Assessing the quality of rangeland soils: Challenges and opportunities

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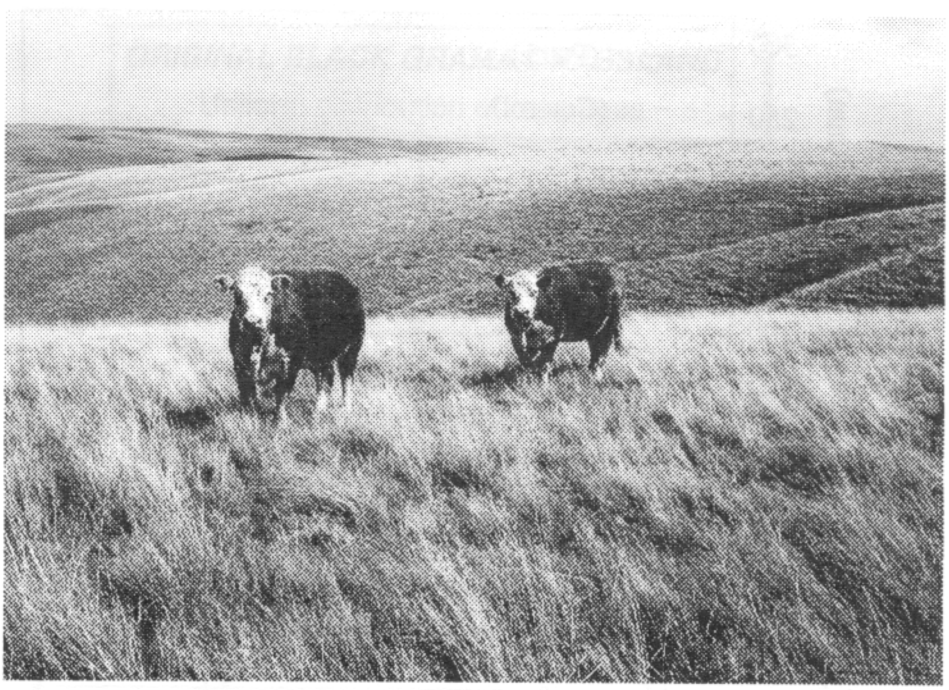

Rangeland soils present unique challenges and opportunities for assessing soil quality. Three characteristics in particular distinguish rangeland soils from cropped soils: (1) spatial variability in rangelands tends to be higher than in cropped systems; (2) temporal variability is high because many biological and physical processes depend on a limited and frequently unpredictable supply of soil moisture; (3) the land often has many uses in addition to food production.

While all three characteristics present obstacles to the development of reliable soil quality indicators, each also presents additional opportunities. Patterns of both spatial and temporal variability can be quantifiable attributes of the system that may provide additional information about soil processes.

Conflicting definitions of soil quality are often implicitly, but not explicitly, based on a particular value or use. These conflicts may be resolved using an alternative paradigm in which soil quality is defined only with respect to the soil's capacity to fulfill clearly defined functions. Ratings for individual functions can then be compared for a variety of values and land uses.

Spatial variability

The spatial variability of many rangeland soil properties is extraordinarily high when compared with typical land under cultivation. This high level of variability occurs at a variety of scales, from regional to microsite.

At the regional level, rangelands may occur on all arable soils, as well as on soils which have little or no potential for crop production. In mountainous and arid regions, this may include land on which little soil development has occurred. On a smaller scale, a single management unit within a region may cover several square kilometers and include a wide variety of landforms and landscape positions spread over more than one watershed. Each unit may include several soil orders. Soil depth and summer soil water potential may vary by several orders of magnitude. The underlying natural variability associated with slope, aspect, and relative landscape position is confounded by a variety of anthropogenic influences. Information on land-use history, which could be used to help separate natural from anthropogenic influences and establish a baseline, is often limited, even on experiment stations.

Within a given landscape unit, it has been shown that soil properties are strongly correlated with shrub distribution in a variety of rangeland ecosystems. (Halvorson et al.; Parker et al.; Virginia and Jarrell). Significant differences in nutrient availability and soil water relations are also associated with animal tracks (Radcliffe), and ant and rodent mounds (Lobry de Bruyn and Conacher; Munson and Whiteford). At a still finer scale, even the decomposition of individual cattle dung patches can generate significant changes in surface hydrology (Herrick and Lal) (Figure 1).

Spatial variability in soil properties is clearly related to differences in soil and ecosystem functions. In many cases, relatively small areas make a large contribution to a particular function. For example, in arid and semi-arid mountainous regions, the majority of palatable biomass production often occurs on deep, well-watered riparian-zone soils. Likewise, a relatively large proportion of resource cycling in

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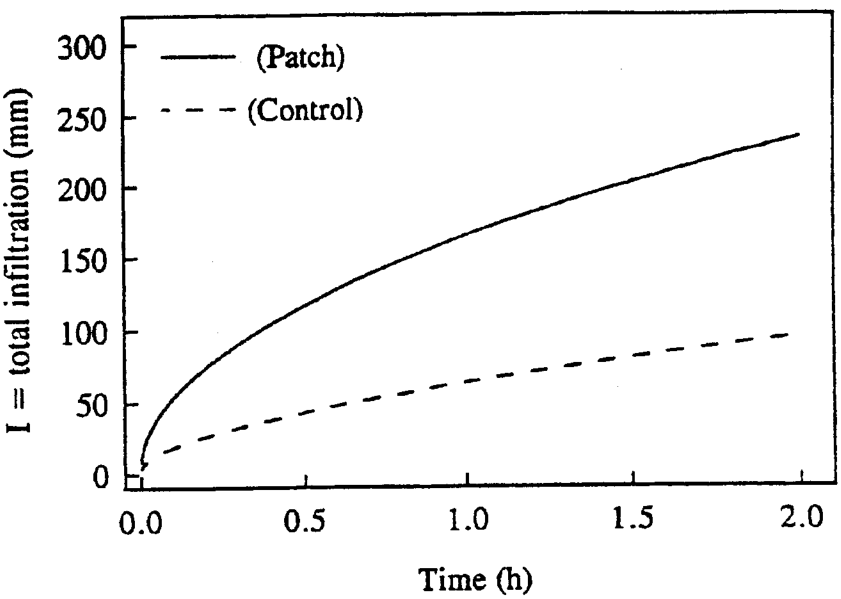


Figure 1. Cumulative infiltration based on double-ring tests compared for control and five month-old cattle dung patch microsites in a Costa Rican pasture (n = 4) (adapted from Herrick and Lal)

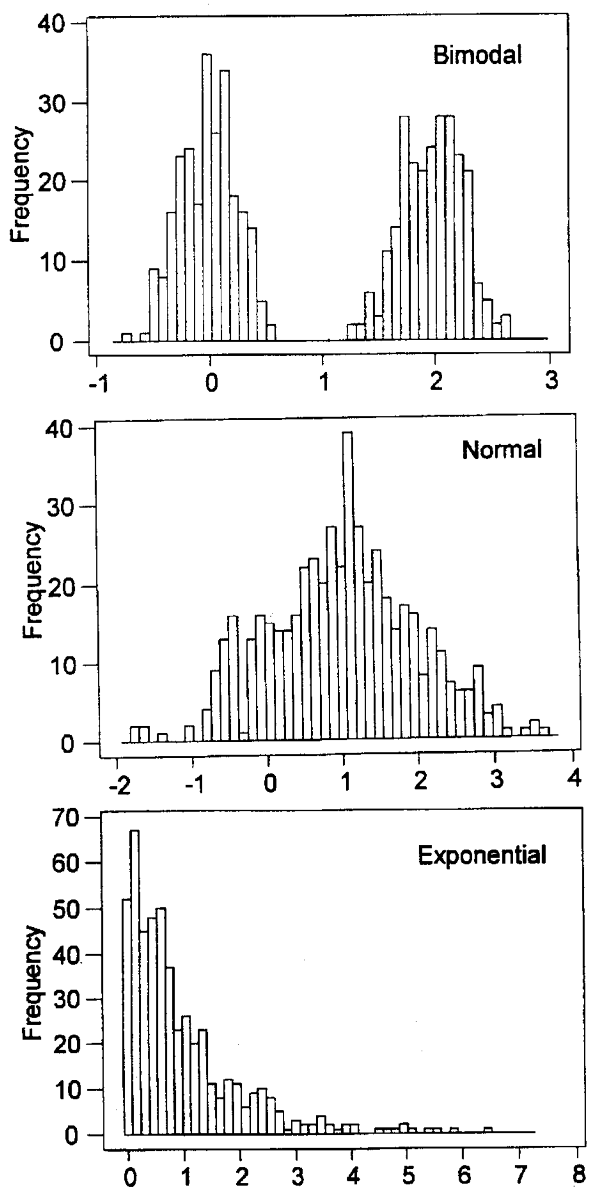


Figure 2. A selection of frequency distributions with mean and standard deviation both equal to one in all cases

shrublands occurs beneath shrub canopies and in the rhizosphere of widely-scattered grass clumps (Schlesinger et al.).

Challenges. A high level of spatial variability clearly presents a problem for sampling. Simple random sampling risks missing small areas that make a large contribution to ecosystem function. Even if these areas are included, a simple average across all landscape units and vegetation microsites may not accurately represent true soil quality at a site. For example, average soil properties could be quite similar for an annual grassland and for a shrubland, due to cancellation of values in shrub and intershrub spaces. Finally, the high level of variance associated with applying a random sampling pattern over a diverse system may make it nearly impossible to detect changes in soil quality without resorting to a level of replication which is beyond the budget of most programs.

Opportunities. While high spatial variability presents a problem for standard sampling and analysis approaches, variance can often be limited by careful stratification. Strata can be nested from the landscape to the microsite. Vegetation patterns and condition, landscape position, topography, parent material, and distance from disturbance foci can all be used at a variety of scales.

Sampling of a stratified design traditionally is based on the relative contributing area of each strata. However, efficiency may be increased by focusing on strata that make the greatest contribution to selected soil functions or are likely to show the greatest change in response to anticipated stressors.

Changes in soil quality in some strata may also indicate changes in other strata. For example, increases in soil depth in a depositional area could indicate increases in erosion rates on slopes above. Recent advances in geographic information systems (GIS) and landscape ecology facilitate identification of strata that are likely to be linked.

In some cases, the soil variability itself may serve as an indicator of how well the soil is performing selected functions. At least three measures of variability might be applied as indicators: (1) the coefficient of variation (CV), (2) ratios between strata, and (3) the scale at which variability occurs.

Coefficient of variation. The coefficient of variation is the ratio of the sample standard deviation to the sample mean expressed as a percentage. It is an indicator of the overall variability of the system. In some low quality sites, in which average resource availability is too low to support desired species, a high CV may indicate that the system is concentrating soil resources, creating favorable microsites for these species. A high CV at a finer scale may indicate that a variety of microsites are available for seedling establishment.

A more detailed analysis might include an examination of the shape of the frequency distribution of the data. A bimodal distribution with the two peaks separated by a relatively short distance could yield a similar CV to a normal distribution with long tails, or an exponential distribution (Figure 2). Each of these distributions suggests different patterns of resource availability.

Ratios between strata. In addition to examining the overall distribution, average values for individual strata may be compared directly. For example, land degradation in the Chihuahuan Desert is associated with increased resource concentration around the bases of shrubs (Whitford and DiMarco). The ratio of shrub vs. shrub interspace soil organic carbon is an indication of the level of degradation. As resource availability declines in the interspaces, grass establishment and survival decline, further reducing the resistance of the system to additional resource concentration beneath the shrubs (Figure 3). In other systems, increased resource concentration associated with tree and shrub invasion is considered to be positive.

Scale of variation. The statistical distribution of values for any given parameter can also be examined spatially. Geostatistics can be used to define the scales at which major changes occur (Halvorson et al.). While variability at the scale of shrub-intershrub spaces may indicate large degraded areas that are more susceptible to further erosion and degradation, variability at a scale of 10 to 50 cm may indicate a relatively stable system where perennials dominate over annuals, creating natural dams that slow the overland flow and allow infiltration to occur. Tongway in Australia and Imeson in Europe, among others, have suggested that the scale and pattern of variation in surface soil characteristics and vegetation provide excellent indicators of the capacity of the system to retain resources. A similar approach was supported in the National Research Council report on rangeland health and is included in continuing work on the WEPP model (Weltz et al.). It is currently under evaluation in a US-EPA project at the USDA-ARS Jornada Experimental Range in New Mexico.

Temporal variability

Temporal variability in rangelands is high and relatively unpredictable. This is largely due to the strong dependence of many physical and biological processes on soil moisture in many rangeland systems. Most temperate rangelands are characterized by low and extremely variable annual precipitation and high summer evaporative demand. As a result, soil moisture is frequently limiting for both plant growth and soil biological activity, particularly during the growing season. When moisture is available, the response of soil organisms and, in turn, their effects on soil properties, depend on species composition and population structure (Figure 4). Species composition and population structure, in turn, depend on soil resource availability during previous seasons. These temporal patterns of biological activity directly affect soil nutrient mineralization and immobilization, aggregate formation and crust stabilization, and pore volume and continuity.

Physical processes in rangeland soils also vary in time as a function of soil moisture content and other factors (Parsons et al.; Warren et al.) (Figure 5). For example, during the winter of 1994, frost heave was relatively insignificant in southern New Mexico due to low surface soil moisture. Consequently, biological crusts remained largely intact. Conversely, precipitation was high during the winter of 1995, shattering the soil crust in many areas.

In addition to the temporal variability in static properties, the capacity of the soil to resist and recover from disturbance also varies in time, depending on the conditions present when the disturbance occurs (Warren et al.). This suggests that sampling timing relative to recent and historic weather patterns, disturbances, and conditions present at the time of disturbance may need to be considered when making a single-point-in-time assessment of soil quality.

Challenges. The challenges associated with sampling at any one particular time are similar to, and potentially greater than, the challenges

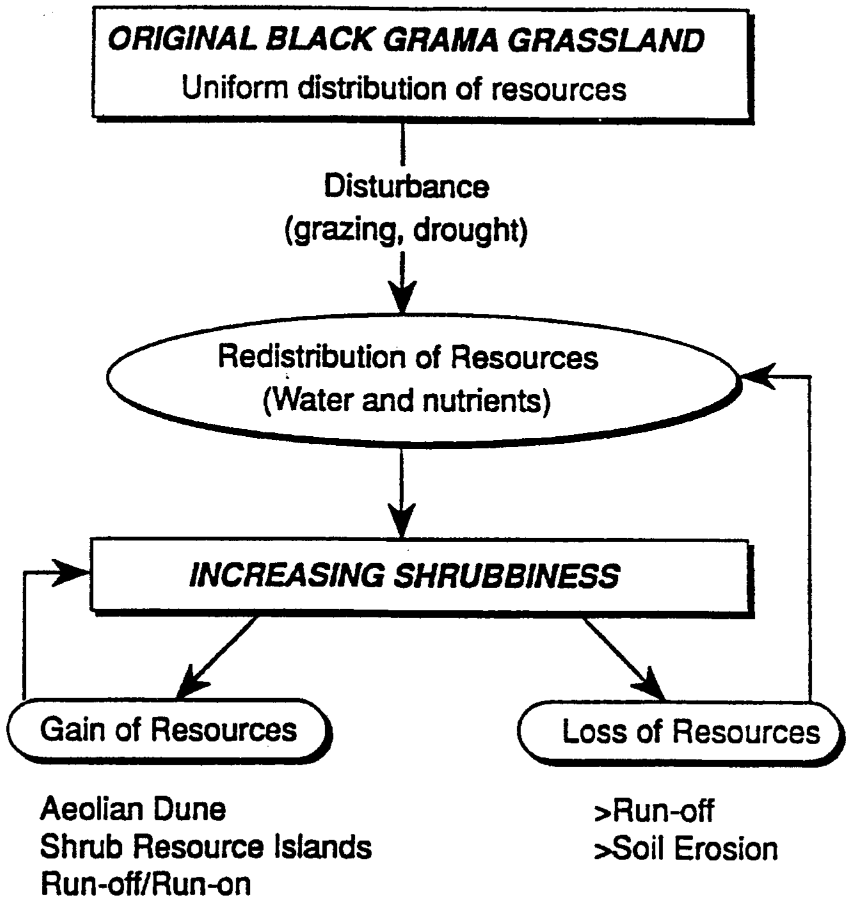


Figure 3. The Jornada model for desertification in the Chihuahuan desert

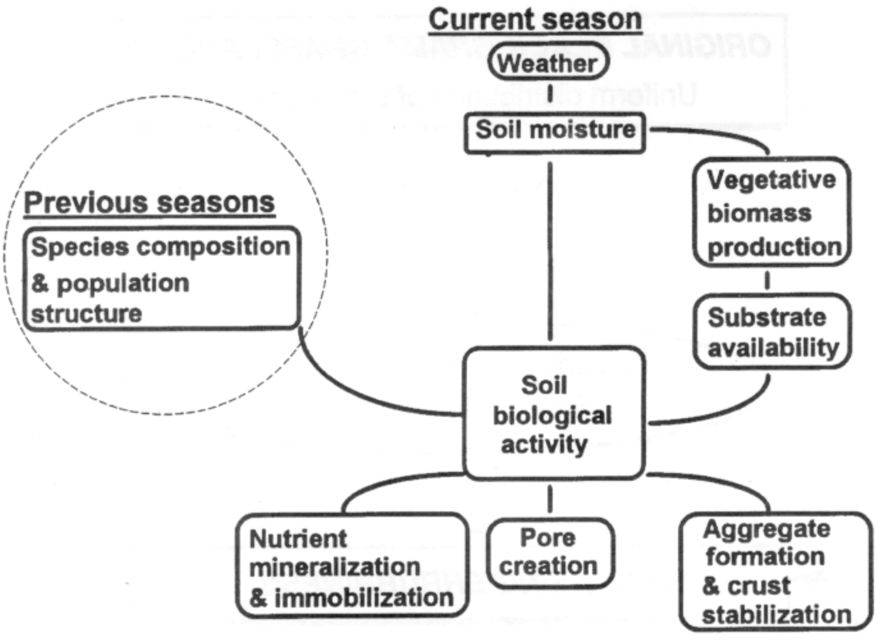


Figure 4. Dependence of biological modification of soil properties on temporal variability in soil moisture

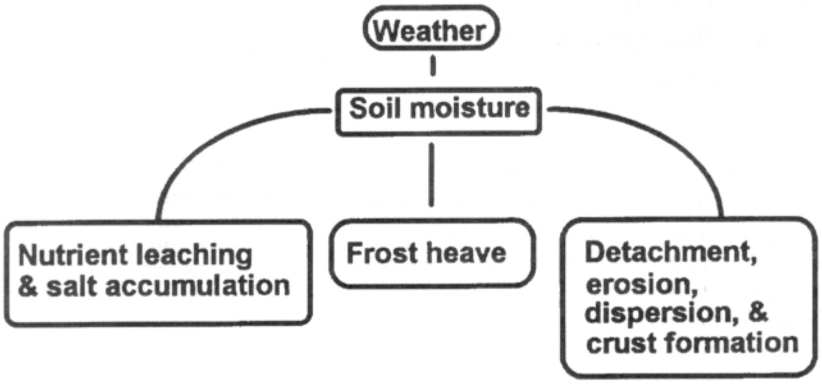


Figure 5. Dependence of physical modification of soil properties on soil moisture

of spatial sampling. The time scale of interest must be defined and the variability at the selected scale must be controlled.

Opportunities. At least four approaches may be taken to control variability within time periods. Each provides opportunities, although not without limitations: (1) restrict measurements to properties that are relatively insensitive to season and weather; (2) remove temporal variability through modeling; (3) sample frequently; (4) restrict sampling to defined periods.

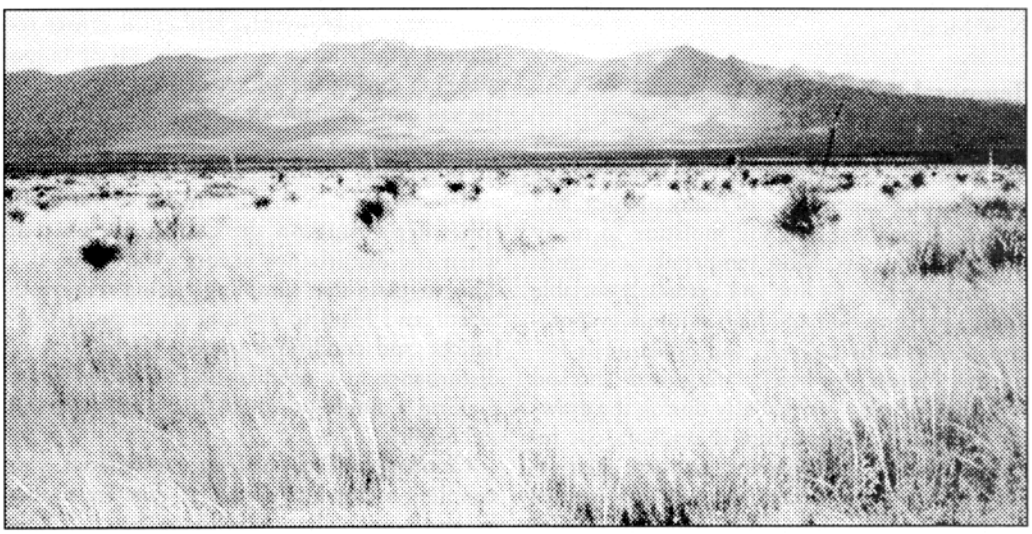
Use only season and weather-insensitive properties. Some useful properties, such as the percentage of soil humus, or non-light fraction organic matter, are relatively stable to short-term environmental fluctuations (Theng et al.). However, many of the potential indicators that are most sensitive to changes in soil function are also sensitive to weather. Examples include aggregate stability and the ratio of soil microbial biomass carbon to total soil carbon. Ideally, indicators of soil quality should register changes in soil functions early in the degradation sequence, while intervention can still be effective.

Remove temporal variability through modeling. This is an increasingly viable option that has great potential for the future. However, our understanding of how soil processes vary over time and in response to weather is still limited. Furthermore, modeling is highly dependent on accurate site-specific weather information. This approach currently offers the greatest potential for long-term monitoring at sites with an existing research infrastructure and historical data. Modeling should increase in importance as our understanding of soil processes develops and weather data for remote sites becomes increasingly available through remote sensing technologies.

Sample frequently. Increasing sampling frequency is clearly an ideal approach when budgets permit. It yields the additional benefit of providing more information on the temporal dependence of soil properties.

Stratify sampling times. Sampling times can

Figure 6. A comparison of two alternative co-occurring systems, both of which could be described as having good soil quality. The system on the left is dominated by Lehmann lovegrass, an aggressive exotic which provides superior vegetative surface stabilization and resistance to grazing. These advantages come at the cost of reduced floral and soil faunal biodiversity, and reduced cover of more palatable native species found in the system shown on the right (Anable et al.)



be stratified by calendar date or, more effectively, by weather, biological cycles, or disturbance events. For example, surface bulk density might be determined in the fall prior to the first frost and in the spring soon after the last frost, while vascular cryptogam cover might be measured before and after grazing each year.

It may not be necessary to account for all periods of the year, particularly if only one period is critical for soil function or if properties covary through time. If controlling summer surface runoff is important, then making relevant hydrological measurements only during the summer may be sufficient.

Ratios of values determined at different times of the year may also prove useful. If nutrient retention in the system is an important function, or nutrients are particularly limiting, then the ratio of nutrient availability during periods of high and low plant uptake could be used. The idea of using the efficiency of coupling of energy and nutrient cycles is discussed in the National Research Council report on rangeland health.

Multiple use demands

Perhaps the greatest challenge to assessing soil quality for rangelands is that they are valued for a variety of different uses. Societal demands on nearly all agricultural lands have increased. In addition to food, fiber, and timber production, rangelands are valued for wildlife, biodiversity, recreation, watershed and groundwater protection.

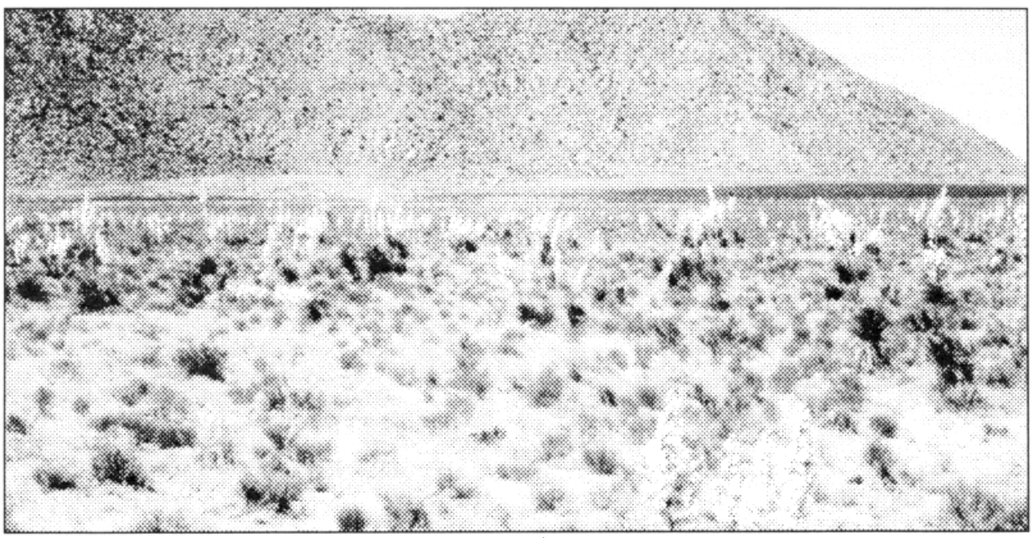
Each use is associated with a different ideal vegetative community structure. Different communities are associated with different soil properties and spatial patterns of those properties. A thick O horizon may indicate good future timber production and surface stability to the forester, but is of little value to the rancher with a permit to graze the forested land. While the uniform soil surface stability provided by aggressive exotic grasses is highly valued by urban watershed and reservoir managers, the associated loss in soil and vegetative heterogeneity is regretted by many ranchers and biodiversity conservationists (Figure 6).

Challenges. A system for evaluating soil quality is needed that can be adapted to different values and uses without being biased toward the values associated with any single use. Continuing debate on whether or not a universal definition of soil quality exists may be relevant only for limited systems and closely-related uses.

Opportunities. An alternative to attempting to identify and calibrate universal indicators of soil quality is to simply develop indicators of specific soil functions. These indicators can then be combined using a variable-weighting system in which the weights reflect the requirements of different uses or values (Table 1). The indicators of soil function, in turn, are based on a variable-weighting combination of measurements of specific soil properties or processes. These properties and processes may be further subdivided using a system such as the one de-

Indicators Level 2	Indicators Level 1	Ecosystem Function/ Attribute	Societal Values/ Management Objectives
			+Productivity
			Food/fiber = f(I,II,IV)
1	A=f(1,2,3)	I=f(A,B)	Wildlife = f(I,II)
2			
3			
2	B=f(2,4)		+Biological Integrity
4			Biodiversity = f(. . .)
			Resistance to stress = f(. . .)
	B	III=f(C,D)	Resilience to stress = f(. . .)
	D		
			+Aesthetics
5	G=f(5,6)	IV = f(G, H)	Wildlife = f(. . .)
6			Vegetation patterns = f(. . .)
	H		
			Off-site
.	.	.	Water harvesting = f(. . .)
.	.	.	Flood/sediment control = f(. . .)
.	.	.	Climate change = f(. . .)

Table 1. Weighting system for combining indicators. Indicators can appear at any level and may contribute to more than one ecosystem function or attribute. Weights assigned at each level are flexible, allowing the system to be adjusted for different societal values and management objectives. Levels may be added to accomodate more complex indicator combinations. See (5) for a more complete description of a hierarchical system used to combine weighted indicators



veloped by Karlen et al. for no-till corn. Properties may contribute to more than one function or even more than once to the same function.

This systems modeling approach has three advantages over attempting to identify one or several universal indicators of soil quality. First, it is inherently flexible, particularly if it is set up in an interactive software environment. It can be easily adapted as our understanding of soil processes increases and can be modified for different ecosystems. Second, it forces both the designer and the user of the system to consider relationships between soil properties and soil quality. Third, this approach clarifies the distinction between relatively objective determinations of relationships between indicators and soil functions, and the relatively subjective selection of which use represents the highest value. It also clarifies the trade-offs in soil function which are necessary when managing for different values or uses.

Summary and conclusions

High levels of spatial and temporal variability increase the challenge of soil quality assessment in rangelands. Interpretation of the data is confounded by competing views on soil quality that are often related to the values that individuals place on the land. However, both the high level of variability and the multiple demands on the land can be viewed as opportunities to introduce new approaches.

Spatial variability can be used to generate indices based on the coefficient of variation, ratios between average values for different strata, and the scale(s) at which variation occurs within the system. By thinking of soil quality as an attribute of the ecosystem, as well as an attribute of single soil pedons, it may be possible to include more soil functions in our definition, more effectively. Ancillary information on the ecosystem, including management history, geomorphology, and vegetation patterns can be used to stratify and interpret soil information.

Temporal variability can also be turned to an advantage. The temporal patterns of the availability of different resources can be compared to determine how efficient the system is in utilizing and retaining resources.

Finally, the problem of multiple-use valuation of rangeland resources may be viewed as an opportunity to clarify the distinction between relatively objective determinations of soil function-indicator relationships and the relatively subjective selection of values. Much information on relationships between soil indicators and soil functions already exists. Future research clarifying these relationships may be linked to broader investigations of how various land uses affect and are affected by the integrity of specific soil functions. Interpretation of the results should be clearly separated into indicator-function and function-use relationships. This approach should reduce conflicts associated with indicator development based on values associated with a specific use.

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REFERENCES CITED

Anable, M.E., M.P. McLaran, G.B. Ruyle. 1992. Spread of introduced Lehmann lovegrass Eragrostis lehmanniana Nees. in Southern Arizona, USA. Biological Conservation 61: 181-188.

Halvorson, J.J., H. Bolton Jr., J.L. Smith, and R.E. Rossi. 1994. Geostatistical analysis of resource islands under Artemesia tridentata in the shrub-steppe. Great Basin Naturalist 54: 313-328.

Herrick, J. E., and R. Lal. 1995. Evolution of soil physical properties during dung decomposition in a tropical pasture. Soil Science Society of America Journal 59: In press.

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.

Lobry de Bruyn, L.A., and A.J. Conacher. 1990. The role of termites and ants in soil modification: a review. Australian Journal of Soil Research 28: 55-93.

Mun, H.T., and W. G. Whitford. 1990. Factors affecting annual plant assemblages on banner-tailed kangaroo rat mounds. Journal of Arid Environments 18: 165-173.

National Research Council. 1994. Rangeland health: new methods to classify, inventory, and monitor rangelands. National Academy Press, Washington, D. C.

Parker, L.W., H.G. Fowler, G. Ettershank, and W.G. Whitford. 1982. The effects of subterranean termite removal on desert soil nitrogen and ephemeral flora. Journal of Arid Environments 5: 53-59.

Parsons, A.J., A.D. Abrahams, and J. Wainwright. 1994. Rainsplash and erosion rates in an interrill area on semi-arid grassland, Southern Australia. Catena 22: 215-226.

Radcliffe, J.E. 1968. Soil conditions on tracked hillside pastures. New Zealand Journal of Agricultural Research 11: 359-370.

Schlesinger, W.H., J.R. Reynolds, G.L. Cunningham, L.F. Huenneke, W.M. Jarrell, R.A. Virginia, and W.G. Whitford. 1990. Biological feedbacks in global desertification. Science 247: 1043-1048.

Theng, B.K.G., K.R. Tate, P. Sollins, N. Moris, N. Nadkarni, and R.L. Tate III. 1989. Constituents of organic matter in temperate and tropical soils. pp. 5-32. In: Dynamics of soil organic matter in tropical ecosystems. D.C. Coleman, J.M. Oades, and G. Uehara, editors. NifTAL Project, University of Hawaii Press, Honolulu, Hawaii.

Tongway, D. 1994. Rangeland soil condition assessment manual. CSIRO, Canberra, Australia.

Virginia, R.A., and W.M. Jarrell. 1983. Soil properties in a mesquite-dominated Sonoran Desert ecosystem. Soil Science Society of America Journal 47: 138-144.

Warren, S.D., S.D. Nevill, W.H. Blackburn, and N.E. Garza. 1986. Soil response to trampling under intensive rotational grazing. Journal of Range Management 50: 1336-1340.

Weltz, M.A., H.D. Fox, S.A. Amer, F. Pierson, and L.J. Lane. 1995. Erosion prediction on range and grazing lands: current perspective. In: USDA-SCS National Resource Assessment. Society for Range Management, Denver, Colorado. In press.

Whitford, W.G. 1994. Desertification: implications and limitations of the ecosystem health metaphor. In: Evaluating and monitoring the health of large-scale ecosystems. Editors D. J. Rapport, C. Gaudet, and P. Calow. Springer Verlag, Heidelberg. In press.

Whitford, W.G., and R. DiMarco. 1995. Variability in soils and vegetation associated with harvester ant, Pogonomyrex rugosus, nests on a Chihuahuan Desert watershed. Biology and Fertility of Soils. In press.