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Soil Health as a Transformational Change Agent for US Grazing Lands Management☆

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ABSTRACT

There is rapidly growing national interest in grazing lands' soil health, which has been motivated by the current soil health renaissance in cropland agriculture. In contrast to intensively managed croplands, soil health for grazing lands, especially rangelands, is tempered by limited scientific evidence clearly illustrating positive feedbacks between soil health and grazing land resilience, or sustainability. Opportunities exist for improving soil health on grazing lands with intensively managed plant communities (e.g., pasture systems) and formerly cultivated or degraded lands. Therefore, the goal of this paper is to provide direction and recommendations for incorporating soil health into grazing management considerations on grazing lands. We argue that the current soil health renaissance should not focus on improvement of soil health on grazing lands where potential is limited but rather forward science-based management for improving grazing lands' resilience to environmental change via 1) refocusing grazing management on fundamental ecological processes (water and nutrient cycling and energy flow) rather than maximum short-term profit or livestock production; 2) emphasizing goal-based management with adaptive decision making informed by specific objectives incorporating maintenance of soil health at a minimum and directly relevant monitoring attributes; 3) advancing holistic and integrated approaches for soil health that highlight social-ecological-economic interdependencies of these systems, with particular emphasis on human dimensions; 4) building cross-institutional partnerships on grazing lands' soil health to enhance technical capacities of students, land managers, and natural resource professionals; and 5) creating a cross-region, living laboratory network of case studies involving producers using soil health as part of their grazing land management. Collectively, these efforts could foster transformational changes by strengthening the link between natural resources stewardship and sustainable grazing lands management through management-science partnerships in a social-ecological systems framework.

Introduction

Grazing lands (pastures and rangelands) comprise almost 236 million ha in the United States and provide an extensive suite of ecosystem goods and services for society, including food and fiber, soil and water resource protection, and biodiversity conservation (Havstad et al., 2007). Increasing weather and climate variability (e.g., greater frequency of deluges and droughts), a growing human population with greater demand for animal protein, and directional changes in atmospheric carbon dioxide (CO_2) concentration and global temperatures challenge the ability of grazing lands to deliver these desired ecosystem goods and services. Maintenance of soil health at minimum, as well as improvement where there is potential, is the underpinning upon which many ecosystem goods and services depend and is foundational for the sustainability and resiliency of grazing lands. Physical, chemical, and biological components (Table 1) of soil health enable the soil's

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Table 1
Commonly measured soil health indicators adapted from cropland and forest systems (adapted from Doran and Jones, 1996; Arias et al., 2005; Zornoza et al., 2015).

Physical	Chemical	Biological
Particle size	Soil organic carbon	Microbial biomass, C and N
Bulk density	Total nitrogen	Microbial community composition
Soil aggregation	pH	Enzyme activities, C, N, P, and S cycling
Available water-holding capacity	Electrical conductivity	
Porosity	Available nutrients	Invertebrates
Penetration resistance	Cation exchange capacity	Pathogens
Water infiltration rate	Heavy metals	

capacity to function as a vital living system to sustain biological functions, maintain environmental quality, and promote plant and animal health and productivity (Doran and Zeiss, 2000). Benefits of soil health are manifest through enhanced soil water holding capacity, improved nutrient cycling, and greater system resilience to weather and climate variability (Doran, 2002). Furthermore, soil health and sustainability are inextricably linked (Doran, 2002; Doran and Zeiss, 2000; Lehman et al., 2016; Scoones, 2016).

In the mid-20th century, far-reaching social-ecological disasters drove the development of soil conservation policies in the United States. Westward expansion of cropping in the early 1900s ultimately led to disastrous consequences during the drought years of the "Dirty Thirties." Subsequent policies to rehabilitate these lands for sustainable agricultural production included formation of the Soil Conservation Service (synonym Natural Resources Conservation Service [NRCS]). Repeated soil erosion from the 1950s drought led to the Soil Bank programs, and in the middle 1980s the Conservation Reserve Program was introduced to protect soil and water resources. More recently, there has been a resurgence in local to national public interest in soil health for grazing lands management (e.g., South Dakota Soil Health Coalition http://www.sdsoilhealthcoalition.org; Soil Health Institute, www.soilhealthinstitute.org; USDA NRCS Soil Health Division). It is important to note that, unlike previous campaigns of the past century, contemporary focus on soil health has not stemmed from broad-scale natural resource degradation but rather from connections among soil biology, productivity, sustainability, and resilience, especially for croplands (e.g., Trivedi et al., 2016).

The four principles of soil health—1) increase plant diversity, 2) reduce soil disturbance, 3) extend period of active plant growth, and 4) maintain soil cover—and the associated linkage of soil ecological processes to management all have roots in cropland management and, therefore, will challenge grazing lands professionals to assess the applicability of these principles to their natural resource concerns. Increasing plant diversity often results in increased aboveground biomass and biogeochemical cycling (Tilman et al., 1997), as well greater temporal stability of productivity (Isbell et al., 2009). Regarding maintenance of soil cover, however, many ecological sites, by their inherent plant-soil-climate relationships, exhibit high amounts of bare ground, even in grazing-resistant grazing lands (e.g., Augustine et al., 2012). Moreover, high amounts (25 − 50%) of bare ground are necessary for some grassland bird species (Augustine and Derner, 2012; Schroeder, 1985). Collectively, spatiotemporal linkages of soil processes and management that emphasize heterogeneity of disturbance and conservation of pattern (Fuhlendorf et al., 2012) should challenge the applicability of soil health principles to grazing lands.

The soil health renaissance for grazing lands is tempered by limited scientific evidence, especially on rangelands (Brown and Herrick, 2016), illustrating positive feedbacks between soil health and grazing land resilience, or sustainability. A body of knowledge on soil health does exist from other agroecosystems over the past 2 decades (e.g., Arias et al., 2005; Doran and Jones, 1996; Jordan et al., 1995; Karlen et al., 1997; Trivedi et al., 2016), but these systems have been substantially altered in structure and function through prior repeated tillage. Linkages have been determined among soil microbial biomass, respiration, and decomposition and plant species diversity on grazing lands (Bardgett and Shine, 1999; Stephan et al., 2000; van der Heijden et al., 2008), but illustrations of how these plant-soil interactions improve grazing land function, resilience, and sustainability are rare. Opportunities for direct soil health improvements on pasture systems are likely constrained to intensively managed plant communities in pastures and formerly cultivated or degraded lands (e.g., Machmuller et al., 2015; Weinhold et al., 2004). This distinction within grazing lands regarding differential capacity between rangeland ecosystems and managed pasture systems regarding improvements to soil health is an important one for land managers, extension professionals, and scientists.

With renewed national interests in policy and planning for soil health in agricultural systems, the goal of this paper is to provide direction and recommendations for grazing lands' soil health efforts. Here, we argue that the current soil health renaissance is an opportunity not to focus on improvement of soil health on lands where potential is limited but rather to forward science-based management on grazing lands via 1) refocusing grazing management on fundamental ecological processes (water and nutrient cycling and energy flow) rather than maximum short-term profit or livestock production; 2) emphasizing goal-based management with adaptive decision making informed by specific objectives incorporating maintenance of soil health at a minimum and directly relevant monitoring attributes; 3) advancing holistic and integrated approaches for soil health that highlight social-ecological-economic interdependencies of these systems, with particular emphasis on human dimensions; 4) building cross-institutional partnerships on grazing lands' soil health to enhance technical capacities of students, land managers, and natural resource professionals; and 5) creating a cross-region, living laboratory network of case studies involving producers using soil health as part of their grazing land management. Explicitly incorporating soil health into grazing management and the matrix of ecosystems services provided by grazing lands provides transformational opportunities by building tangible links between natural resources stewardship and sustainable grazing management (e.g., Brown and Herrick, 2016), as well as providing paths to reach broader audiences and enhance communications among producers, customers, and the general public (Fig. 1).

Refocus Grazing Management from Practices to Ecological Processes

Ecoregional differences across grazing lands in the United States influence types of forage species, plant growth patterns, scale of operation, and management practices such as stocking rate and type of grazing system (Roche et al., 2015). A primary management issue for both extensively managed rangelands and intensively managed pasture systems is overcoming the temptation to rely on a prescriptive practice (e.g., "one size fits all") or set of practices rather than to incorporate fundamentals of ecological processes within the existing spatiotemporal heterogeneity and complexity of ecosystems (Boyd and Svejcar, 2009; Derner et al., 2009; Fuhlendorf and Engle, 2001; Fynn, 2012). For example, the 1985 Farm Bill legislation substantially increased conservation funding for NRCS (Monke and Johnson, 2010) and accelerated producer deployment of prescriptive rotational grazing strategies through cost-sharing facilitating practices of cross-fencing and water development. However, these practices, in and of themselves, are not likely to be

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Grazing Lands Soil Health

Potential for Transformational Changes by Strengthening Links Between Natural Resources Stewardship and Sustainable Grazing Lands Management

Rangelands

Opportunities

1) Focus on maintaining existing levels; very limited scientific evidence for improvement.
2) Target formerly cultivated or degraded lands.
3) Development of process-based, management-scale soil health indicators.

Pastures

Opportunities

1) Improvement with intensive management; limited scientific evidence.
2) Target formerly cultivated or degraded lands.
3) Development of process-based, management-scale soil health indicators.

Focal efforts through management-science partnerships:

1) Re-focus grazing management on fundamental ecological processes.
    - Connecting underlying drivers to management outcomes within the complex plant-soil-grazing animal-human system.
2) Use goal-based management with adaptive decision making.
    - Contemporary paradigm of grazing land management, which emphasizes conservation of pattern and process.
3) Emphasize integrated approaches highlighting interdependencies of social-ecological-economic systems.
    - Foster individual and societal norms that encourage stewardship of natural resources and sustainable behavior.
4) Facilitate building of cross-institutional partnerships.
    - Multi-directional knowledge exchange to integrate participatory and stakeholder-engaged approaches.
5) Create a cross-region, living laboratory network.
    - Observational, field-based implementation of management strategies under real-world environmental variability.
    - Participatory, grassroots efforts and peer learning opportunities.

Figure 1. Conceptual outline for soil health as a transformational change agent for US grazing lands.

effective outside of an adaptive management context (Briske et al., 2011). Thus, there is an emergent need to refocus management, education, and technical assistance on fundamental ecological processes (water and nutrient cycling and energy flow), especially within the complex plant-soil-grazing animal-human system (Boyd and Svejcar, 2009). For example, the connection of underlying drivers to management outcomes through ecologically based invasive-plant management (Sheley et al., 2010) has transformed modern approaches to natural resource problems.

The current soil health renaissance provides an opportunity to investigate connections of rangeland health indicators (Table 2) to soil health and to expand use of soil health indicators on pastures (Table 3) (Toledo et al., 2014). Rangelands lag considerably behind croplands for development of process-based, management-scale soil health indicators (e.g., Bezdicek et al., 1996; Brown and Herrick, 2016; Derner et al., 2016). The rangeland health assessment protocol (Pellant et al., 2005; Pyke et al., 2002) includes soil health indicators integrated to hydrologic function and plant community attributes that help evaluate rangeland function based on ecological processes (Printz et al., 2014, see Table 2), but scales of these indicators are not congruent with ranch-scale objectives. Development of standard place-based references or baselines for grazing land soils would create a more consistent approach for quantitative assessments of the influence of ecological processes on the connections among management, soil health, and ecosystem services (Brown and Herrick, 2016). However, we caution that plant-based indicators of soil health can be temporally disjunct with changes in soil properties and there are complexities with scaling up place-based assessments in highly spatiotemporally variable grazing lands.

Integrating Soil Health Into Goal-Based Adaptive Management

Adaptive management—an ongoing process of strategic planning and goal setting, design and implementation, resource monitoring, and frequent evaluation of management success—can provide feedback

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Table 2
Four basic soil health principles and corresponding rangeland health indicators (adapted from Printz et al., 2014).

Soil health principle	Qualitative rangeland assessment indicator
Increase plant diversity	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
Reduce soil disturbance	Indicator 9–Soil surface loss or degradation Indicator 8–Soil surface resistance to erosion Indicator 11–Compaction layer
Extend period of active plant growth	Indicator 4–Bare ground Indicator 12–Functional/structural groups Indicator 15–Annual production Indicator 16–Invasive plants
Maintain soil cover	Indicator 4–Bare ground Indicator 14–Litter amount

of information between decision making and desired outcomes and facilitate management-science partnerships (Wilmer et al. in press). Rather than implement management prescriptions, producer-determined goals would direct grazing management decisions within the context of 1) local understanding of variability and spatiotemporal patterns of historic drivers (Fuhlendorf and Engle, 2001; Fynn, 2012); 2) management experience and capacity, including skills, knowledge, structural and natural resource availability, learning, and flexibility (Roche et al., 2015); and 3) changing operational constraints of the ranch enterprise (Budd and Thorpe, 2009; Kachergis et al., 2014). The focus would then be to integrate soil health into grazing management decision making within the contemporary paradigm of rangeland management, which emphasizes conservation of pattern and process (Fuhlendorf et al., 2012). For example, the Collaborative Adaptive Rangeland Management (CARM) project uses a suite of social-ecological monitoring indicators to enhance decision making and data-driven management via a participatory approach (Wilmer et al. in press). Monitoring information from soil health indicators, as well as vegetation, livestock, and wildlife habitat data, is used by the CARM Stakeholder Group to adjust interannual and intra-annual decision making related to grazing sequences, stocking rate, pasture rest, and incorporation of prescribed burns.

Assessing the difficulty and uncertainty associated with modifying ecological processes to achieve desired goals sets adaptive management apart from the more typical static implementation of prescribed management practices, which assumes the practices, when properly implemented, attain desired outcomes. Monitoring is vital to adaptive management by incorporating appropriate metrics for assessments of management and weather and climate influences on attaining desired goals. Using adaptive management to achieve soil health goals a priori rather than relying on ex post facto decisions can provide more insightful discussions concerning contingencies associated with ecological processes. Recognizing that there are different types of monitoring indicators (drivers, short-, intermediate- and long-term responses, Herrick et al., 2012), it is important to correctly develop and use soil health monitoring metrics to provide essential information to producers regarding accomplishment of desired goals.

Table 3
Commonly measured soil health indicators for pasture (adapted from Sanderson, 2014).

Indicator	Description and purpose
Plant cover	Live stems and green leaf cover of all desirable and intermediate species. Indicator of hydrologic condition
Plant diversity	Number and proportion of forage grass and legume species
Plant residue	Amount of standing dead and litter ground cover. Related to nutrient cycling
Plant vigor	Visible signs of nutrient, drought, or pest stress
Soil compaction	Estimates of animal treading resulting in soil compaction
Soil erosion	Visual estimates of degree of sheet, rill, wind, gully, streambank, and shoreline erosion

From Financial Incentives to Participation: The Human Dimension

Financial incentives encouraging conservation efforts from producers on private grazing lands have been included in recent conservation programs (e.g., Environmental Quality Incentives Program and Conservation Stewardship Program, CSP). Payments for beneficial management practices can help producers overcome financial barriers; however, these barriers to practice adoption may be overstated (Prager and Posthumus, 2010; Reimer and Prokopy, 2014; Sorice and Donlan, 2015). Research findings from other fields (e.g., conservation, education, human health, workplace) concur that external rewards such as incentive payments can reduce intrinsic motivations (Gneezy and Fessler, 2011; Rode et al., 2015).

How, then, does a shift in focus occur from programs that emphasize financial incentives to more broadly encouraging producer participation in conservation efforts associated with incorporating soil health into grazing management for grazing lands? One suggestion is a "human-centered design" approach whereby programs addressing 1) maintenance of soil health on natural grazing lands and 2) increasing soil health where potential improvements are likely such as intensively managed plant communities in pastures, as well as formerly cultivated or degraded lands, are explicitly tailored to the needs of the target audience via social science research (Sorice and Donlan, 2015). A human-centered approach to conservation emphasizing soil health in grazing management decision making would seek to develop programs that private lands producers are drawn to because they need or want them rather than being primarily attracted due to financial incentives. Thus, the transformational shift involving soil health as a conservation focus for grazing management on grazing lands should be fostering individual and societal norms that encourage stewardship of natural resources and sustainable behavior (e.g., Leopold land ethic, Leopold, 2014). Prior underuse of social science in conservation has likely limited our understanding of conservation behavior and how to establish sustainable norms in agriculture (Bennett, 2016).

Building Cross-Institutional Partnerships

Emphasizing soil health in educational efforts as an integrator of the effects of management decisions for grazing lands' resilience provides an opportunity to strengthen and prioritize soil science within range, forage, and natural resource—related university degree programs. Soils are frequently undervalued by students seeking traditional production-oriented degrees; the integrative nature of soil health may help students better comprehend and appreciate the critical role soils play in grazing lands. Furthermore, the concept of soil health has direct links to sustainability (Lehman et al., 2016; Scoones, 2016), a topic very much in the mind of today's students, with international relevance and broad land management applicability (Doran, 2002). As such, soil health may offer an opportunity to attract and recruit students with diverse backgrounds to otherwise often shrinking traditional degree programs, and it may help stimulate the creation of innovative and integrative skills-based curricula.

Developing management-relevant and timely soil health information will require multidirectional knowledge exchange, rather than the traditional, one-way technology transfer (i.e., technical service provider to producer, the "loading dock") (Andrews et al., 2003). Soil health efforts that integrate participatory and stakeholder-engaged approaches better align research with on-the-ground management challenges, ensuring the relevance of the work, as well as improving outcomes and policy impacts (Roche et al., 2015). Communications with producers on incorporating soil health into grazing management considerations on grazing lands should focus on technical services

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linking ecological processes to management to address natural resource problems (see earlier), which will necessitate a multipronged, cross-institutional approach. Technical services should be integrated, combining science-based information and experiential knowledge to bridge management-science gaps.

Living Laboratory Network of Case Studies

Although soil health indicators for grazing lands are still in the developmental stage (see earlier), proactive establishment of a "living laboratory" network of case studies from producers engaged in incorporating soil health into grazing management considerations on grazing lands would foster 1) participatory research opportunities for producers; 2) use of citizen science in grazing lands management and research (Sayre et al., 2012); 3) integration of management and research for successful adaptive decision making (Reever Morghan et al., 2006); 4) creation of multi-institutional partnerships that would address contemporary production-conservation issues for grazing lands (Briske et al., 2011); and 5) cross-scale and cross-regional databases that would eventually support assessments of the efficacy of incorporating soil health into grazing management considerations on grazing lands, which would complement existing regional/national assessments (e.g., NRCS–National Resources Inventory data, Herrick et al., 2010). Rather than a traditional brick and mortar building where laboratory studies are conducted under controlled conditions, a soil health "living laboratory" would incorporate 1) case studies of observational, field-based implementation of management strategies under real-world environmental variability; 2) participatory, grass-roots efforts led by producers incorporating adaptive management at locally relevant scales to achieve desired goals; and 3) peer learning opportunities among producers facing similar ecological, economic, and social constraints.

A "living laboratory" network could operate within the framework of volunteer participation of producers that have existing NRCS conservation program contracts in addition to other producer-led groups (e.g., South Dakota Soil Health Coalition), local-, state- and national-level commodity organizations (e.g., grazing associations, Soil and Water Conservation Districts, Resource Conservation Districts, livestock associations, and the National Grazing Lands Coalition) and through conservation and environmental organizations (e.g., Environmental Defense Fund, The Nature Conservancy, Noble Foundation). For example, there were 19 830 producers enrolled in grazing-related CSP contracts between 2010 and 2014 (Environmental Working Group, 2017). The formation of a "living laboratory" network for soil health would complement the existing National Conservation Planning Partnership that was created in 2015 by five national conservation partners as a result of the renewed recognition of the critical role that conservation planning plays in advancing conservation efforts on private lands. Further, case studies from "living laboratories" could be used in training courses in grazing management, conservation planning on grazing lands, vegetation monitoring, and data evaluation for adaptive management. Current societal interest in soil health and the development of a Soil Health Division and associated personnel within NRCS provides the opportunity to assess and evaluate grazing management strategies adopted for the purpose of maintaining soil health in natural grazing lands through conservation programs or potentially improving soil health on intensively managed plant communities in pastures and previously cultivated or degraded lands (Derner et al., 2016).

Conclusions

Incorporating soil health into the matrix of ecosystem goods and services from grazing lands can foster transformational changes by strengthening the link between natural resources stewardship and sustainable grazing lands management. The current soil health renaissance offers the transformational opportunity for a next-generation approach to science-based grazing lands management through explicit use of relevant monitoring data in adaptive decision making. Rather than conventional approaches for grazing lands management in which prescriptive practices are implemented with assumed benefits or outcomes, adaptive management incorporates fundamentals of ecological processes within the context of ecosystem complexity through the use of feedback (learning) loops. Integrated decision making associated with vegetation-soil-livestock ecological processes highlights social-ecological-economic interdependencies of these systems. Further, an emphasis on human dimensions fosters individual and societal norms that encourage behavior by producers as a conservation focus for sustainable grazing lands management. We note, however, that current soil health renaissance is an opportunity not to focus on improvement of soil health on lands where potential is limited but rather to forward science-based management for improving grazing lands' resilience to environmental change and sustainability.

A similar transformational change for agencies—from focusing on programs to provision of technical services—is possible with the renaissance of soil health and renewed commitments to science-management intercommunication through cross-institutional partnerships. As such, soil health offers an opportunity to attract and recruit people with diverse backgrounds from innovative and integrative skills-based curricula. Benefits abound from resultant cross-cultural conversations and cross-institutional partnerships among universities, Cooperative Extension Services, natural resource agencies, environmental nongovernmental organizations, private industry, and the agricultural community. In addition, moving from the traditional, one-way technology transfer to more collaborative frameworks of multidirectional knowledge exchange, as well as the rise of participatory and stakeholder-engaged approaches, better align research with on-the-ground management challenges of producers. A soil health "living laboratory" network of case studies from producers enrolled in grazing lands conservation programs provides a tangible example of connecting management via ecological processes associated with incorporating soil health into grazing management from concept to implementation. Collectively, these efforts could foster transformational changes by strengthening the link between natural resources stewardship and sustainable grazing lands management through management-science partnerships in a social-ecological systems framework.

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References

Andrews, S.S., Flora, C.B., Mitchell, J.P., Karlen, D.L., 2003. Growers' perceptions and acceptance of soil quality indices. Geoderma 114, 187–213.

Arias, M.E., Gonzalez-Perez, J.A., Gonzalez-Vila, F.J., Ball, A.S., 2005. Soil health—a new challenge for microbiologists and chemists. International Microbiology 8, 13–21.

Augustine, D.J., Derner, J.D., 2012. Disturbance regimes and mountain plover habitat in shortgrass steppe: large herbivore grazing does not substitute for prairie dog grazing or fire. Journal of Wildlife Management 76, 721–728.

Augustine, D.J., Booth, D.T., Cox, S.E., Derner, J.D., 2012. Grazing intensity and spatial heterogeneity in bare soil in a grazing-resistant grassland. Rangeland Ecology & Management 65, 39–46.

Bardgett, R.D., Shine, A., 1999. Linkages between plant litter diversity, soil microbial biomass and ecosystem function in temperate grasslands. Soil Biology and Biochemistry 31, 317–321.

Bennett, N.J., 2016. Using perceptions as evidence to improved conservation and environmental management. Conservation Biology 30, 582–592.

Bezdicek, D.F., Papendick, R.I., Lal, R., 1996. Introduction: importance of soil quality to health and sustainable land management. In: Doran, J.W., Jones, A.J. (Eds.), Methods for assessing soil quality. SSSA Special Publication Number 49. SSSA, Madison, WI, USA, pp. 1–8.

Boyd, C.S., Svejcar, T.J., 2009. Managing complex problems in rangeland ecosystems. Rangeland Ecology & Management 62, 491–499.

Briske, D.D., Sayre, N.F., Huntsinger, L., Fernandez-Gimenez, M., Budd, B., Derner, J.D., 2011. Origin, persistence, and resolution of the rotational grazing debate: integrating human dimensions into rangeland research. Rangeland Ecology & Management 64, 325–334.

Brown, J.R., Herrick, J.E., 2016. Making soil health a part of rangeland management. Journal of Soil Water Conservation 71, 55A–60A.
Budd, B., Thorpe, J., 2009. Benefits of managed grazing: a manager's perspective. Rangeland 31 (5), 11–14.
Derner, J.D., Lauenroth, W.K., Stapp, P., Augustine, D.J., 2009. Livestock as ecosystem engineers for grassland bird habitat in the western Great Plains of North America. Rangeland Ecology & Management 62, 111–118.
Derner, J.D., Stanley, C., Ellis, C., 2016. Usable science: soil health. Rangeland 38, 64–67.
Doran, J.W., 2002. Soil health and global sustainability: translating science into practice. Agriculture, Ecosystem Environment 88 (2), 119–127.
Doran, J.W., Jones, A.J., 1996. Methods for assessing soil quality. Special Publication 49. SSSA, Madison, WI, USA.
Doran, J.W., Zeiss, M.R., 2000. Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology 15, 3–11.
Environmental Working Group, 2017. Farm Subsidy Database. Conservation Security Program. Available at: https://conservation.ewg.org/csp.php?fips=00000&regionname=theUnitedStates, Accessed date: 17 April 2017.
Fuhlendorf, S.D., Engle, D.M., 2001. Restoring heterogeneity on rangelands: ecosystem management based on evolutionary grazing patterns. BioScience 51, 625–632.
Fuhlendorf, S.D., Engle, D.M., Elmore, R.D., Limb, R.F., Bidwell, T.G., 2012. Conservation of pattern and process: developing an alternative paradigm of rangeland management. Rangeland Ecology & Management 65, 579–589.
Fynn, R.W., 2012. Functional resource heterogeneity increases livestock and rangeland productivity. Rangeland Ecology & Management 65, 319–329.
Gneezy, A., Fessler, D.M.T., 2011. Conflict, sticks and carrots: war increases prosocial punishments and rewards. Proceedings of the Royal Society B 279, 219–223.
Havstad, K.M., Peters, D.P.C., Skaggs, R., Brown, J., Bestelmeyer, B., Frederickson, E., Herrick, J., Wright, J., 2007. Ecological services to and from rangelands of the United States. Ecology Economics 64, 261–268.
Herrick, J.E., Lessard, V.C., Spaeth, K.E., Shaver, P.L., Dayton, R.S., Pyke, D.A., Jolley, L., Goebel, J.J., 2010. National ecosystem assessments supported by scientific and local knowledge. Frontiers in Ecology and Environment 8, 403–408.
Herrick, J.E., Duniway, M.C., Pyke, D.A., Bestelmeyer, B.T., Wills, S.A., Brown, J.R., Karl, J.W., Havstad, K.M., 2012. A holistic strategy for adaptive land management. Journal of Soil Water Conservation 67, 105A–113A.
Isbell, F.I., Polley, H.W., Wilsey, B.J., 2009. Biodiversity, productivity and temporal stability of productivity: patterns and processes. Ecology Letters 12, 443–451.
Jordan, D., Kremer, R.J., Bergfield, W.A., Kim, K.Y., Cacnio, V.N., 1995. Evaluation of microbial methods as potential indicators of soil quality in historical agricultural fields. Biology Fertility Soils 19, 297–302.
Kachergis, E., Derner, J.D., Cutts, B.B., Roche, L.M., Eviner, V.T., Lubell, M.N., Tate, K.W., 2014. Increasing flexibility in rangeland management during drought. Ecosphere 5, 1–14.
Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F., Schuman, G.E., 1997. Soil quality: a concept, definition, and framework for evaluation. Soil Science Society of America Journal 61, 4–10.
Lehman, R.M., Cambardella, C.A., Stott, D.E., Acosta-Martinez, V., Manter, D.K., Buyer, J.S., Maul, J.E., Smith, J.L., Collins, H.P., Halvorson, J.J., Kremer, R.J., Lundgren, J.G., Ducey, T.F., Jin, V.L., Karlen, D.L., 2016. Understanding and enhancing soil biological health: the solution for reversing soil degradation. Sustainability 7, 988–1027.
Leopold, A.C., 2014. Living with the land ethic. Bioscience 52, 149–154.
Machmuller, M.B., Kramer, M.G., Cyle, T.K., Hill, N., Hancock, D., Thompson, A., 2015. Emerging land use practices rapidly increase soil organic matter. Nature Communications 6, 6995.
Monke, J., Johnson, R., 2010. Actual Farm Bill spending and cost estimates. Congressional Research Service, Washington, DC, USA, p. R41195.
Pellant, M., Shaver, P., Pyke, D.A., Herrick, J.E., 2005. Interpreting indicators of rangeland health, version 4. Technical Reference 1734-6. USDI, Bureau of Land Management, National Science and Technology Center, Denver, CO, USA BLM/WO/ST-00/001 + 1734/REV05. 63 p.
Prager, K., Posthumus, H., 2010. Socio-economic factors influencing farmers' adoption of soil conservation practices in Europe. Human Dimensions of Soil and Water Conservation 12, 1–21.
Printz, J.L., Toledo, D., Boltz, S., 2014. Rangeland health assessment: the key to understanding and assessing rangeland soil health in the Northern Great Plains. Journal of Soil and Water Conservation 69, 3 73A.
Pyke, D.A., Herrick, J.E., Shaver, P., Pellent, M., 2002. Rangeland health attributes and indicators for qualitative assessment. Journal of Range Management 55, 584–597.
Reever Morghan, K.J., Sheley, R.L., Svejcar, T.J., 2006. Successful adaptive management – the integration of research and management. Rangeland Ecology & Management 59, 216–219.
Reimer, A.P., Prokopy, L.S., 2014. Farmer participation in U.S. Farm Bill conservation programs. Environmental Management 53, 318–332.
Roche, L.M., Cutts, B.B., Derner, J.D., Lubell, M.N., Tate, K.W., 2015. On-ranch grazing strategies: context for the rotational grazing dilemma. Rangeland Ecology & Management 68, 248–256.
Rode, J., Gómez-Baggethun, E., Krause, T., 2015. Motivation crowding by economic incentives in conservation policy: a review of the empirical evidence. Ecology Economy 117, 270–282.
Sanderson, M.A., 2014. Evaluating the USDA-NRCS pasture condition score system with weighted indicators. Ecology Indicators 41, 183–186.
Sayre, N.F., duBuys, W., Bestelmeyer, B.T., Havstad, K.M., 2012. "The range problem" after a century of rangeland science: new research themes for altered landscapes. Rangeland Ecology & Management 65, 545–552.
Schroeder, R.L., 1985. Habitat suitability index models: northern bobwhite. US Fish and Wildlife Service Biology Report 82 (10.104) 33 p.
Scoones, I., 2016. Transforming soils: transdisciplinary perspectives and pathways to sustainability. Current Opinion in Environmental Sustainability 15, 20–24.
Sheley, R., James, J., Smith, B., Vasquez, E., 2010. Applying ecologically based invasive-plant management. Rangeland Ecology & Management 63, 605–613.
Sorice, M.G., Donlan, C.J., 2015. A human-centered framework for innovation in conservation incentive programs. Ambio 44, 788–792.
Stephan, A., Meyer, A.H., Schmid, B., 2000. Plant diversity affects culturable soil bacteria in experimental grassland communities. Journal of Ecology 88, 988–998.
Tilman, D., Knops, J., Wedin, D., Reich, P., Ritchie, M., Siemann, E., 1997. The influence of functional diversity and composition on ecosystem processes. Science 277, 1300–1302.
Toledo, D.N., Sanderson, M.A., Herrick, J.E., Goslee, S.C., 2014. An integrated approach to grazing land ecological assessments and management interpretations. Journal of Soil Water Conservation 69, 110A–114A.
Trivedi, P., Delgado-Baquerizo, M., Anderson, I.C., Singh, B., 2016. Response of soil properties and microbial communities to agriculture: implications for primary productivity and soil health indicators. Frontiers in Plant Science 7, 990.
van der Heijden, M.G.A., Bardget, R.D., van Straalen, N.M., 2008. The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. Ecology Letters 11, 296–310.
Weinhold, B.J., Andrews, S.S., Karlen, D.J., 2004. Soil quality: a review of the science and experiences in the USA. Environmental Geochemistry and Health 26, 89–95.
Wilmer, H, Derner, J. D., Fernandez-Gimenez, M. E., Briske, D. D., Augustine, D. J., Porensky, L. M., the CARM Stakeholder Group. Collaborative adaptive rangeland management fosters management-science partnerships. Rangeland Ecology & Management (in press).
Zornoza, R., Acosta, J.A., Bastida, F., Dominguez, S.G., Toledo, D.M., Fax, A., 2015. Identification of sensitive indicators to assess the interrelationships between soil quality, management practices and human health. The Soil 1, 173–185.

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