Table 4 contains a list of parameters/attributes/indicators (from both subjective qualitative approaches and quantitative approaches) for assessing rangeland health that different individuals have proposed. The articles by de Soyza and his colleagues (de Soyza et al., 1997, 1998, 2000a, 2000b) recommended that only parameters that could be directly measured be utilized in assessing health. Bedell & Buckhouse (1994) provided an excellent list of 26 references to describe how indicators of rangeland health can be measured. They also discussed which technique was appropriate for what functional plant group and ecosystems. Additional recommendations on how to measure these parameters/attributes/indicators and how many samples need to be acquired to achieve a specific statistical goal are presented in Cook & Stubbendieck (1986), Bonham (1989), Woodley (1993), Heady & Child (1994), Tongway (1994), Marshall et al. (1993), Breckenridge et al. (1995), Interagency Technical Reference (1996a, 1996b), Watters et al. (1996), de Soyza et al. (1997, 1998, 2000a, 2000b), Tongway & Ludwig (1997), Whitford et al. (1998), Herrick et al. (1999), West (1999), Ludwig et al. 2000, and Snyman (2000), CAST (2002).

Based on the work of Watters et al. (1996) and de Soyza et al. (2000a, 2000b) the single most useful and reliable indicator of sustainability is the size and connectivity of bare patches because of its relation to so many important ecosystem functions (e.g., water storage, wind and water induced soil erosion, productivity, nutrient cycling, and other functions and processes). The minimum suites of indicators recommended from a recent workshop for consideration in a monitoring system are listed in Table 5. In conjunction with the monitoring system an operator needs to collect precipitation data to quantify the major abiotic stressor of the system. Long-term climate data is essential if an operator is going to use decision support systems effectively to evaluate alternative scenarios (drought periods) and develop proactive management plans.

Potential Quantitative Indicators of Sustainable Rangeland Ecosystems

Nutrient Cycling and Soil Stability

The NRC recommended that indicators that evaluate the integrity of nutrient cycles be included as part of a comprehensive evaluation of rangeland health because not only are most of the nutrients needed for plant growth provided by the soil (Brady & Weil, 1999), but the amount of nutrients available, as well as the rate in which nutrients cycle between plants, animals, and the soil, are fundamental processes of rangeland ecosystems. However, an evaluation of nutrient cycles has not been part of traditional assessments of rangelands (NRC, 1994). This is because relatively few studies have been conducted to quantify the distribution of carbon and nutrients in rangelands, the key belowground processes involved in carbon and nutrient cycling, or the effects of grazing management strategies on soil properties (Smoliak et al., 1972; Burke et al., 1989; Dormaar & Williams, 1990; Milchunas & Laurenroth, 1993;

TABLE 4 Parameters and Attributes of the Site that Have Been Proposed to Estimate Health or Sustainability of Rangeland Ecosystems

Attribute or indicator	Pellant et al. 2000	Bedell and Buckhouse 1994	NRC 1994	Kepner et al. 1993
Gullies	Yes	No	Yes	No
Rills	Yes	No	Yes	No
Scouring or sheet erosion	No	No	No	Yes
Water flow patterns	Yes	No	No	No
Pedestals or terracetts	Yes	No	Yes	No
Bare ground	Yes	Yes	No	Yes
Ground cover by class[1]	No	No	No	Yes
Wind scour or blowouts	Yes	No	No	No
Litter movement-debris dams	Yes	No	Yes	No
A horizon	No	No	Yes	Yes
Soil profile	No	No	No	Yes
Soil surface resistance to erosion[2]	Yes	No	No	No
Soil surface loss or degradation	Yes	No	No	No
Compaction layer	Yes	No	No	Yes
Plant community composition	Yes	Yes	Yes	Yes
Functional/structural groups	Yes	No	No	No
Plant mortality and decadence	Yes	No	No	No
Litter amount	Yes	No	No	No
Annual production	Yes	No	No	No
Invasive plants	Yes	No	No	No
Reproductive potential of perennial plants	Yes	No	No	No
Plant vigor	No	No	Yes	No
Plant canopy cover	No	Yes	No	Yes
Grass and forb basal area	No	Yes	No	Yes
Plant density	No	Yes	No	Yes
Standing biomass	No	Yes	No	No
Plant frequency	No	Yes	No	Yes
Species composition	No	Yes	No	Yes
Utilization	No	Yes	No	No
Residual vegetation	No	Yes	No	No
Vegetation height	No	No	No	Yes
Age classes of trees and shrubs	No	Yes	Yes	Yes
Canopy diameter of trees and shrubs	No	No	No	Yes
Basal diameter of trees	No	No	No	Yes
Root distribution	No	No	Yes	No
Distribution of photosynthesis	No	No	Yes	No
Germination microsites	No	No	Yes	No
Weather and/or climate	No	Yes	No	Yes

[1]Classes include bare ground, rock, litter, plant basal area, cryptobiotic crusts, and scat.
[2]Determined through use of aggregate stability analysis and a measurement of crust thickness.

Frank et al., 1995; Derner et al., 1997; Schuman et al., 1999). This lack of basic knowledge of the role of soil properties and processes on rangeland health has limited the development of soil indicators of nutrient cycling.

TABLE 5 Minimum Potential Set of Indicators that can be Used to Determine Current Status and Trend of Rangeland and Ecosystems with Current Technology and Techniques

Class	Variable	Adequate current methods available	Opportunities for improvement through research
Climate	Precipitation: form, amount, and timing	Yes	Yes
Surface water	Kinds and amounts (over both time and space)	Yes	Yes
Animal	Species and numbers (over both time and space)	Yes	Yes
Plant	Patchiness	Yes	Yes
	Cover by life-forms	Yes	Yes
	Stem density of woody plants	Yes	Yes
Soil	Albedo	Yes	Yes
	Bare patches (size, distribution, frequency)	Yes	Yes
	Soil series and map units	Yes	Yes
Integrative	Permanent photo points	Yes	Yes
	Journals including observations of amounts and locations of poisonous, invading, noxious plants, threatened, endangered species	Yes	Yes
	Rare events •fire •insects •drought •flood •hail •frost		
	Other users •off road vehicles •mountain bikes •camping •hiking •hunting/fishing		
	Infrastructure •roads •trails •fences •corrals •salt/mineral licks		
	Ecological sites		
	Historical records		

Some progress has been made in recent years to develop sensitive soil indicators of nutrient cycling and range condition. A recent study by Jezile (2001) on a sagebrush-grass Dry Mountain Loam range site suggested that the concentrations of water soluble organic carbon (C) and nitrate nitrogen (N) in the soil show promise as sensitive indicators of fragmentation of N cycling and degradation of range health. Jezile (2001) found that the concentration of soluble organic C was lower, and the nitrate-N concentration higher, in the soil of a heavily grazed mid-seral range site designated as in "fair" condition, compared to a moderately grazed late-seral rangesite designated as in "good" condition. The trend was particularly strong for nitrate-N concentration, with significant differences observed between the two range conditions regardless of whether sampled in bare ground areas, in grass areas, or beneath the sagebrush canopy. They suggested that the high grass production and low proportion of bare ground area of the late-seral range site was likely associated with a larger root biomass and thus higher levels of soluble C exudates released from the roots into the soil, while the combination of N immobilization by soil microorganisms and N uptake by the plant community resulted in negligible levels of nitrate-N in the soil profile. In contrast, the low grass production and a large proportion of bare ground area of the heavily grazed mid-seral site was conducive to fragmentation of the N cycle. Nitrogen mineralization was stimulated in the bare ground areas, and the less productive plant community was unable to utilize all of the N being mineralized in the soil.

Using remote sensing from satellite, aircraft, or hand held sensors to measure soil albedo or reflectance is a promising technique to document changes in plant community composition and distribution, soil stability and, by inference, nutrient cycling (Major et al., 1990; Post et al. 1994, 1999). Albedo is the fraction of incident electromagnetic radiation reflected by a surface. The albedo increases as the number of bare spaces increases, and it provides a potentially rapid and cost efficient way to quantify changes in the system, because the degree of fragmentation of nutrient cycles may be suggested by the pattern in which litter and plants are distributed across a site. Large bare areas interspersed in the plant community suggest unfilled niches as well as decreased infiltration rates and increased runoff, and opportunities for accelerated nutrient loss by soil erosion. Until measurable indicators of nutrient cycling and energy flow are developed, assessment of the status of health of a rangeland based on distribution of plants, bare areas, rooting depths, and length of growth periods will depend primarily on informed judgements (NRC, 1994).

Sheet erosion can be monitored by measuring the deflation of the soil surface in reference to permanently placed erosion pins placed within interspace areas. Rill and gully erosion can be directly measured through monitoring changes in the height and width of micro channels or gully cross sections using traditional surveying equipment. However, recent advances in the use of airborne laser altimeters have resulted in cost efficient systems to quantify gully erosion at watershed and regional scales (Ritchie & Jackson, 1989). The laser altimeter can also be used to measure canopy cover and plant height, to map plant community distributions, and to measure many other environmental attributes (Ritchie et al., 1992, 1995; and Weltz et al., 1994). Recent efforts to develop measurable indicators of soil properties and processes for integration into rangeland monitoring programs also include the monitoring program designed by Herrick et al. (2001). Herrick et al. (2001) propose that the selection and interpretation of soil and soil quality indicators into rangeland health assessments should be based on: site-specific resource concerns and inherent soil and site characteristics; consistent correlation of the soil indicator with the functional status of one or more critical ecosystem processes; incorporating spatial variability in the development of indicators to make them more representative of ecological processes; and interpreting indicators in the context of dynamic ecological processes. They developed a set of quantitative measurements that are used to calculate a suite of indicators are related to three rangeland ecosystem attributes: soil and site stability, hydrologic function, and biotic integrity (i.e., the capacity of the system to resist and recover from catastrophic disturbance) (Herrick et al., 2001b). Three core measurements include: (1) a line-point intercept to quantify plant cover and composition, and soil surface characteristics; (2) a continuous line intercept to quantify the size of canopy gaps; and (3) a soil aggregate stability test to rate the degree of water stable aggregation in the surface soil. Supplementary measurements may also be applied depending on resource concerns and site characteristics. These include belt transects for woody and invasive plants, species richness, plant production by species, impact penetrometer, single-ring infiltration, riparian channel vegetation survey, riparian channel profile, and tree density. This monitoring system is designed to detect long-term trends in the three ecosystem attributes noted above. An ongoing research program is testing and calibrating the indicators to ecosystem processes, developing complementary landscape-level indicators, and generating more effective interpretation tools (Herrick et al., 2001b).

Runoff and Infiltration

Recent studies are showing that traditional models of infiltration and runoff do not always work on rangeland sites (Weltz et al., 2000; Pierson et al., 2001). Most of the theory and computer models predicting runoff and soil erosion were developed for cropland where soils and vegetation are more homogenous and the vegetation spacing is uniform (Weltz et al., 1998). On rangelands, there is a highly variable spatial distribution of vegetation both in type and density. Furthermore, rangeland soils frequently have thin or discontinuous surface layers. The decaying organic matter laying on the surface can cause a chemical layer which will repel water and reduce infiltration. Runoff on these sites occurs as small flows in microchannels rather than as sheet flow. The most important criteria to describe this type of flow, and potentially soil erosion, is stem diameter, stem density of the plants (Flenniken et al., 2001), and the spatial arrangement of the plants down the hillslope (Weltz et al., 1998). As stem density decreases, the hydrologic roughness/friction is also decreased. Decreased hydrologic roughness/friction results in increased velocity of the runoff water and less water infiltrating into the soil surface.

Remote Sensing

The digital revolution over the last four decades has resulted in numerous new tools and techniques for quantifying and monitoring environmental attributes (satellites using multispectral, microwave, radar, aerial photographs, and thermal sensors, geographic information systems, image processing systems, digital cameras, and hand held computers, etc.) that are of interest to rangeland managers. Remotely sensed data, collected and analyzed with these techniques, provide an extremely valuable source of data for many rangeland management and monitoring tasks, at a range of scales and frequency of collection, that can never be addressed using traditional ground based sampling techniques. Remote sensing has been used to develop rangeland condition assessments, estimate aboveground biomass and changes in canopy cover, quantify leaf area index, quantify soil erosion, estimate livestock carrying capacity, map soils, estimate soil water content, track water pollution, and assess numerous other important ecological attributes (Tuller, 1989; Anderson et al., 1993; Henebry, 1993; Pickup et al., 1993, 1994, 1995; Frank & Aase, 1994; Moran et al., 1994; Engman & Gurney, 1995; Lauver, 1997; Yool et al., 1997; Wessman et al., 1997; Saltz et al., 1999; de Soyza et al., 2000a, 2000b; Qi et al., 2000). Several federal agencies (EPA, U.S. Geological Survey, and Forest Service) currently use some form of remote sensing and geographic information systems routinely to complete agency missions.

Among the reasons that remote sensing has not been used routinely to address rangeland management, inventory, and assessment questions have been the lack of individuals trained in both remote sensing and range management, the cost to purchase computer equipment, the cost and training associated with the specialized software and equipment needed to interpret the data, the cost of purchasing the data, and the resistance of federal agencies to adopting new methods of monitoring federal lands. Remote sensing is not a panacea and currently cannot address all the data needs of range managers (e.g., identify individual plant species). However, remote sensing can be used as a scouting tool to identify and document where change is occurring. The range manager can then go directly to the effected area and document what is changing and begin to investigate why the change occurred.

Simulation Modeling and Decision Support Systems

Changing societal values have resulted in increased demands for environmentally sustainable management practices. The growing trend to try to meet these demands through increased regulation requires improved prediction technology. While traditional rangeland research has led to the development of improved vegetation management practices and germplasm for a site, it has done little to enhance the predictive capabilities of complex ecosystem processes (Hanson et al., 1999). Rangeland managers must account for interactions among soils, water, plants, animals, air, and the economic concerns of humans, if they are going to achieve sustainable systems. Decision support systems (DSS) with embedded simulation models can integrate these ecosystem components to facilitate evaluation of alternative management systems. Simulation is a process in which selected aspects of systems behavior can be represented by mathematical relationships and then reproduced by applying those relationships.

Decision support systems and simulation models are most often used to answer "what if" questions concerning the consequences of change in the system(s) characteristics, behavior, or utilization (Pickup & Smith, 1999). Management systems can be optimized through the use of DSSs to predict which system or suite of systems will be ecologically and economically sustainable for a given set of assumptions and constraints.

In theory, decision support systems and simulation models offer rangeland managers planning assistance that is based on state-of-the-art science and technology. A number of rangeland resource simulation models and decision support systems have been developed. The purpose and designs vary considerably and are discussed more fully by Hanson et al. (1985), Weltz et al. (1996), Weltz et al. (1998), Hanson et al. (1999), and Pickup & Smith (1999). Simulation models can assist the rangeland manager in the evaluation of large databases more accurately than by intuitive judgement. However, to utilize these tools fully, the manager must have access to national, regional, and local databases related to climate, soils, topography, hydrology, plant community composition, attributes related to plant succession, plant community response to disturbance, attributes related to forage preference and animal performance by species, and economic variables like interest rates, labor cost, commodity prices, inflation rates, and most importantly, access to training and guidance on when and how to use a DSS or simulation model. Historically rangeland managers have encountered problems when they have tried to use simulation models and DSSs because of the complexity of the software, limited scope or objective of the simulation model or DSS, availability of databases, lack of validation for specific sites or circumstances, and lack of appropriate equipment and training to use these tools.

One of the most complete DSSs is GPFARM (Great Plains Framework for Agricultural Resource Management) being developed by the USDA-ARS (Shaffer et al., 2000) for use in the central Great Plains region of the United States. This approach uses a daily time step simulation model to estimate plant production, forage consumption by livestock, weight gain or loss by livestock, soil erosion, and economic returns from alternative management systems. The simulation model is coupled to a DSS to display the information spatially in a geographic information system framework and a multi criteria, decision analysis tool to help the user select the optimal management system to minimize ecological and environmental consequences and maximize economic returns.

For GPFARM, as with many similar decision support tools, the minimum time interval to estimate or simulate ecological sustainability with a single management practice is 50 years. This long time frame is required to incorporate the stochastic nature of climate and its affect on ecosystem processes. However, for determination of economic sustainability, the time interval that can be projected is as short as one year with a maximum logical projection of 20 to 30 years. The short time step for assessing long-term economic sustainability is required due to assumptions about commodity prices, inflation and interest rates, labor costs, tax structures, and legislation. These all affect the economic viability of the management practice but are less predictable than the uncertainty in predicting climatic variability.

If properly configured and used, DSSs should usher in the information age for rangeland managers. These tools can provide a useful technique for exploring management activities, identifying both ecological and financial risk, and planning future actions. These tools, coupled with a greater understanding of biological, ecological, economic, and social factors that occurs through the use of them by rangeland managers, should advance decision making to a level whereby sustainability of the natural resources and the enterprise is better assured.

Conclusions

The deleterious consequences of anthropogenic activities on ecosystems worldwide have resulted in efforts to develop and employ sustainable management systems to avoid irreversible damage and desertification of rangelands. Changing societal values have resulted in increased demands for environmentally sustainable management practices. By the time landscape deterioration is detected with most classical monitoring approaches, ecosystem function and processes have already been adversely affected. Once ecosystem functions have been compromised, simply removing the anthropogenic stress is generally not sufficient to halt or reverse the degradation (de Soyza et al., 2000a). Therefore, it is critical that we develop monitoring systems that can alert us to pending changes in ecosystem function before the threshold of change is crossed, if we are going to achieve ecologically and economically sustainable management systems. Monitoring systems for ecological sustainability must be sensitive to environmental and anthropogenic stresses, must focus on minimizing the risk of ecosystem degradation related to ecosystem goods, services, and function, and must be robust and cost effective to implement.

Unfortunately, rangeland managers must deal with spatial and temporal variability in the ecological functioning of the system and in the market prices they receive for goods and services. Grazing is a spatially variable process that is implemented within a nonuniform landscape where forage quantity and quality, vegetation response to precipitation, precipitation amount and distribution, and risk of degradation all vary seasonally and annually (Pickup & Smith, 1999). A major question for science is how do we manage the inherent spatial and temporal variability in the most efficient manner to minimize the risk of degradation on rangelands.

The challenge in achieving sustainable utilization of rangeland ecosystems is in how we optimize the long-term productivity of the site with profitability of the enterprise at the lowest risk of failure (Snyman, 2000). The interactions among ranch resources, such as people, finances, land, vegetation, climate, and so on, as well as external influences must be understood and taken into account by the decision maker. The successful rancher is the one who can avoid a crisis situation based on the application of sound rangeland management principles that include detailed planning, monitoring, and evaluation of the entire enterprise. The impact of each action taken by the decision maker must be evaluated in advance of the action, and the outcome monitored for its impact. The best way to accomplish this planning is through use of decision support systems. Decision support systems facilitate the analysis of alternative scenarios (e.g., predict how much forage will be available based on cumulative precipitation for the year) and the development of an action plan prior to a crisis. Prior planning minimizes the risk of having to make emergency decisions with little information that may result in economically and ecologically deleterious results.

The best recommendation we can make at this time is to implement a tiered approach. The first phase is to define clearly what question(s) are to be answered by the monitoring program and at what level of precision and accuracy. The second phase would be to evaluate the economic/financial resources of the enterprise to determine the capital available to invest in the monitoring program. The third phase would be to conduct a systematic assessment of all grazing lands to stratify the areas into zones that are currently stable, areas at risk to loss of productivity, and areas where change has already occurred. Based on risk factors, monitoring sites should be in each of the zones. Sites that are stable may have to be evaluated once every 3 to 5 years only and require fewer sampling locations. Sites that are at risk should be evaluated every year and have the highest density of sampling locations. Sites where change has already occurred and which are now stable should be evaluated every 3 to 5 years only with a minimal number of sampling stations. The fourth phase would be to use a decision support system such as GPFARM to develop a proactive management plan to deal with economic and ecological risks (e.g., drought, disease, crash in livestock market) that have a high probability of occurring during a 30-year planning horizon. By adopting this tiered approach, we have the greatest chance of achieving ecological and economical sustainable rangeland management systems.

Ranchers as stewards of the land have a responsibility to ensure that their management actions do not result in loss of goods and services from rangeland ecosystems. However, ranchers currently lack economically feasible and scientifically-based tools to assess the current status of the land and long-term environmental sustainability of rangeland ecosystems. A coordinated research and technology transfer effort is required to develop, evaluate, and employ new models of change for rangeland ecosystems that utilize the concepts of ecological thresholds. The research must address the spatial and temporal variability and uncertainty that rangeland managers face in making daily management decisions. This research effort should address the difficulty that arises in rating areas as healthy, at risk, or unhealthy and provide techniques that are unambiguous in identifying the thresholds that allow an area to move from one category to another. The research needs to focus on developing robust indicators of the health of the system and to provide for a means to quantitatively aggregate the indicators into a single assessment of health or sustainability of the system. These indicators need to provide an early warning system that alerts managers to the risk that serious degradation is imminent if management does not change or if certain extreme events occur [e.g., significant gully erosion will occur because of lack of sufficient vegetative and ground cover if rainfall exceeds a threshold ($>$25-year 2-hour return period precipitation event)].

This research effort must incorporate and address social factors, be inexpensive to implement, and be easy to utilize if we expect voluntary adoption of these new tools and techniques as they become available. We believe there will be many far-reaching benefits from the development of a science-based monitoring program for ranchers including: (1) a means and structure for empowering ranchers to document stewardship and the sustainability and health of rangelands they use within their livestock production operations; (2) a science-based decision making process; (3) a base for communication in planning, developing, and implementing sustainable grazing systems and range improvements on a local, regional, and national level; (4) an unbiased tool to assist in conflict resolution; (5) a means to evaluate the cost effectiveness of both public and private rangeland improvement programs; and (6) more science-based and more holistic technical assistance and advice to ranchers in terms of rangeland ecosystems and ranch resources to encourage improved stewardship, land management, and decision making toward continued ecological and economic sustainability of rural America.

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