FEATURE

Rangeland health assessment: The key to understanding and assessing rangeland soil health in the Northern Great Plains

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As the science related to soil and rangeland health evolves, so do protocols and assessment methodologies. Rangeland health assessments consist of evaluating how well ecological processes, such as the water cycle, energy flow, and nutrient cycling, are functioning at a site. Maintained ecological functions provide support for specific plant and animal communities (Pellant et al. 2005) and ensure a flow of ecosystem services. The most commonly used protocol to assess US rangelands has become the Interpreting Indicators of Rangeland Health (IIRH) assessment (Pellant et al. 2005; Pyke et al. 2002). Rangeland health assessments use 17 indicators to rate 3 attributes of rangeland health that integrate soil and plant indicators together with other abiotic factors into one scientifically tested assessment tool. Attributes rated as part of rangeland health assessments are soil and site stability, hydrologic function, and biotic integrity (Pellant et al. 2005). Additionally, rangeland health protocols have been tested across a broad range of ecosystems and are already in use by thousands of individuals worldwide. Other common tools used to evaluate rangelands include similarity indices and trend studies, which can be used alone or in conjunction with the rangeland health assessment methodology.

Soil health is the capacity of a soil to maintain its function and flow of ecosystem services given a specific set of physical, chemical, and environmental boundaries (USDA NRCS 2013; Doran et al. 1994). When a soil's health deteriorates, its capacity to support and regulate ecosystems is diminished, affecting energy flows, nutri-

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Table 1

Four basic soil health principles and corresponding rangeland health indicators.

Soil health principle	Qualitative rangeland assessment indicator
Plant diversity increases diversity in the soil.	Indicator 10–Plant community composition and distribution relative to infiltration and runoff
	Indicator 12–Functional/structural groups
	Indicator 13–Amount of plant mortality and decadence
	Indicator 15–Annual production
	Indicator 16–Invasive plants
Manage soils more by disturbing them less.	Indicator 9–Soil surface loss or degradation
	Indicator 8–Soil surface resistance to erosion
	Indicator 11–Compaction layer
Keep plants growing throughout the year to feed the soil.	Indicator 4–Bare ground
	Indicator 12–Functional/structural groups
	Indicator 15–Annual production
	Indicator 16–Invasive plants
Keep the soil covered as much as possible.	Indicator 4–Bare ground
	Indicator 14–Litter amount

ent cycling, and productivity. There are four broadly accepted principles used to sustainably maintain or improve soil health (Karlen et al. 1997):

1. Use plant diversity to increase diversity in the soil.
2. Manage soils more by disturbing them less.
3. Keep plants growing throughout the year to feed the soil.
4. Keep the soil covered as much as possible.

These soil health principles were developed primarily for agricultural systems, yet they are relevant to most soils and also apply to rangelands. However, there are concerns regarding the application of these four soil health principles to rangeland ecology and management amongst resource professionals and managers of private/public rangelands. This paper will attempt to clarify how each of these principles applies to rangeland ecology and describe the ways existing science-based inventory protocols should be used to assess not only the health of the rangeland soil resource but also the overall health of the rangeland resource. Our approach consists in explaining how each of the four soil principles listed above is relevant to rangeland health and listing the indicators of rangeland health to which each soil health principle relates (table 1). In the

same way that one indicator (i.e., soil resistance to erosion) can relate to more than one attribute (i.e., soil and site stability, hydrologic function, and biotic integrity) in a rangeland health assessment, one indicator can also be related to multiple soil health principles.

PRINCIPLE 1: USE PLANT DIVERSITY TO INCREASE DIVERSITY IN THE SOIL

The diversity of plants at a site provides a suite of ecological functions and interactions. Photosynthesizers (plants, lichens, mosses, photosynthetic bacteria, and algae) form the first trophic level of the soil food web. Plants support the organisms in the second trophic level by producing organic matter, which feeds the soil bacteria and some fungal species. Plant roots directly feed both symbiotic and saprophytic fungi as well as nematodes (USDA NRCS 2013; Kennedy and Smith 1995; van Straalen and van Gestel 1998; Ferris et al. 2001). The diversity of native plants on rangeland sites contributes to the maintenance and enhancement of above- and belowground biological interactions that keep the ecological interactions described in ecological site descriptions (ESD) intact. Disruptions in plant diversity by loss of species that are potentially important to the site or by

the introduction of exotic species affect the dynamics of these ecological sites and degrade sites into alternate states. Presence of the right species in the right proportions based on site potential and management objectives is important for maintaining above- and belowground ecosystem health.

The importance of plant diversity in relation to rangeland health has long been recognized as one of the primary tenets of rangeland ecology and management (West 1993). Plant diversity gives rangeland plant communities resistance to disturbance-driven change and provides resilience once a change has occurred following a disturbance such as severe long-term drought, fire, and/or long-term overgrazing. Expected plant diversity will vary by ecological site and needs to be evaluated on an ecological site basis using available tools such as ESDs and similarity indices. It is important to note that in cropland systems, unlike rangelands, the suite of species used to improve soils rarely includes native plants, and species chosen are used as part of a manmade rotational system.

Ecological site descriptions serve as the primary resource for developing standards of comparison to assess current plant diversity versus the potential plant diversity at a site. Plant diversity, based on current year's annual production by species, is one of the primary measurements recorded when conducting a rangeland inventory. This measurement of plant diversity/ productivity is known as the similarity index. Similarity index is a measure of the amount of reference plant community (or desired plant community) still present on the ecological site. Once completed, a similarity index provides insight into the health of the plant community, including the soil biology associated with the various plant species inhabiting the site. Just as important, a comparison of the current plant community with the reference plant community provides information on what plant species or functional/structural groups (F/S groups) have been reduced, have been eliminated, or have invaded the site. Shifts in plant species or F/S groups will affect the hydrology, energy capture, and nutrient cycling capabilities of the site, as well as have the potential to directly impact soil biology.

In addition to similarity index, the IIRH protocol evaluates the impact of plant diversity changes to ecological processes. While all 17 indicators are inter-related, we list those indicators that relate more directly to plant diversity, production, and soil biology. For each indicator, the ESD and rangeland health reference worksheet are used as the assessment standard of comparison.

Indicator 10: Plant Community Composition and Distribution Relative to Infiltration and Runoff. Plant root morphology and biomass, litter production and associated decomposition processes, basal area, and spatial distribution can all affect infiltration and/or runoff. Community composition changes, such as a decline in native bunchgrasses, an increase in shrubs, or an increase in invasive cool-season sod-forming grasses, can also negatively impact soils (Jordan and Larson 2007) leading to reduced infiltration.

Reduced infiltration not only affects available water but also contributes to runoff. Runoff transports soil, soil organic matter, and soil nutrients off the site further reducing soil health. Maintaining plant species diversity and plant structural diversity as well as adequate amounts of basal and canopy foliar cover can aid infiltration and reduce runoff.

Indicator 12: Functional/Structural Groups. Functional/structural groups are defined as a suite or group of species that because of similar shoot or root structure, photosynthetic pathways, nitrogen (N) fixing ability, life cycle, etc., are grouped together on an ecological site basis. This indicator assesses the number and relative dominance of F/S groups and the number of plant species comprising each group as compared to the reference condition. A change in the number or relative dominance of the F/S groups and/or a reduction in the number of species comprising a F/S group would indicate some level of departure from the reference condition. Since some F/S groups are more dependent on properly functioning soil biology than others (e.g., warm-season native grasses; obligate vs. facultative vs. non-mycorrhizal plant species), this indicator can be used to assess the impacts of plant diversity changes on soil biology.

Carbon to nitrogen (C/N) ratio of different F/S groups is also a consideration when assessing the effectiveness of nutrient cycling and the impacts on soil biology. Native grasses and forbs are generally high to medium C/N ratio, while some F/S groups not expected for the site are low C/N ratio species. When these low C/N groups become established on the site, the nutrient cycle is altered, and biological activity is affected.

A change in dominance of F/S groups could indicate a change in soil biology. For example, a F/S group not expected for the site, such as a short-statured, cool-season, rhizomatous non-mycorrhizal grass, replaces a dominant F/S group, such as tall-statured, warm-season, rhizomatous obligate grasses, on a Loamy Overflow ecological site. Although more detailed, this F/S group indicator would be similar to the "crop type" categories used to describe and develop cropping rotations (Liebig et al. 2013).

Indicator 13: Amount of Plant Mortality and Decadence. Plant mortality and decadence is the proportion of dead or decadent (e.g., moribund or dying) to young or mature plants in the community, relative to that expected for the site under normal disturbance regimes. Healthy rangeland has not only a diverse plant community but also a mixture of many age classes of plants. If existing plants are either dead or dying and no recruitment is occurring, the diversity and stability of the plant community is jeopardized as is the resistance and resilience to disturbance.

Indicator 15: Annual Production. Annual production as used in rangeland health assessments is the net quantity of aboveground vascular plant material produced within a year. It is an indicator of the energy captured by the plants and its availability for secondary consumers in an ecosystem given current weather conditions. Aboveground production is also a source of organic matter at the soil surface and provides protection from physical stressors, such as raindrop impact, runoff, and erosion. Belowground root production is closely related to aboveground production with approximately 80% of the total annual production occurring below the soil surface in mixed-grass

prairie (Willms and Jefferson 1993). The amount of root material produced (assessed in relation to aboveground production) and its distribution within the soil profile (related to F/S plant groups) is critical to properly functioning soil biology. Actively growing roots provide food to soil organisms and, depending upon the plant species, actively provide food (C) to mycorrhizal fungi, which in turn support further plant growth.

Indicator 16: Invasive Plants. Invasive plants (as defined for the purposes of rangeland health assessments) are plants that are not part of (if exotic), or are a minor component of (if native), the original plant community or plants that have the potential to become a dominant or codominant species on the site if their future establishment and growth is not actively controlled by management interventions (Pellant 2005). Exotic species may not have the same symbiotic relationship to the soil biological community as the native species they displace. Invasive annuals and perennial plants that shift the ratios of cool- and warm-season plants affect the seasonal soil water balance, which will in turn affect soil biota. Some invasive species, such as exotic perennial or biennial leguminous forbs, may alter the nutrient cycling of the site.

PRINCIPLE 2: MANAGE SOILS MORE BY DISTURBING THEM LESS

The intended purpose of this principle is to reduce or prevent unnecessary tillage of many agricultural areas. In terms of rangelands, this principle could also apply to chronically overgrazed areas, but in the Northern Great Plains this has not been an issue with the possible exception of limited areas adjacent to permanent watering locations. It is important to note, however, that most rangelands have evolved with grazers and fire as a disturbance, and in most cases, some level of disturbance is needed to maintain ecosystem health.

Research suggests that tillage can result in degraded and compacted soils with diminished soil microbial activity. On Northern Great Plains rangelands, physical disturbance of the soil measured using field aggregate stability shows very little departure from reference conditions. Health

assessment of rangeland soils include observing the amount and type of erosion during apparent or measured trend determinations and selected rangeland health indicators, including those listed here.

Indicator 9: Soil Surface Loss or Degradation. The loss or degradation of part or all of the soil surface layer or horizon is an indication of a loss in site potential. Primary assessment indicators are organic matter content and soil structure in the surface layer or horizon. Observations of the soil surface layer/horizon at several locations across the evaluation site permit a determination of the level of departure (if any) between observed organic matter content (color) and structure (e.g., granular versus blocky versus platy) and what is expected for the site as described on the rangeland health reference worksheet. Presence of a thatch layer (intermingled organic layer of dead and living roots, stems, stolons, rhizomes, and shoots that develops between the soil surface and the zone of green vegetation above) usually associated with Kentucky bluegrass (*Poa pratensis* L.) invasion is also evaluated under this indicator. This indicator focuses directly on the soil surface layer/horizon where detrimental physical disturbance of the soil would be first observable. This indicator is one of three applicable to the functional status of all three rangeland health attributes (soil/site stability, hydrologic function, and biotic integrity).

Indicator 8: Soil Surface Resistance to Erosion. This indicator assesses the resistance of the soil surface to erosion. Stability of the soil surface is key, and surfaces may be stabilized by soil organic matter that has been fully incorporated into aggregates at the soil surface, adhesion of decomposing organic matter to the soil surface, and biological crusts. This indicator is most often assessed by performing a soil stability test (or slake test) and comparing the results to the reference condition described for the site on the rangeland health reference worksheet. Reduced aggregate stability would indicate a reduction in soil surface organic matter and/or a reduction in glomalin due to reduced mycorrhizal fungi populations at the soil surface. This indicator directly assesses the impacts of excessive soil surface disturbance and is one of three

indicators applicable to the functional status of all three rangeland health attributes (soil/site stability, hydrologic function, and biotic integrity).

Indicator 11: Compaction Layer. A compaction layer is a near-surface layer of dense soil caused by repeated impacts on or disturbances of the soil surface. Compaction can also occur below the surface at the bottom of a tillage layer. This indicator addresses only management-induced compaction layers and does not include naturally occurring compaction layers, such as sodium induced claypans. On most ecological sites, the near-surface (within 3 to 5 cm [1 to 2 in]) compaction is characterized by a change in expected soil surface structure (i.e., granular to platy). This is most often observed in areas with excessive animal traffic (e.g., near water sources or livestock trails) or vehicle trails. Deeper compaction layers (15 to 20 cm [6 to 8 in] below the soil surface) associated with past tillage may also be visible on sites that were farmed in the past and allowed to return to native vegetation. These compacted layers may exist many years after tillage ceased and are characterized by an abrupt change in the expected vertical soil structure to horizontal. This indicator directly assesses the impacts of excessive soil surface disturbance, and is one of three applicable to the functional status of all three rangeland health attributes (soil/site stability, hydrologic function, and biotic integrity).

PRINCIPLE 3: KEEP PLANTS GROWING THROUGHOUT THE YEAR TO FEED THE SOIL

Rangeland reference plant communities in the Northern Great Plains are characterized by high plant diversity, including numerous warm- and cool-season grasses, forbs, and shrub species. This ensures actively growing plants are present throughout the growing season, supporting active soil biology as well as providing high quality habitat for both grassland-dependent wildlife species and domestic livestock.

As explained under Principle 1, rangeland similarity index provides the manager detailed information on the current plant community composition, including the number and amount of different warm-

and cool-season species present on the site. Comparing current plant community composition to the reference plant community table in the ESD gives the manager insight into how well the current plant community is functioning, what changes have occurred due to management and/or weather conditions, and whether the site has the proper balance of warm- versus cool-season species to support properly functioning soil biology.

Indicator 4: Bare Ground. Bare ground is exposed mineral or organic soil that is susceptible to raindrop splash erosion. It is the remaining exposed soil after accounting for ground surface covered by vegetation, litter, standing dead vegetation, gravel/rock, and visible biological crust. In the same way cover crops have been used in agricultural systems to maintain the soil cover and produce healthy soils, reducing bare ground by maintaining actively growing plants present throughout the year maintains the necessary levels of belowground diversity that help feed the soil.

Indicator 12: Functional/Structural Groups. The "functional" component of F/S groups refers to which photosynthetic pathway a plant species utilizes. Warm-season (C4) and cool-season (C3) are the dominant photosynthetic pathways of plants in the rangelands of the Northern Great Plains. A shift in functional groups from a balance of warm- and cool-season species to a dominance by either warm- or cool-season species would result in less active plant growth during some portion of the growing season and be detrimental to soil biology.

Indicator 15: Annual Production. Solar energy that is captured by plants moves up the food chain, including soil biota. A shift from a mixed community to one dominated by either cool- or warm-season plants will likely alter annual production and alter the availability of root exudates as food sources for soil biota.

Indicator 16: Invasive Plants. Primary invasive species on rangeland in the Northern Great Plains are exotic, cool-season rhizomatous grasses. Once established on an ecological site, these species tend to increase and dominate ecological processes at a site. This results in a shift from a diverse plant community with actively growing plants supporting soil biological activity throughout the growing season to one with plants actively growing for only a short portion of the growing season, negatively impacting soil biology. Exotic species may also not have the same symbiotic relationship to the soil biological community as the native species they displace.

PRINCIPLE 4: KEEP THE SOIL COVERED AS MUCH AS POSSIBLE

Keeping the soil covered by crops, cover crops, or crop residue protects soils in agricultural systems. In rangeland ecosystems, reducing the amount of bare ground by maintaining adequate amounts of plant cover and litter cover provides protection from abiotic factors such as extreme temperatures and raindrop impact. Rangeland health assessments evaluate the amount of bare ground and litter cover for a site and evaluate these indicators based on the amount of each that we would expect to see in reference condition.

Indicator 4: Bare Ground. The amount and distribution of bare ground is one of the most important contributors to site stability relative to the site potential. Therefore, it is a direct indication of site susceptibility to accelerated wind or water erosion.

Some amount of bare ground would be expected to occur in reference condition plant communities due to the natural disturbance regime, which included fire, drought, and intense but infrequent defoliation by grazing animals and insects. The amount (percentage) and distribution (patch size and connectivity) of bare ground are important indicators of a site's susceptibility to wind and water erosion. A decrease in the expected amount of bare ground could be an indicator that an invading species is expanding into available niches or that natural disturbance processes, such as fire, are not occurring.

Indicator 14: Litter Amount. Litter is any dead plant material (from both native and exotic plants) that is detached from the base of the plant. The portion of litter that is in contact with the soil surface (as opposed to standing dead vegetation) provides a source of soil organic material and raw materials for on-site nutrient cycling. Litter helps to moderate the soil microclimate and provides food for microorganisms. Excessive litter can be detrimental due to shading of the plant crowns (especially for warm-season grasses), reduce hydrological function, and reduce nutrient cycling. Percentage litter cover, litter depth, and proximity to soil surface (in contact with soil surface) are considered during the evaluation of this indicator. Changes in available litter can point to changes in ecological processes, such as nutrient dynamics and soil-water dynamics.

SUMMARY AND CONCLUSIONS

This approach relates the four soil health principles—plant diversity, reduced physical soil disturbance, year-round plant growth, and maintained soil cover—to indicators used for rangeland health assessments. It directly links attributes used for rangeland health assessments (soil and site stability, hydrologic function, and biotic integrity) and soil health, highlighting the importance of current methodologies and their broad-scale application. Using the IIRH as a framework for information related to soil health will be useful to land managers and scientists as they interpret the more complex interactions occurring within the different assessment attributes. We strongly recommend that the IIRH protocol be applied in its entirety instead of a separate rangeland soil quality protocol for four reasons: (1) the protocol has been extensively tested across a broad range of environments and was codeveloped by a soil scientist and reviewed by hundreds of individuals; (2) thousands of individuals have already been trained on the protocol; (3) ecological site reference conditions for the evaluation have already been established; and (4) rangeland soil quality cannot be evaluated independently of an evaluation of the plant community. However, rangeland health protocols are not a comprehensive tool, and there are many other aspects related to soil health, such as spatial dynamics of nutrient availability, organic matter availability, and microbiological activity, that we cannot fully address with the rangeland health approach but that could potentially be incorporated as an additional indicator. Therefore, this should be seen as the starting point of an iterative process that will

ultimately depend on management and research objectives.

Our approach and examples are related to our experiences with the Northern Great Plains of the United States. However, most of the connections and examples made above also apply to other regions. We urge natural resource professionals to adapt and interpret this application of rangeland health methods for other regions of the country.

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