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Integrating soil processes into management: from microaggregates to macrocatchments

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Introduction

Soil properties and processes are rarely considered in range management, or in monitoring or assessment of range condition. An implicit assumption of most management programs is that soil properties are correlated with vegetation, so it is only necessary to manage and monitor the plant community. However, most range managers recognize that the plant communities which could exist at a particular site fundamentally depend on soil properties, and that many of these properties are dynamic and respond to management. A reduction in soil organic matter content, or a change in its distribution (dynamic properties), are frequently cited as indicators of land degradation (Northup & Brown 1999a,b). There are numerous reports demonstrating relationships between soil properties and processes and the capacity of rangelands to support diverse plant and animal communities (National Research Council 1994) and plant and animal production (Elkins *et al.* 1986; Whitford *et al.* 1987; Whitford & Parker 1989; Whitford & Herrick 1995), and maintain air quality (Belnap & Gillette 1998) and water quality (National Research Council 1993).

In addition to strong, clear relationships to a variety of ecosystem functions and other components of environmental quality, soil properties and processes have high potential value as early warning indicators of both degradation and recovery. Perennial plant cover and composition are frequently used as key indicators of ecosystem health (National Research Council 1994), yet many perennial plants are capable of persisting long after soils are degraded to the point that establishment of new plants from seed is virtually impossible.

When range managers ask soil scientists to provide information which could inform management decisions, they are frequently disappointed by the responses: the information is often impractical because the soil properties measured (e.g. cation exchange capacity and pH) reflect processes which occur over time periods much longer than those during which vegetation changes. These measurements yield a 'post-mortem' assessment at best. Furthermore, the soil properties are generally measured at a scale which is irrelevant to community and landscape-level management decisions (e.g. a soil pit), or the parameters are not sensitive to changes in the function of the particular site (e.g. mineral content instead of mineral availability, or the availability of one mineral when another is limiting).

These lost opportunities to better inform management decisions with soils information are due in part to the complexity of rangeland ecosystems and our incomplete understanding of how they function (Brown *et al.* 1998). The disciplinary nature of soil science and the relatively large knowledge base required to correctly apply and interpret many soil measurements also makes application of soils information difficult. Furthermore, key soil processes are nearly impossible to measure directly due to the fact that most occur at sub-microaggregate (micron) scales. The training of soil scientists tends to reinforce and exacerbate the gap between theoretical knowledge and its application to management. For example, in shrublands, soil pits are frequently dug and samples are removed in the plant interspaces only. While the interspaces may be of interest, they provide little information without reference to the soil beneath the shrubs. It is this soil which most directly affects, and is affected by, the plants (Whitford *et al.* 1995 1997). In summary, rangeland monitoring programs rarely include soil measurements and rangeland management is rarely informed by soils information because of problems associated with sampling, interpreting and applying information about soils in the context of a highly spatially and temporally variable environment.

The objectives of this paper are to review some of the challenges associated with scale, explore some approaches to monitoring and management which either limit or exploit these challenges, and finally outline a flexible, multi-scale monitoring strategy which can be applied to management.

The problem of scale

Most soil processes operate at a sub-millimetre scale, are observed at a centimetre scale but are often managed at a scale of a kilometre or more. These processes may vary by several orders of magnitude at any or all of these scales. The degree to which spatial heterogeneity is expressed also depends on the scale at which observations or measurements are made (Pickett & Cadenasso 1995). Consequently, the scale at which processes are most easily observed or conveniently managed is rarely the scale which is most relevant.

The problem of scaling up from processes which occur at a single point to paddock-level impacts is compounded by the patchiness of soil and vegetation (Schlesinger & Pilmanis 1998) and by previous land uses (Blackmore *et al.* 1990). Spatial variability in rangelands at individual plant, patch, plant community, and landscape scales has been well described, particularly for nutrients (Mazzarino *et al.* 1996; de Soyza *et al.* 1998), organic matter (Burke *et al.* 1995) and to a lesser extent for microbial activity (Herman *et al.* 1995; Mazzarino *et al.* 1996) and microarthropods (Cepeda-Pizarro & Whitford 1989). Soil processes often vary by several orders of magnitude over time at intervals as short as several minutes in response to changes in resource availability (Lange *et al.* 1992). These changes in resource availability occur at multiple temporal and spatial scales (WallisDeVries *et al.* 1998), and are most obviously associated with external factors such as grazing and dung and urine deposition (Kellner & Bosch 1992).

The relationships between patterns of soil properties and processes are further complicated by biological feedbacks occurring within and among patches at different spatial and temporal scales. Biopedoturbation (soil movement by living organisms) dramatically affects both the soil microenvironment and the availability of air, water and nutrient resources. The relatively coarse-scale disturbances of burrowing mammals are among the most visible of these patch disturbances (Whitford & Kay 1999). However, the cumulative impact of individual burrows and excavations by ants, termites and earthworms can also be quite significant in their effects on the resource availability in many environments (Lobry de Bruyn & Conacher 1990; Edwards & Bohlen 1996).

One potential solution to at least some of these problems is to use indicators which tend to integrate the effects of a variety

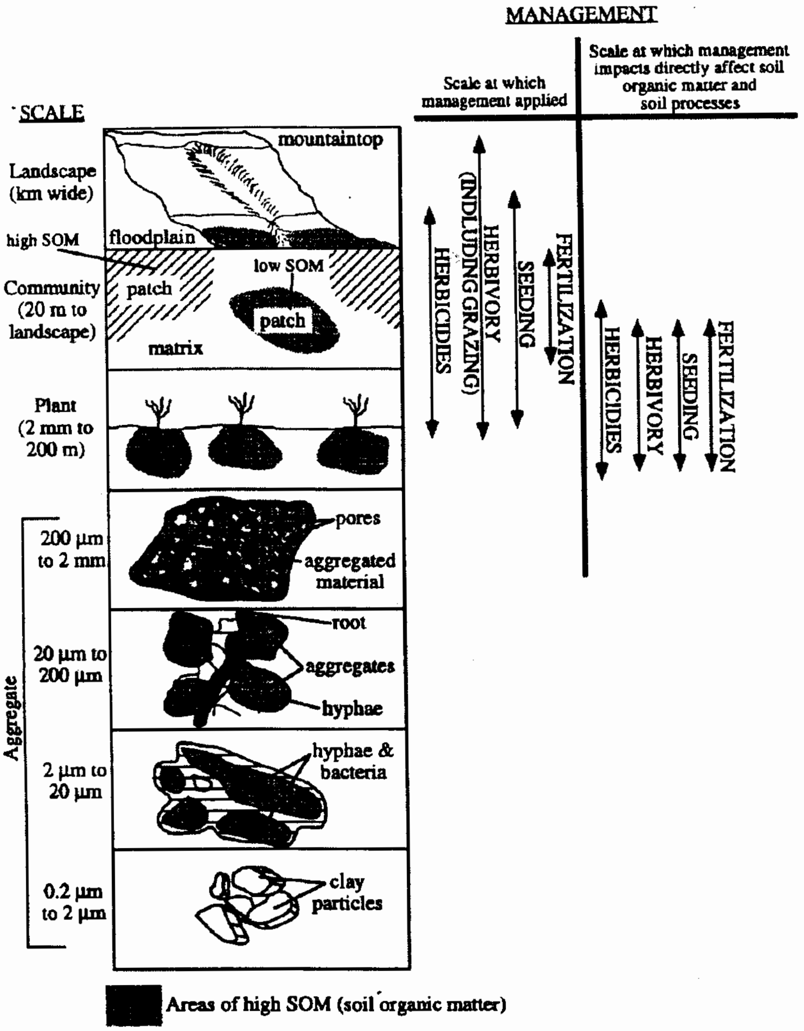

Fig. 1. Conceptual diagram illustrating differences in the scale at which management practices are applied and the scale at which they affect soil processes and properties such as organic matter cycling

of processes. Soil organic matter is a key soil property which reflects the status of a wide range of soil physical, chemical and biological processes. The spatial distribution of soil organic matter therefore reflects the variability in these processes across different spatial scales. A comparison of the scales at which soil organic matter varies with the scales at which it is managed illustrates the problem of linking management with processes (Fig. 1). For example, in a patchy arid grassland, incorporation of standing dead grass stems and leaves into the soil by the hoof action of grazing animals can enhance organic matter cycling. However, the identical disturbance by animal hooves in an adjacent interspace can dramatically reduce the capacity of the soil to absorb water and increase soil loss due to both wind and water erosion. This is just one situation in which a management tool applied at one scale (the paddock) can have dramatically different effects in different patches at the scale of an individual plant.

The spatial distribution and temporal pattern of processes can also be very important. Just as the simultaneous removal of multiple stresses in a particular microsite can facilitate seedling establishment (Grime 1977), so also can the simultaneous application of stresses lead to degradation in areas in which sequential application of the same stresses would have little or no effect (Whitford & Rapport 1999). For example, most arid and semi-arid plants are adapted in some way to drought and tolerate grazing. However, when overgrazing is combined with drought, the resistance of the system to degradation is overwhelmed.

We suggest that these barriers can be overcome by (i) adopting integrative soil indicators which reflect the function of a range of ecosystem processes, (ii) exploiting spatial variability in both monitoring and management, and (iii) applying and interpreting these indicators in the context of variability at scales ranging from the microaggregate to macrocatchments.

Integrative indicators which reflect multiple processes

It is highly unlikely that a single indicator exists which can reliably reflect changes in ecosystem function across rangeland systems or even within a single ecosystem (National Research Council 1994). However, it should be possible to identify a suitable suite of rapid, repeatable, cost-effective measurements which together reflect a variety of processes and functions. Key soil processes are nearly impossible to measure directly. Indicators of soil processes fall into two categories: 'input' indicators which reflect the conditions necessary for the process to occur (e.g. presence of organic matter inputs for decomposition, mineralization, formation of soil aggregates, etc.) and 'output' indicators which suggest that a process has occurred in the past (e.g. nutrient availability). Some indicators, such as pore size distribution, fall into both categories. Simple input-type predictive indicators are rare because biological processes are generally controlled by more than one factor and it is impossible to measure all factors. The application of indicators which reflect historic function is limited by the fact that it is usually impossible to know how long ago a process was functioning or whether it is still functioning. Indicators which reflect more recent activity tend to have a higher signal to noise ratio compared to those which reflect cumulative historic activity. For example, microbial biomass carbon is a reasonable indicator of a system's capacity to convert organic inputs into soil organic matter. However, this ability varies with season, recent weather patterns and interactions with soil flora and fauna. It also varies with substrate availability. High microbial biomass carbon often simply reflects a recent organic matter input, such as leaf fall from deciduous shrubs or roots from annuals. Conversely, trends in the humic fraction tend to be insensitive to short-term weather patterns, but are also unlikely to reflect short-term management-induced changes. In some cases, it is possible, if not likely, that there are management-associated differences, but sampling and measurement-induced variability masks them. Some sensitive indicators which have a low signal to noise ratio because of weather and season can still be used if a local reference site is available for comparison. In summary, ideal indicators for early detection of ecosystem change are those which reflect the status of a variety of processes, are temporally stable and, most importantly, reflect susceptibility of the system to degradation (resistance) or capacity to recover (resilience) if degradation occurs.

This definition of an ideal indicator has quickly led many soil ecologists to the conclusion that individual organisms, which depend on and contribute to a variety of processes, should be excellent indicators. Unfortunately, many ecologists have simply selected their favourite organism and designed experiments to build a case in support of this organism. Specific organisms such as ants may be extremely useful in some situations, such as mineland rehabilitation (Majer 1983). However, these organisms may be far too variable for broad use as indicators of rangeland health (Whitford *et al.* 1999). More extensive research in cultivated systems appears to suggest that the biological indicators with the highest potential are those, such as various forms of soil organic matter, which tend to integrate the activity of a variety of organisms (Herrick & Wander 1998).

Exploiting spatial variability in monitoring and management

Monitoring

Spatial variability is widely viewed as a challenge in rangeland monitoring programs. Vegetation growth patterns in particular routinely confound efforts to estimate cover, composition and standing-crop utilization. In response, a number of procedural and statistical approaches have been developed to minimize or attempt to account for this (e.g. Bork & Werner 1999). A number of authors have recently recognized that both the pattern and scale of spatial variability can serve as excellent indicators (e.g. Tongway & Ludwig 1996; de Soyza *et al.* 1998). Characterization of existing plant resource distribution patterns must be complemented by an understanding of how temporal and spatial variability in grazing and other disturbances (Kellner & Bosch 1992) are scaled across the landscape and how the aboveground evidence of these disturbances is reflected belowground.

Aboveground disturbance patterns which appear to be quite dramatic are not always reflected in changes in belowground processes. Fine root production measured in 10 m x 10 m experimental gaps in northern temperate forests in Quebec was only minimally changed in quantity and composition relative to controls in spite of the removal of all trees from the experimental areas (Campbell & Finer 1998). This was apparently due to ingrowth and expansion of roots from surrounding individuals. Some desert shrubs show a similarly dispersed root growth pattern. In one case, roots from one plant were found to pass directly beneath the canopy of another (Gile *et al.* 1998).

Geostatistics have often been used to identify the scale at which individual properties vary across the landscape. Their usefulness in addressing processes is limited by at least two factors. The first is that geostatistics cannot be used to describe processes and properties, such as decomposition, which are linked spatially through time. The expression of fine scale processes, such as local nutrient enrichment associated with decomposition, in coarser scale patterns, such as the establishment of a shrub, is frequently separated by years or even decades (Ponge *et al.* 1998). The second limitation is that geostatistics can only deal with one variable at a time, while most processes are defined by multiple variables.

The first limitation can be partially overcome by linking geostatistics with time series analyses and by expressing the results in temporally explicit models of landscape evolution based on changes occurring at the patch level (Coffin & Lauenroth 1990). Recognition of pattern-based linkages across time can frequently lead to a more complete understanding of the processes which drive these patterns (Ponge *et al.* 1998). The second limitation can be overcome by combining geostatistics with ordination. Ordination places plots or points in an x–y plane. The location of each point on the plane is based on the relative similarity of, for example, species composition. The axis scores (x and y values) from the ordination can then be used as a regionalized variable in constructing a semivariogram. The semivariogram is used to define the range of spatial correlation for the suite of properties included in the ordination. This approach was recently applied to patterns in species associations in plant communities (Jonsson & Moen 1998) and should work equally well for soils. For example, a suite of properties associated with a particular process (e.g. litter, soil organic matter and microbial biomass for decomposition) could be analysed together.

Management

The variability in soil resource availability across the landscape can be exploited, especially in systems in which the resources required for plant establishment are only episodically available. Native cultures have long exploited and enhanced this variability in resource availability in runoff gardens. Targeted utilization of smaller patches such as dung (Auman *et al.* 1998) can also be used to modify vegetation structure, composition and productivity. Until recently, however, fine- to medium-scale variability (i.e. less than a hectare) has been largely ignored in rangeland rehabilitation efforts (Whisenant 1996; Whisenant & Tongway 1996). The susceptibility to change varies across landscapes, largely as a function of resource availability. This variability can be exploited by targetting management and inputs to those parts of the landscape with the highest potential for change. This approach explicitly incorporates and exploits the secondary effects of inputs on resource availability through biological feedbacks, such as termite modification of soil surface hydrology in response to organic inputs (Herrick *et al.* 1997).

A multi-scale approach to monitoring

Most monitoring programs are based on measurements made at individual points. As discussed above, this approach misses many of the important processes which are only expressed at coarser scales. Furthermore, a point-based approach to monitoring diverse rangeland ecosystems frequently leads to impractical and unaffordable numbers of replications. The use of emergent properties of landscapes is often suggested as a way to integrate multi-scale processes and identify changes in these processes before a threshold is reached. Some properties, such as sediment loads and stream hydrographs, are relatively straightforward to interpret when appropriate reference data are available. More frequently, however, these properties (such as spatial organization of aggrading and degrading areas) are difficult to identify and even more challenging to quantify. Even when they can be quantified in one landscape, it is often difficult to develop tools, such as filters and algorithms for pattern analysis, which can be applied systematically across a variety of landscapes.

In response to the challenge of providing management information applicable at the landscape level while measuring patterns of properties (reflecting processes) at the point scale and incorporating qualitative information extracted from multiple scales, we have developed a flexible approach to rangeland monitoring. Qualitative soil and vegetation indicators are used together with information about soils, geomorphology, and current and historic vegetation and land use patterns to stratify the landscape. Emergent properties which can be observed, but not quantified, are also recorded at this first stage. This information is then interpreted in the context of monitoring objectives to select specific monitoring points and indicators, and to establish appropriate monitoring frequencies for quantitative measurements (Table 1). A core set of measurements is included at all monitoring points. Other indicators are added depending on site characteristics and monitoring objectives. These measurements are designed to generate a basic set of indicators of soil and site stability, watershed function and plant community integrity. Additional indicators can be calculated which reflect differences in the capacity of the land to support specific values or uses such as forage production for livestock or biodiversity conservation. Decisions about which measurements to include are guided by decision trees and tables.

Table 1. Selection of monitoring locations, indicators and monitoring frequency based on monitoring objectives

Objectives	Monitoring locations	Indicators	Frequency
Inventory (single property)	Stratified random sampling based on landscape and management units	Primarily point-based. Emphasize indicators relatively unaffected by short-term dynamics (e.g. basal cover & penetrometer resistance)	1–10 years
Inventory (multi-property, regional)	Stratified random sampling based on landscape and management units for point-based indicators	Combination of point-based and watershed (see references). Point-based indicators as above.	Continuous–10 years
Risk	High-risk locations (e.g. vegetation boundaries) where management can have a significant effect)	Point-based, highly responsive (e.g. canopy cover and soil stability)	6 months–2 years
Recovery	High-potential locations e.g. riparian, and areas of historic nutrient accumulation where management can have a significant effect	Point-based, responsive (e.g. canopy cover and soil stability)	6 months–2 years
Management	As above, depending on overall objective	Depend on use	Daily–monthly

The core set of quantitative measurements includes line–point intercept for measurement of plant cover and composition and soil surface characteristics. The line–point measurements are supplemented by a continuous line intercept in which all canopy and basal interspace intercepts longer than 10 cm are recorded. Intercepts smaller than 10 cm are assumed to be sub-threshold for most degradative processes including plant invasions and wind and water erosion. A test for soil stability in water is also included in the core set of measurements. The test is rapid (18 can be completed in under 10 minutes), allowing the full range of spatial variability to be characterized. Because it reflects the strength of aggregates larger than 1.5 mm in diameter, it is assumed to reflect more active soil organic matter (which is therefore more sensitive to changes in condition) (Fig. 1; Herrick *et al.* 1999). Cover-specific means (grass, shrub, no-canopy) and ratios can all be used. The inclusion of two additional soil measurements, penetrometer resistance and infiltration capacity, is optional. Penetrometer resistance is included only if qualitative indicators (platy structure and rooting structure) and/or quantitative indicators (resistance at 5–15 cm greater than resistance at 15–25 cm) indicate that compaction is already a problem, or if current management practices indicate that it could become a problem (e.g. use by off-road vehicles or livestock when the soil is wet). The inclusion of infiltration capacity depends on site characteristics, site accessibility and time availability.

A similar, but more regionally- and site-specific approach was recently used in the development of a monitoring program in Denali National Park, Alaska, USA (Thorsteinson & Taylor 1997). In this program, as in the approach outlined above, different indicators are selected for measurement at different sites. The emphasis in this case is on hydrologic characteristics and habitat quality.

Conclusions

For monitoring, early warning indicators of changes in the susceptibility of rangeland to changes in vegetative cover and composition are clearly needed. Soil properties and processes have the potential to serve this role. However, focused research is needed to identify cost-effective indicators and the spatial and temporal scales at which these properties are best measured and interpreted.

For management, soils and vegetation must be managed together, with a recognition that the scale at which processes function and are affected in one is not necessarily reflected in the other. Variability in resource distribution presents numerous opportunities for management, particularly when interactions between soil biotic processes and spatial and temporal differences are exploited. In addition to recovery, short-term resilience is strongly related to differences in soil processes, and in the spatial pattern at which these processes occur.

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