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INTEGRATION OF SOIL INDICATORS INTO MULTI-ATTRIBUTE RANGELAND MONITORING AND ASSESSMENT SYSTEMS

Jeffrey E. Herrick* and Kris M. Havstad

USDA-ARS
Jornada Experimental Range
MSC 3JER, NMSU, Box 30003
Las Cruces, NM 88003-8003
e-mail: jherrick@nmsu.edu and khavstad@nmsu.edu

*All correspondence to Herrick

ABSTRACT

Rangeland health and soil quality are frequently defined in terms of the capacity of the land to conserve soil and water resources, cycle nutrients and support productive plant communities. Rangeland monitoring programs in most countries have traditionally focussed, almost exclusively, on plant community composition. An implicit assumption is that other properties and processes are correlated with vegetation, so measurements are unnecessary. In many cases, however, soil degradation or improvement can occur in the absence of easily detectable vegetation changes until a threshold is crossed resulting in dramatic and frequently irreversible changes in plant community composition. We suggest that easily-measured soil properties can serve as early-warning indicators of potential transitions between vegetation states in rangeland ecosystems. These indicators and associated vegetation measurements are by no means universal. Both the selections of quantitative indicators, and the identification of appropriate monitoring points, depend on monitoring objectives and resource availability. Rapid, qualitative indicators can aid in the design of a quantitative monitoring program. They can also be applied together with quantitative indicators to aid interpretation. We describe how quantitative and qualitative soil and vegetation indicators can be used together to monitor rangeland health.

KEYWORDS: rangeland health; soil quality; monitoring; assessment; thresholds; soil and water conservation

1 Introduction

Rangeland monitoring efforts have traditionally focussed on plant community composition and cover. Monitoring efforts were often designed to address one land use: livestock production. An implicit assumption has been that changes in soil condition are correlated with, if not preceded by, changes in plant community composition. This assumption is based on few data, and was recently questioned in a report sponsored by the New Mexico Range Improvement Task Force which concluded that, "If one agrees that a variety of current and potential plant communities can occur above a conservation threshold for a particular ecological site, then monitoring vegetation has to take a backseat to monitoring soils" (West et al., 1994).

In effect, a reduction in the capacity of the soil to provide water and nutrients to plants, and plant propagules may increase the risk that the plant community will fail to recover from the next catastrophic disturbance. The impacts of progressive soil degradation may not become apparent for decades. Established perennial plants can persist long after the regenerative capacity of the community has diminished, either through the loss of suitable microsites for seedling establishment or through reduced seed production and/or vegetative reproduction. Erosion models show that soil loss is positively correlated with bare soil. Consequently, soil degradation can following defoliation, particularly when the soil surface is disturbed and the defoliation occurs during or immediately prior to a period of intense winds (Belnap and Gillette, 1998) or rains (Greene et al., 1994). Many rangeland soils are particularly susceptible to soil erosion due to the concentration of soil organic matter near the soil surface. Other degradation processes are difficult to detect from vegetation data. Salinization of irrigated pastures can occur with little effect on existing plants long after seedling establishment has been affected. Similarly, subsurface compaction can increase in many soils before threshold conditions are reached for root growth and soil biotic activity.

Most of the emphasis in monitoring is on degradation. Soils also provide early indications that a site is recovering. Soil quality can improve under a "degraded" plant community until threshold conditions are reached for the establishment of more desirable plants. This improvement is associated with an improvement in plant vigor, suggesting that a plant-based indicator could still be applied. However, relevant differences in plant vigor are frequently obscured by variability associated with precipitation differences in many arid and semi-arid rangeland ecosystems.

In summary, soil indicators of rangeland health can provide additional information on current and potential future condition. Some may directly reflect changes in the capacity of the system to conserve soil and water resources, while serving as early-warning indicators of changes in the plant community.

2 Soil properties and processes as potential early-warning indicators

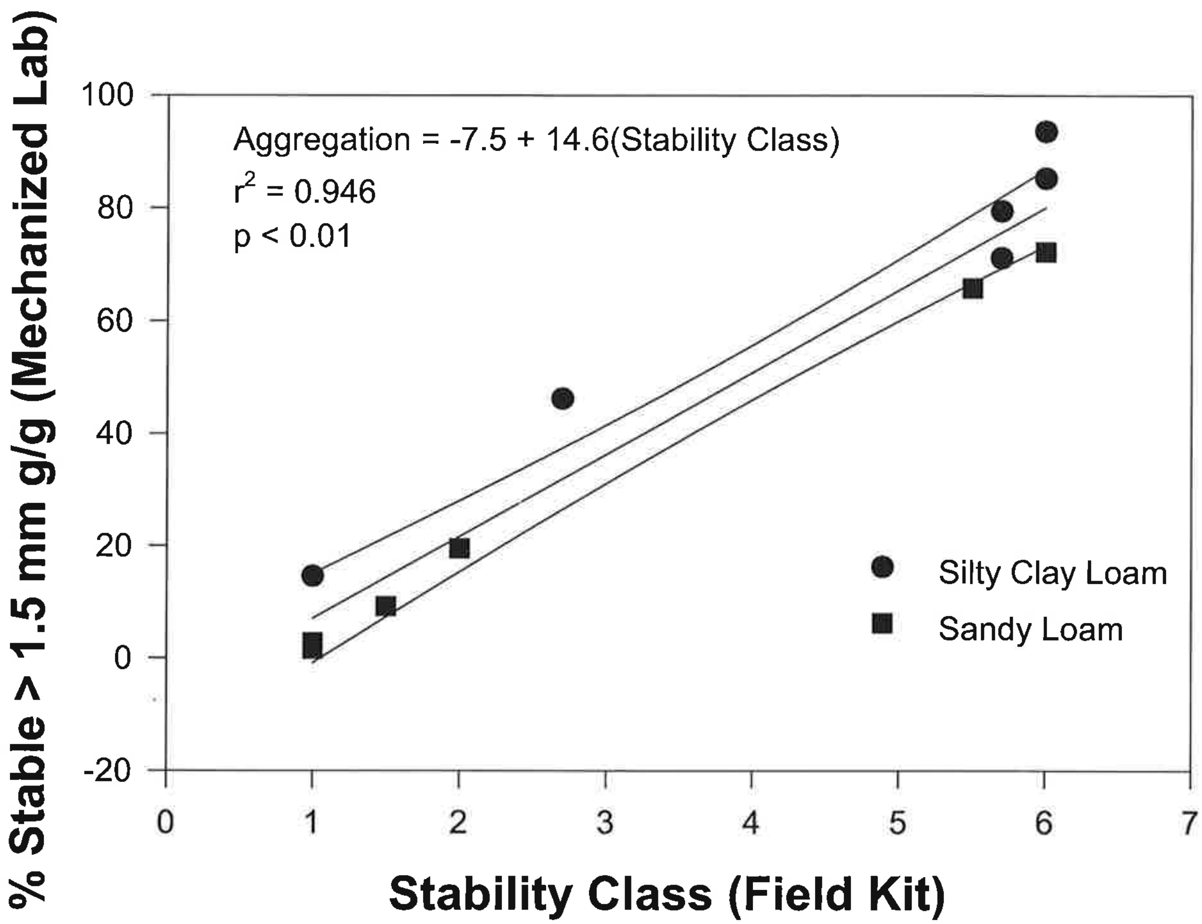
There are two basic types of early-warning indicators: input and output. Input indicators reflect the conditions necessary for soil processes to occur. For example, organic matter inputs are necessary for decomposition and mineralization processes. These types of indicators are tend to be less temporally variable and relatively easy to measure. However, they are based on assumptions about what is necessary for a process to occur, but do not acknowledge that another factor may be limiting.

Output indicators are indicators which reflect the results of soil processes. Soil aggregation is an output indicator which integrates organic matter inputs with biotic and abiotic processes. Some indicators can be either input or output indicators, depending on the context. Soil microbial biomass is an output indicator which integrates the quality and quantity of organic matter inputs together with environmental conditions over time. However, it is also an input indicator relative to microbial respiration. The advantage of output indicators is that they reflect processes which actually occurred in the past, and therefore the potential for the future. In theory, a combination of input and output indicators should provide the best predictor, or early warning indicator, of the sustainability of the system through multiple catastrophic disturbances.

There are very few studies which have directly addressed the use of soil properties and processes as integrative, early-warning indicators of potential degradation or recovery. However, there is a relatively large body of ecological research which may be used to point to potential indicators. The best indicators would reflect properties or processes which are limiting when the system is at or near a threshold. Unfortunately, relatively little is known about which processes are limiting, even in extensively studied systems. For example, the United States Environmental Protection Agency (EPA) is now re-evaluating its analysis procedures after spending millions of dollars on phosphorus research and on prevention and mitigation of agricultural runoff into the Everglades in Florida (Kaiser, 1999). It is now understood that while phosphorus plays a role, it is actually human-induced changes in hydrology which were primarily responsible for changes in the ecosystem. The agency blames "blinders". Similar blinders are cited by Hammer (1998) in an article critiquing much of the ecological literature for misinterpretations of data due to insufficient knowledge or understanding of the soils on which the studies were conducted.

Notwithstanding these limitations, there are clearly some opportunities to develop indicators which have some predictive power, including the presence of suitable microsites for plant establishment (Grime, 1977), changes in the spatial and temporal availability of plant resources (Rietkerk and van de Koppel, 1997), and changes in the processes necessary for nutrient cycling and energy flow. Most of the studies on microsites are descriptive and relatively few have addressed the processes which generate and maintain these sites. Temporal changes in the availability of resources, such as plant nutrients, can increase the "leakiness" of the system if nutrients become available when plants and/or microbes are unable to absorb them. In many parts of the world, changes in the spatial distribution of nutrients in water are used as key indicators of degradation and recovery. In the Chihuahuan Desert, an increase spatial variability, and in the size of nutrient-enriched patches, is associated with degradation (Schlesinger et al., 1990), while in Australia, an increase in heterogeneity is required to initiate recovery (Ludwig and Tongway, 1995).

Processes associated with nutrient cycling and energy flow have been the subjects of a number of studies initiated during the past decade. Properties cited include total soil organic matter (SOM), soil microbial biomass, other specific soil organic matter fractions, and aggregate stability. Total SOM is generally regarded as a good indicator of long-term changes in soil quality (Doran and Parkin, 1994). However, SOM changes too slowly to be a used as a sensitive indicator of shorter-term change in most cases. Conversely, soil microbial biomass is extremely sensitive to changes in environmental conditions. Its high sensitivity to annual differences in weather and organic matter inputs make it a difficult indicator to interpret on a routine basis, although it is frequently cited as a useful research tool where multiple measurements can be made over time. Based on theoretical and practical considerations, non-living soil organic matter fractions would appear to have the greatest potential as early warning indicators. These fractions can be directly related to specific processes, such as aggregation and nutrient cycling, and unlike indices based on specific soil organisms, there are few sample-handling requirements. Furthermore, the skills required for analysis are widely available. Wright and Upadhyaya (1998) have been exploring the potential of glomalin, a material associated with soil fungi, to serve as an indicator. Early tests indicated that it has high potential, as it was both sensitive to management and correlated to changes in aggregate stability (Wright and Upadhyaya, 1998). However, more recent studies indicate that these relationships may not hold in all systems (Franzluebbers et al., 2000). The "light", or low-density, soil organic matter fraction is also frequently cited because of its sensitivity to management changes (Cambardella and Elliott, 1992). Aggregate stability is an attractive indicator because it is directly related to the susceptibility of the soil to physical crusting and erosion, water holding capacity, and is highly correlated with active soil organic matter in most systems. However, widespread adoption of aggregate stability as an indicator has been limited by difficulties in generating consistent results. In rangelands, sampling and sample transport are further complicated by the fact that the most relevant part of the soil profile for many processes is the top few millimeters. These problems have been partially addressed through the development of field kits (e.g. Herrick et al., 2000). Laboratory tests have shown that these field kits, which generate an index of stability between one and six, are correlated with the percent water stable aggregates larger than 1.5mm (Fig. 1).



3 Incorporation of soil indicators into assessment

The interdependence of soil and vegetation patterns and processes, and the particular importance of soil and site stability, are emphasized in the National Research Council's 1994 report on rangeland health (National Research Council, 1994) and are reflected in the structure of several recently developed assessment and monitoring protocols.

The United States Natural Resource Conservation Service (NRCS) and Bureau of Land Management (BLM), together with scientists from the United States Geological Survey's Biological Research Division (USGS-BRD), the Agricultural Research Service (ARS), and representatives from the Forest Service (USFS) have developed a qualitative evaluation tool based on qualitative assessments. The current (August, 1999) draft of the technical reference, "Interpreting Indicators of Rangeland Health" includes 17 indicators. Each of the indicators applies to one or more of three attributes of rangeland health: soil and site stability, hydrologic function, and biotic integrity (Table 1). The first 11 of the 17 indicators are based on either soil processes, or on processes, such as water flow patterns, which are significantly affected by soil surface characteristics. Although this protocol focuses on the soil surface, sub-surface processes and properties are addressed in indicators 9 (Soil Loss) and 11 (Compaction Layer). The system was developed in arid and semi-arid rangelands in the western United States and is being adapted for use in more humid areas. For example, indicator 9 (soil loss) includes both soil erosion, and non-erosional degradation of the soil profile to the extent that a horizon (generally A or O) is partially or completely lost.

Table 1. Application of qualitative indicators to three attributes of rangeland health. The list of indicators and the three attributes are based on an August, 1999 draft technical reference, "Interpreting Indicators of Rangeland Health". An earlier draft of this protocol was published in the Pasture and Range Handbook (Natural Resource Conservation Service, 1997).

Indicators	Soil/Site Stability	Hydrologic Function	Biotic Integrity
1. Rills	X	X	
2. Water Flow Patterns	X	X	
3. Pedestals and/or Terracettes	X	X	
4. Bare Ground	X	X	
5. Gullies	X	X	
6. Wind Scoured Areas	X		
7. Litter Movement		X	
8. Soil Surface Resistance to Erosion	X	X	
9. Soil Loss	X	X	
10. Plant Community Composition and Distribution Relative to Infiltration & Runoff	X	X	
11. Compaction Layer	X	X	
12. Plant Functional/Structural Groups			X
13. Plant Mortality/Decadence			X
14. Litter Amount		X	X
15. Annual Production			X
16. Noxious & Invasive Plants			X
17. Perennial Plant Reproductive Capability			X

4 Incorporation of soil indicators into monitoring

A flexible monitoring protocol developed by scientists at the USDA-ARS Jornada Experimental Range incorporates soil indicators at both the design and implementation stages. The protocol is designed to be adapted to suit a variety of monitoring objectives. The level of precision (a function of the sampling intensity within a site and the number of sites sampled) can also vary depending on objectives and time constraints. The design phase begins with the definition of objectives: monitoring for risk, recovery or inventory. The land area is then stratified into relatively uniform monitoring units based on soil-geomorphic-vegetation patterns and current and historic management. Each upland monitoring unit or type of monitoring unit is visited and qualitatively rated with respect to the three rangeland health attributes: soil and site stability, hydrologic function and biotic integrity. Riparian units are similarly evaluated based on 17 items in three categories: hydrology, vegetation, and erosion/deposition. A rating of "Proper functioning condition, "Functioning – at risk" and "non-functioning" is applied. (This protocol should not be confused with the riparian assessment process used in the United States as developed by an interagency task force and commonly labeled "Proper Functioning Condition".) A subset of the sites is then selected for monitoring based on the objectives and the current condition of each monitoring unit.

4.1 Basic measurements.

In addition to photo points, there are three measurements which are strongly recommended for all sites, three which are applied depending on site characteristics and time availability, and three which are specific to riparian systems (Table 2). A variety of indicators are calculated from each of the nine measurements and applied to the appropriate criteria (examples for line-point in Table 3).

The core set of measurements includes a line point intercept, a limited continuous line intercept, and a soil surface stability test. The line point intercept is used to quantify plant cover and composition and soil cover, including rocks, lichens, mosses, and plant litter. This method was selected because it balances repeatability and speed and is readily interpretable. However, this method does not provide any information on the spatial distribution of the plants and intercanopy spaces which have the potential to develop into erosion cells and/or colonization sites for invasive plants. A continuous line intercept is used to quantify the area covered by gaps larger than a minimum diameter (e.g. 15 cm). Vegetation is not recorded by species as this information is already collected using the line point intercept, making this measurement relatively rapid. A soil surface stability test, which is essentially a modified slake test, is used to evaluate the stability in water of soil macroaggregates larger than 1.5 mm. Small (6 x 6 x 3 mm) soil fragments are rated on a scale from one to six based on slaking behavior and the amount of sample remaining on the screen following five minutes of immersion and five dipping cycles. The measurements are completed in the field. Eighteen samples can be evaluated consecutively over a period of 10 minutes. Statistically significant differences ($p < 0.05$) of 0.5 units can usually be detected with this 10-minute test (unpubl. data).

Table 2. List of measurements included in the quantitative monitoring system and the rangeland health attributes to which each applies.

Measurement	Soil & Site Stability	Hydro-logic Function	Biotic Integrity
BASIC			
1. Photo points	X	X	X
2. Line point intercept	X	X	X
3. Continuous line intercept (minimum 10cm between canopy elements (live or dead))	X	X	X
4. Soil stability test	X	X	X
OPTIONAL			
5. Species richness			X
6. Impact penetrometer		X	
7. Single-ring infiltration		X	
RIPARIAN			
8. Channel profile		X	
9. Channel veg. survey ('Green Line')		X	X
10. Woody seedlings			X

Table 3. Indicators calculated from the line-point intercept data and the rangeland health attributes to which they apply.

Indicators Calculated from Line-Point Intercept Data	Soil & Site Stability	Hydro. Function	Biotic Integrity
Basic			
Total cover (live canopy, gravel, dead canopy, litter, moss, lichen)	X	X	X
Total live canopy cover	X	X	X
Total basal cover	X	X	X
Optional			
Species resistant to catastrophic disturbances: % cover	X		X
Standing dead vegetation as a proportion of total canopy			X
Invasives: % cover			X
Plant species which retard infiltration: % cover		X	

4.2 Optional measurements.

The protocol includes three optional measurements which are included if the objectives and site conditions justify their use and if resources permit: plant species richness, compaction, and water infiltration. A minimal estimate of species richness can be obtained from the line point data. However, monitoring programs in which the total number of species present on a site is required, or when exotic species invasion is a concern, should include a plot-based method such as that described by Stohlgren et al. (1995).

Compaction is best assessed qualitatively using a combination of soil profile characteristics (e.g. platy structure) and root morphology and distribution. Once an assessment has been made that soil compaction exists, a penetrometer can be used to quantify recovery. The penetrometer can also be used to quantify recovery and to track the development of a compaction layer by comparing relative changes in the resistance of different layers.

Actual rates of water infiltration during natural rainfall are nearly impossible to quantify without the use of runoff plots and/or rainfall simulation studies. However, a relative indication of changes in infiltration capacity can be obtained using cylinder infiltrometers. In rangelands, we have found that the problems associated with cylinder insertion (which tends to shatter the crust) can be minimized by pre-wetting the surface with a wet towel and using aluminum irrigation pipe instead of tubing made from synthetic materials, such as PVC. Most simple methods are based on a falling head in which the time required for 2.5 cm of water to infiltrate into a saturated soil is recorded. We use a simple single chamber mariotte bottle constructed from a single plastic tube and a 1 l (for 12.5 cm cylinders) or 2 l (for 15 cm cylinders) plastic container, such as a commonly available soda bottle.

4.3 Riparian measurements.

Riparian system function is better described by including several additional measurements: channel profile, channel vegetation survey, and woody seedling density. All three of these are based on a more intensive monitoring system developed by Al Winward of the USFS. The channel vegetation survey has been simplified to permit it to be used by personnel who are not trained in plant community classification.

4.4 Applications and future development.

The monitoring system outlined above has been developed over a period of five years and is now described in a draft manual. The manual includes instructions on monitoring program design, including selection of appropriate sites and indicators, and implementation. Parts of the system are now being applied by state and federal land management agencies in the western United States, and by several non-profit conservation organizations in New Mexico. A statewide voluntary monitoring program in Illinois is using the penetrometer and stability kit. The indicators have been shown to be sensitive to management and are currently being tested against more rigorous measurements of different ecosystem functions.

5 Soil quality and rangeland health: a note

There are a number of currently accepted definitions of soil quality and rangeland health. For the purposes of this paper, soil quality is defined as, "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Soil Science Society of America, 1997), while rangeland health is, "the degree to which the integrity of the soil, vegetation, water and air as well as the ecological processes of rangeland ecosystems are balanced and sustained (National Research Council, 1994). In croplands, soil quality is commonly defined solely on the basis of soil properties. In rangelands, it is difficult if not impossible to define soil quality independently of characteristics of the plant community, just as it is impossible to define rangeland health without reference to soils. The traditional concepts of soil productivity, and the concept of similarity of the plant community to some reference community, are implicitly retained in soil quality and rangeland health, but their relative importance is reduced. Both soil quality and rangeland health emphasize the sustainability of critical ecosystem functions on which both the maintenance of plant communities and biomass production depend.

6 Conclusions

Rangeland health evaluations can be improved through the integration of soil indicators. Some of these may serve as early-warning indicators of vegetation change. Resistance to adoption of soil measurements can be reduced by presenting them as part of an integrated, flexible rangeland monitoring system which can be tailored to specific objectives and site conditions. Finally, further research is required to better calibrate these indicators to specific ecosystem functions.

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