# Soil and Vegetation Indicators for Assessment of Rangeland Ecological Condition[1]

**Herrick, J.E.[2,4], W.W. Whitford[3], A.G. de Soyza[2] and J. Van Zee[2]**

In: North American Workshop on Monitoring for Ecological Assessment of Terrestrial and Aquatic Ecosystems. C.A. Bravo (ed) 1996. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO Gen. Tech. Rpt. RM-GTR-284

Abstract.—Indicators of rangeland ecological condition should be (1) quantitative, (2) rapid, (3) repeatable, (4) easily communicated, and (5) susceptible to sensitivity analysis. Most importantly, the indicators should be related to ecosystem function and to the capacity of the system to resist and recover from disturbance. Based on these criteria, we have developed a suite of indicators for North American desert rangelands. Most of these rangelands are located on fragile, nutrient- and organic matter-poor soils and suffer from periodic moisture deficits. Consequently, we have focused on indicators which reflect the capacity of the system to trap and retain soil and water resources. These indicators include size of bare soil patches, cryptogamic crust cover and soil surface stability, and the ratio of long-lived to short-lived perennials. Another suite of indicators reflect rangeland productivity. These include proportion of total perennial plant cover of species palatable to livestock as well as total biomass production. We have developed and tested these and a number of other indicators in a wide variety of plant communities with known disturbance histories at the Jornada Experimental Range in the Chihuahuan Desert in New Mexico, and validated them on cooler, more mesic rangelands in Idaho and Oregon, as well as an arid site in Utah. We will present results from the Chihuahuan Desert evaluation, together with a preliminary version of a variable-weighting system to combine these indicators into flexible indices of ecological condition which can be adapted to address the objectives of individual agencies and land managers.

## INTRODUCTION

Ecological condition is defined as the relative capacity of a system to (1) perform selected functions, and (2) to maintain these functions following disturbance through processes of resistance and recovery. The emphasis of this definition is on *selected* functions. Ecosystems perform a variety of functions. While many of these functions are mutually compatible, the optimization of one function may at times require a reduction in the capacity to fulfill a second function. For example, the revegetation of graded coal mine spoils in southern Ohio with aggressive perennial grasses optimizes the ecological function of soil conservation in a relatively short period of time. However, reestablishment of the highly diverse native forest system is blocked by competition from the grasses. The forest system, once established, would more effectively fulfill a number of functions

---

*[1] The U.S. Enivironmental Protection Agency partially funded and collaborated in the research described here. It has been subjected to the Agency's administrative review. The U.S. Government has a non-exclusive, royalty-free licencse in and to any copyright covering this article.*

*[2] USDA-ARS, Jornada Experimental Range, Las Cruces, NM.*

*[3] USEPA-ORD, NERL, Las Vegas, NV.*

*[4] Preparation of article was partially supported by a USDA-NRI grant.*

than the perennial grassland, including biodiversity conservation, wood production, microclimate modification, and carbon storage.

The determination of the relative importance of various functions (and thus the ultimate determination of ecological condition) is a policy issue which must be completed independently of the evaluation of the relative capacity of the system to perform each function. Consequently, we have divided the process for developing an ecological condition indicator system into four stages. Stage I involves selecting the ecosystem functions of particular interest and is completed by managers and policy-makers in consultation with scientists. Scientists select and develop function-specific indicators in stage II and then combine them to assess each function individually in stage III. These functions are then combined by teams of policy-makers, managers and scientists in stage IV according to the relative societal values placed on each function. A feedback loop clearly exists through the four stages. The relative weights assigned to various indicators and functions can be modified as our understanding of ecological processes and the relative value society places on different functions evolve.

## STAGE I: FUNCTION SELECTION

The ecosystem functions selected should be based on current and anticipated future societal values. While many functions overlap, few can be characterized by an identical set of indicators. Consequently, it is important to incorporate the views of as many interested parties as possible at this stage in order to identify all potentially relevant functions.

## STAGE II: INDICATOR SELECTION AND DEVELOPMENT

### Indicator Selection Criteria

Indicators of ecological condition should be (1) quantitative, (2) rapid, (3) repeatable, (4) easily communicated, and (5) susceptible to sensitivity analysis. Most importantly, the indicators should be related to ecosystem function and to the capacity of the system to resist and recover from disturbance.

#### Quantitative

Quantitative indicators are preferred over qual tative or subjective indicators in nearly all cases b cause they tend to be more repeatable and are easie to combine with other indicators. However, som ecosystem functions, such as providing scenic value are difficult to measure quantitatively. In these cases rating or ranking systems may be applied to subjective assessments to provide a semi-quantitative indicator. The numerical values or ranks can then be calibrated with quantitative data. For example, Watters *et al.* (in press) developed an exponential relationship between a subjective "site stability rating" and sediment yield predicted by WEPP (Water Erosion Prediction Project). Any evaluation system which includes this approach should include a precise description of how the individuals making the subjective assessments are to be selected, as well as the type of guidance which these individuals will receive. In many situations, however, quantitative indicators can and should be substituted for qualitative indicators by using quantitative parameters which have been calibrated with qualitative assessments in controlled studies.

#### Rapid

The indicators and measurements selected should be as rapid as possible in order to minimize costs and to permit data collection at as many sites as possible. There are at least four factors which determine how rapidly the information needed for an indicator can be collected: (1) time per measurement, including preparation, (2) number of different types of measurements needed for the indicator, (3) number of replicate measurements needed per site, and (4) operator training time. The number of replicates needed per site depends on the ratio of the expected maximum range of values between sites to the expected within-site variance. This can be thought of as one component of a signal-to-noise ratio for the indicator. The other component depends on how accurately and precisely an indicator reflects the ecosystem function of interest. Measurements and indicators with a high signal-to-noise ratio will require fewer within-site replications.

Site assessment speed can frequently be increased by recognizing that different indicators have different signal-to-noise ratios at different spatial and temporal scales and therefore require different levels of replication. For example, while relatively large plots are required to assess shrub or tree cover, annual and perennial grasses and forbs can often be quantified in several smaller sub-plots.

### Repeatable

Identifying indicators which can be consistently evaluated by a wide variety of observers over a number of years or decades is one the most difficult and important tasks for indicator development. While a number of quality-assurance techniques have been developed to promote observer consistency within a team operating during a single season, it is much more difficult to maintain a high level of uniformity between years, even when the same observers are involved. Indicators which are simpler and involve fewer subjective decisions will tend to be more repeatable over the long-term.

Methods for collecting data should be clearly defined before actual data collection begins. Any changes to the methodology should be explicitly recorded and reported with the results, even if it does not immediately appear that these changes will have any impact on the results.

### Easily Communicated

Where possible, the connection between the indicator and the function should be intuitively obvious to the general public. Clear connections between indicators and functions may minimize future conflicts over interpretation of the assessments and facilitate the assignment of relative weights to each indicator. The selection of indicators with an intuitive connection to function should not, however, come at the expense of the other four factors. For example, while large-scale rainfall simulation and natural precipitation runoff plots are clearly related to hydrological function, their high cost generally precludes sufficient replication.

### Susceptible to Sensitivity Analysis

Ideally, it should be possible to test the sensitivity of the indicators against quantitative changes in the capacity of the system to perform the selected function(s). This type of information is frequently not available. A suitable substitute is to test the indicators along gradients which have a known disturbance history.

### Related to Function and System Resistance/ Resilience

The most important attribute of an indicator is its ability to reflect changes in the capacity of the system to perform selected functions, and to maintain those functions following disturbance. Indicators which reflect changes in the capacity of the system to maintain functions following disturbance serve as a kind of "early warning system" for those areas which are "at risk". These are particularly useful in targeting areas for remediation measures.

North American forests and rangelands are required to perform a wide variety of functions, including (1) soil and water conservation for flood control, (2) groundwater and surface water recharge, (3) and maintenance of clear streams for fish production and human consumption, (4) animal production for food and fiber, (5) wildlife conservation for sightseeing and hunting, (6) biodiversity conservation of non-game species, and (7) open space conservation for fulfillment of humans' desire to temporarily distance themselves from other members of our own species (Klinkenborg 1995). Increasingly, forests and rangelands outside of national parks are also viewed as sinks for increases in carbon emissions from burning of fossil fuels. Soil and water conservation is the most fundamental of the functions listed as it is necessary for the preservation of the other functions. While there are a few cases in which soil erosion can lead to temporary increases in productivity due to the exposure of more nutrient-rich subsoil, or in which catastrophic events can increase biodiversity by increasing landscape heterogeneity, a large proportion of the earth's rangelands and forests are limited to soils which have bedrock or a limiting horizon close to the surface, soils in which most of the nutrient capital is confined to the top few centimeters, or soils in which water limits plant growth throughout most of the year. In these systems, increases in the "leakiness" of the system with respect to soil, water and nutrients nearly always leads to degradation in other ecosystem functions.

The capacity of the system to maintain or recover ecosystem functions following disturbance depends on both the integrity or condition of the system and on the nature of the disturbance: disturbance history, seasonality and time scale, intensity and frequency, and combination with other disturbances or stressors. The nature of the expected disturbance regime must be defined before ecosystem condition can be assessed. Using the analogy of human health to illustrate the importance of disturbance history, a doctor working in the infectious diseases ward of a hospital in Alberta, Canada would be expected to have an extremely robust immune system. The same doctor, however, may succumb to heat exhaustion following only a brief walk in the Sonoran Desert of Mexico. Similarly, a Mojave desert system which has evolved to resist and recover from drought may collapse when subjected off-road vehicle traffic.

Even in cases in which the system has evolved in response to a particular type of disturbance, changes in the timing, intensity, frequency, can yield significant differences in relative ecosystem condition relative to the new disturbance regime. For example, Chihuahuan desert rangelands appear to be much more resistant to winter than to summer grazing and least resistant to grazing immediately following drought.

### Timing of Measurements

The time of year when measurements are to be made should be chosen during the indicator selection process. Where possible, measurements should be made during a period when (1) the indicator is relatively stable, and (2) the indicator best reflects ecosystem status within the context of long-term trends in ecosystem condition.

## STAGE III: INTEGRATION OF MEASUREMENTS, INDICATORS, AND FUNCTIONS FOR ASSESSMENT OF ECOLOGICAL CONDITION

Very few ecosystem functions can be assessed using only one indicator. We have adopted a relatively simple, flexible system for integrating indicators. The process is similar to that used by Karlen *et al.* (1994) for the evaluation of cropland soil quality. The following steps are involved: (1) conversion of each indicator value to a standard score (Figure 1), (2) assignment of weights to each factor at each level, and (3) combination of scores to yield an integrated index for each ecosystem function (Table 1).

### Conversions of Factor Values to Scores

The value for each factor is scored on a scale of 0 to 1 based on a scoring function, with scores of 0 and 1 signifying poor and excellent, respectively. Most factors follow one of the standard scoring functions illustrated in Figure 1; however many other scoring functions are possible.

Selection of scoring functions should ultimately be based on calibration from field data. However, few data are available which can be used to directly calibrate indicators against current ecosystem function and even fewer studies have yielded quantita-

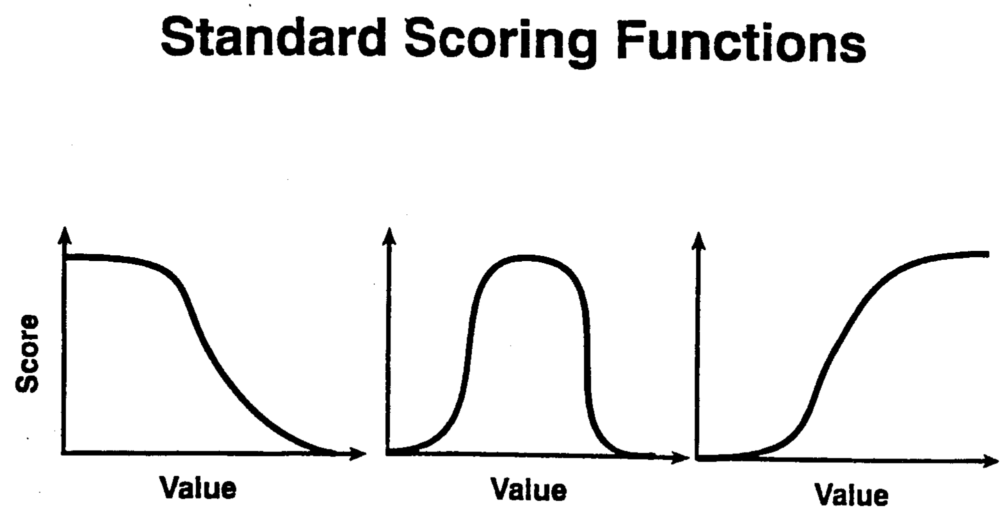


Figure 1. Sample standard scoring functions for converting indicator values (from data) to a score between 0 and 1. Other curve shapes are possible. To determine a score, locate the value on the x-axis and locate the corresponding coordinate to the line on the y-axis.

**Table 1. System for combining indicators into scores for individual functions and function scores into a single condition rating. Note that the condition score should always be reported with the contributing function scores. See text description of Stage III and Stage IV for more detail.**

STAGE III ——————————> STAGE IV ——————>

| Indicator Name | Value | $\text{Score}_i{}^1$ (0-1) | $\text{Weight}_i$ (0-1) | Function Name | $\text{Score}_j{}^2$ (0-1) | $\text{Weight}_j$ (0-1) | Condition Score$^3$ (0-1) |
|---|---|---|---|---|---|---|---|
| a | 30 | 0.8 | 0.5 | | | | |
| b | 2 | 1.0 | 0.2 | | | | |
| c | 5 | 0.7 | 0.1 | | | | |
| d | 12 | 0.8 | 0.3 | A | 0.81 | 0.6 | |
| a | 30 | 0.4 | 0.5 | | | | |
| e | 342 | 0.2 | 0.5 | B | 0.21 | 0.2 | |
| f | 65 | 0.9 | 1 | C | 0.90 | 0.2 | 0.71 |

$^1$Indicator score: from standard scoring functions

$^2$Function score: $\Sigma[(\text{Indicator score})_i * (\text{Indicator weight})_i]$

$^3$Condition score: $\Sigma[(\text{Function score})_j * (\text{Function weight})_j]$

tive relationships between indicators and ecosystem resistance and resilience. The most comprehensive literature in this area is related to the development of erosion and erosion-productivity models such as the USLE (Universal Soil Loss Equation), RUSLE (Revised Universal Soil Loss Equation), EUROSEM (European Soil Erosion Model), MEDALUS (Mediterranean Desertification and Land Use), and WEPP (Water Erosion Prediction Project) (Nearing *et al.* 1994). However, these models were designed primarily for use on croplands and/or involve measurements which are not cost-effective for large-scale monitoring programs. More process-level studies are needed to quantify indicator-ecosystem function relationships.

In the absence of these studies, however, scoring functions can be selected by groups of experts for each function. As more information becomes available, the scoring functions can be revised retroactively in the computer database and reports on ecosystem condition trends modified accordingly. The potential for abuse of this system clearly exists and the revision process would need to be documented and subjected to independent peer-review.

### Assignments of Weights

After the values of each factor have been scored, the factors (measurements or indicators) must be assigned a relative weight with the sum of the weights for each function set equal to one. The approach used is similar to that applied to scoring functions and is subject to the same limitations.

### Combination of Scores

The scores are combined by summing the product of the score for each factor with its respective weight, yielding a new score ranging from 0 to 1. For example, in Table 1, the score for function A is simply the sum of the individual products of the scores and weights for indicators a, b, c, and d. Individual indicators can be used to assess more than one function, as illustrated in Table 1 for indicator a, which is used to calculate scores for both functions A and B.

## STAGE IV: COMBINATION OF SELECTED ECOSYSTEM FUNCTIONS

Stage IV is very similar to stage III except that the scores are based on combinations of function scores (from Stage III) and the weights are based on current and anticipated future societal values. When reporting ecological condition ratings based on combinations of function scores, the component function scores should also be reported in order to facilitate interpretation of the composite rating. The advantage of this system is that it is simple and flexible enough to be used to facilitate more objective discussion by policy-makers, managers and the general public on what actually constitutes "good" or "poor" ecological condition. Selecting ecosystem functions and assigning weights to those functions can help identify areas of consensus as well as areas in which trade-offs might be made.

## CASE STUDY

The following case study is based on preliminary data from the USDA-ARS Jornada Experimental Range and the Chihuahuan Desert Rangeland Research Center. Both are located in the northern Chihuahuan Desert in southern New Mexico, USA. This study is incomplete and is presented only to illustrate the points discussed above. A more comprehensive analysis of a complete set of indicators and a more thorough presentation of this approach will be presented in forthcoming publications.

For the purposes of this paper, we have selected three important functions which rangelands perform. The first is their capacity to conserve soil and water resources. The second is their capacity to provide forage for animal production. The third is their capacity to conserve biodiversity. These three functions were selected because of the relatively high value which various sectors of society place on each. Each function is discussed in the context of an arid rangeland system in the Chihuahuan Desert where annual precipitation averages 225 mm/yr. The sensitivity of selected indicators is illustrated with a comparison of average values at each of three pairs of relatively undisturbed (lightly to moderately grazed grassland) and heavily disturbed (areas around watering points) sites.

### Function 1: Conservation of Soil & Water Resources

#### Indicators

Water may be lost from the system through runoff, evapotranspiration, and drainage beyond the rooting zone. The latter rarely occurs. Runoff then is the primary cause of non-evapotranspirative water losses. Soil can be lost or redistributed through both water (runoff) and wind erosion. However, wind and water redistribute soil fractions differently. Nutrients may be lost through either type of erosion and, rarely, leaching beyond the rooting zone. Increased mineralization of soil organic matter associated with breakdown in soil structure can also significantly deplete soil nutrient storage (for nitrogen) and nutrient retention capacity (for cations). Other processes may be important for specific limiting nutrients, such as denitrification for nitrogen and fixation for phosphorus. For most arid and semi-arid rangeland ecosystems, however, increases in losses of soil, water and nutrients are associated with increased runoff due to reductions in the rate of water movement into the soil (infiltration capacity) and the amount of time water remains ponded on the surface (flow rates). Flow rates, in turn are a function of both slope, which is recorded as a semi-permanent site characteristic, and the surface roughness and density of obstructions to runoff, including plant bases, large debris, and litter accumulations.

The following indicators are among those which may be used to assess infiltration capacity and runoff under natural rainfall, which is too expensive to measure directly: total plant cover, long-lived grass cover, average length of bare patches (parallel to slope), soil surface stability (using slake test (Whitford *et al.* in preparation)). Soil texture (by hand) is recorded as a site characteristic. Additional indicators currently under consideration are listed in Table 2. All of the measurements necessary for these indica-

**Table 2. List of possible indicators for three functions which rangeland ecosystems perform. The list is not exhaustive and evaluation is in progress for many of the indicators listed below.**

ECOSYSTEM FUNCTION: Conservation of soil and water resources
    Long-lived grass cover
    Total plant cover
    Mean length of bare soil patches
    Soil stability (field slake test)
    Cryptogamic crust cover
    Legume cover (potential nitrogen fixers)
    Size and spatial distribution of litter patches, root density, and depth (based on species composition and cover)
    Soil texture
    Clay % ratio (vegetated/bare)
    Infiltration capacity
    Penetrometer resistance
    Rill density and morphology
    Soil aggregate stability
ECOSYSTEM FUNCTION: Animal production
    Palatable vegetation index
    Forage value index
    Soil productivity index
    Toxic species cover (extent and duration)
ECOSYSTEM FUNCTION: Biodiversity conservation
    Native grass cover
    Species richness (limited value)
    Landscape diversity, structure, and connectivity of patches
    Invasive species cover

tors can be made with relatively little training and the only tools required are a measuring tape and a small compartmentalized box to hold water for the slake test. This permits evaluation of remote sites not accessible by car. For sites with road access, simple single-ring and other infiltration tests (e.g. Dobrowlowski 1994) can be performed. We have also developed a simple, inexpensive soil penetrometer to quantify the level of soil compaction (Herrick *et al.* in preparation)). At the highest level of effort, soil samples can be returned to the laboratory for determination of bulk density and organic matter content, and more precise measurements of texture. Ratios and the magnitude of variation of selected parameters may also serve as useful indicators (Herrick and Whitford 1995). For example, the extent of resource redistribution which has occurred within a system is indicated by the ratio of clay and/or soil organic matter content under vegetation and in bare areas.

### Comparisons for Selected Indicators

Of the four indicators displayed, basal cover of long-lived grasses proved to be the most sensitive (Figure 2). It is also a relatively important indicator for integrating inter-annual variability in this system. While the cover of all plant species and, correspondingly, mean bare patch length, vary widely with annual precipitation, the cover of long-lived grasses tends to be somewhat more stable. The relatively small difference in soil stability was due to the insensitivity of the measurement system. The measurement system has been revised since this dataset was collected.

### Timing of Measurements

Variability in rangeland soil erosion may be greater within-years than between-years due to seasonal changes in climate, vegetation and litter structure and cover, and the physical characteristics of the soil

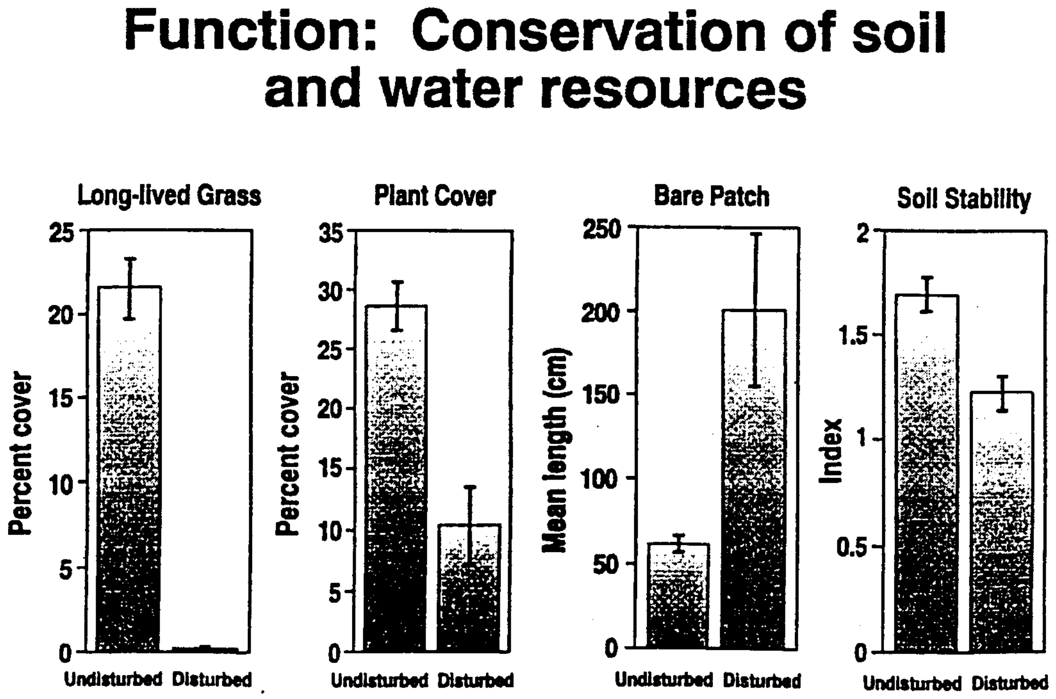


Figure 2. Values for indicators related to the function of conservation of soil and water resources (n = 3 sites; ±1 S.E.).

surface (Blackburn and Pierson, 1994). If measurements can be made at only one time during the year, we suggest that they be made immediately prior to, or at the beginning of, the period the system is most susceptible to resource loss. An indication of when this period occurs may be obtained by examining records of sediment loads in local streams and rivers.

## Function 2: Animal Production

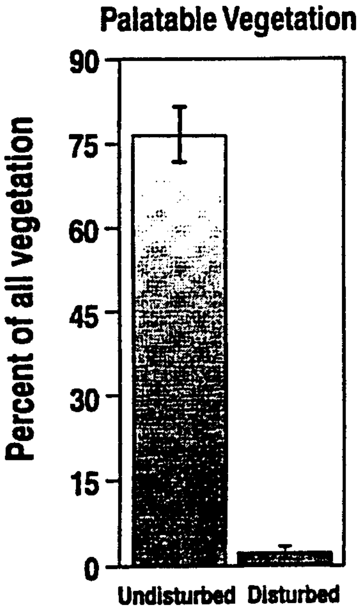
### Indicators

The value of an area for animal production depends on the quantity, nutritive value, and palatability of the vegetation at different times of the year. We plan to use a forage value index which combines these three elements (Figure 3). Depending on the availability of soils data, a soil productivity index can be used to dampen interannual fluctuations associated with precipitation. Animal production in the Chihuahuan Desert is currently dominated by cattle raised for beef consumption. Changes in the animal products expected from the land could require the substitution of different indicators, or the assignment of different weights to existing indicators.

### Comparisons for Selected Indicators

The proportion of all vegetation which is palatable to cattle at some time during the year (not including mesquite pods and yucca flowers which provide relatively little value per unit area covered) was reduced to near zero in the highly disturbed sites (Figure 3). This corresponds with, but is not identical to, the percent cover of long-lived grass used to assess the function of resource conservation described above, and illustrates how the indicators used for different functions are often based on the same measurements, but are interpreted in slightly different ways.

**Function: Animal production**



**Additional Indicators**

- **Soil Productivity Index**
- **Index of Palatability**

**= $\sum_{sp=1}^{s}$ [% cover * (months useable/12) * palatability rating]**

- **Index of Forage Value**

**= $\Sigma$[% cover * Index of palatability * nutritive value * biomass rating]**

Figure 3. Values for indicators related to the function of animal production (n = 3 sites; ±1 S.E.).

## Function 3: Biodiversity Conservation

### Indicators

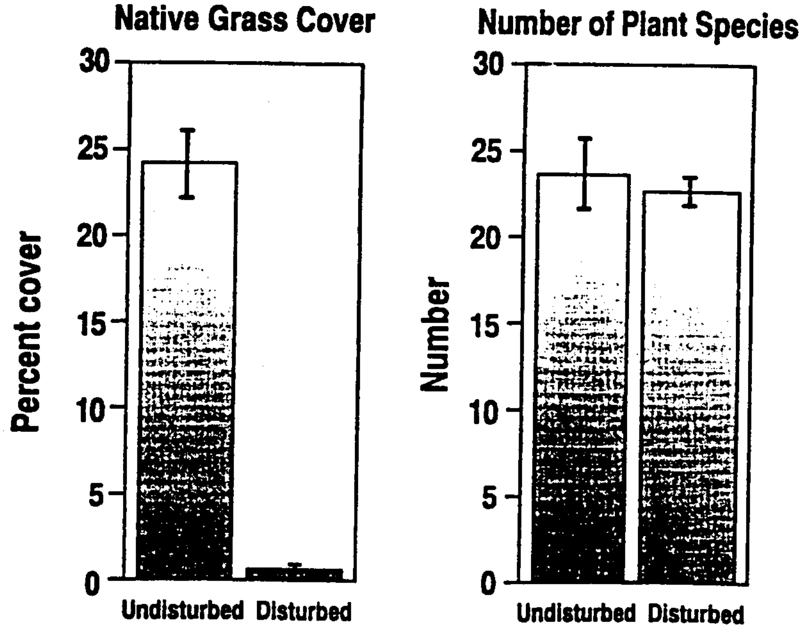
The function of biodiversity conservation is perhaps one of the most difficult to evaluate. Simple species counts and simple diversity indices are useful only as starting points. They cannot be consistently related to ecological condition because high plot species diversity frequently indicates a system in decline due to the increase in diversity associated with the invasion of exotics and disturbance-tolerant species. Diversity may be highest when the system is in an unstable transition state between two or more plant communities. Long-term studies of bird communities in the Chihuahuan Desert show highest diversity on disturbed sites with heterogeneous vegetation and lowest diversity on relatively undisturbed sites with homogenous vegetation (Whitford *et al.* unpublished data). In a related study, ant communities provided no reliably interpretable patterns of composition or diversity over a wide range of disturbances (Whitford *et al.* unpublished data).

Furthermore, many species are difficult, if not impossible, to census. Consequently, indicators of long-term trends in the biodiversity of all taxa are more important than indicators based on point-in-time counts. An example is the percent cover of aggressive exotic species which have the potential to outcompete natives. Finally, in order to assess current and potential long-term patterns in biodiversity, data from plot-level studies should be interpreted, where possible, at the landscape level. This is important both to incorporate the effects of landscape heterogeneity (Forman and Godron 1986) and to predict potential future extinctions based on patch size and edge effects.

### Comparisons for Selected Indicators

Native grass cover (Figure 4) was selected for illustration because of its relative sensitivity to disturbance and because it again illustrates the congruence between some indicators for different functions (long-lived grass cover for resource conservation and palatable vegetation for animal production). The num-

**Function: Biodiversity**



**Additional Indicators**

- **Structural diversity**
- **Invasive species**

Figure 4. Values for indicators related to the function of biodiversity conservation. Note that number of plant species is not generally a good indicator (see discussion in text) (n = 3 sites; ±1 S.E.).

ber of plant species clearly says little about the status of the system. The disturbed site is dominated by disturbance-tolerant annuals and invasive shrubs, while the relatively undisturbed site has a higher proportion of native perennials.

### Combination of Indicators

The procedure for combining the indicators follows Table 1. We are currently in the process of developing scoring functions and weights for these indicators.

## APPLICATION TO OTHER ECOSYSTEMS

The four-stage approach to indicator selection and integration described above is equally applicable to forest and agricultural ecosystems. In most cases, however, indicators will need to be changed or adapted for each system, even when the ecosystems perform similar functions. For example, both forest and rangelands are expected to perform many similar functions, and many of the indicators described above for rangelands would also be expected to apply to forests. However, some of the indicators, such as structural diversity, would need to be modified and applied at a different scale, while others, such as perennial grass cover, would be less relevant for mature forested systems.

## LITERATURE CITED

Blackburn, W. H., and F. B. Pierson Jr. 1994. Sources of variation in interrill erosion on rangelands. In: Variability in rangeland water erosion processes. W. H. Blackburn, F. B. Pierson Jr., G. E. Schuman, and R. Zartman, eds. Soil Science Society of America, Madison, Wisconsin, pp. 1-10.

Dobrowolski, J. P. 1994. In situ estimation of effective hydraulic conductivity to improve erosion modeling for rangeland condition. W. H. Blackburn, F. B. Pierson Jr., G. E. Schuman, and R. Zartman, eds. Soil Science Society of America, Madison, Wisconsin, pp. 83-92.

Herrick, J. E., and W. W. Whitford. 1995. Assessing the quality of rangeland soils: challenges and opportunities. *Journal of Soil and Water Conservation* 50: 237-242.

Karlen, D. L., N. C. Wollenhaupt, D. C. Erbach, E. C. Berry, J. B. Swan, N. S. Eash, and J. L. Jordan. 1994. Long-term tillage effects on soil quality. *Soil Tillage Research* 31: 149-167.

Klinkenborg, V. 1995. Good news in the badlands: ranchers greens and feds save a wide open space. *Audubon* 97 (5): 34-47.

Nearing, M. A., L. J. Lane, and V. L. Lopes. 1995. Modeling soil erosion. In *Soil erosion research methods*, 2d ed. R. Lal. St. Lucie Press, Delray Beach, Florida, 127-156.

Watters, S. E., M. A. Weltz, and E. L. Smith. *In press.* Evaluation of a site conservation rating system to describe soil erosion potential on rangelands. *Journal of Range Management*.