Chapter 16
Monitoring Protocols: Options, Approaches, Implementation, Benefits

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Abstract Monitoring and adaptive management are fundamental concepts to rangeland management across land management agencies and embodied as best management practices for private landowners. Historically, rangeland monitoring was limited to determining impacts or maximizing the potential of specific land uses—typically grazing. Over the past several decades, though, the uses of and disturbances to rangelands have increased dramatically against a backdrop of global climate change that adds uncertainty to predictions of future rangeland conditions. Thus, today's monitoring needs are more complex (or multidimensional) and yet still must be reconciled with the realities of costs to collect requisite data. However, conceptual advances in rangeland ecology and management and changes in natural resource policies and societal values over the past 25 years have facilitated new approaches to monitoring that can support rangeland management's diverse information needs. Additionally, advances in sensor technologies and remote-sensing techniques have broadened the suite of rangeland attributes that can be monitored and the temporal and spatial scales at which they can be monitored. We review some of the conceptual and technological advancements and provide examples of how they have influenced rangeland monitoring. We then discuss implications of these developments for rangeland management and highlight what we see as challenges and opportunities for implementing effective rangeland monitoring. We conclude with a vision for how monitoring can contribute to rangeland information needs in the future.

Keywords Rangeland monitoring • Management objectives • Remote sensing • Sampling design • Core indicators • Land health

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16.1 Changing Needs for Rangeland Monitoring

Monitoring has long been recognized as a critical tool for rangeland management. The collection and use of monitoring data to protect and improve rangelands (i.e., principles of adaptive management) have been promoted since the early twentieth century (West 2003a). In 1915, just 3 years after the creation of the Jornada Experimental Range in southern New Mexico, a large network of monitoring plots was established to better understand and address the rapid degradation that was already occurring from excessive livestock grazing (Gibbens et al. 2005). In the first textbook on range management, Sampson (1923) promoted the idea of "a systemized study, designed to secure the data that will lead to permanent improvement in management and to increased profits from the lands." The basic concepts of monitoring and adaptive management are now fundamental to rangeland management across land management agencies and embodied as best management practices for private landowners (West 2003a; Boyd and Svejcar 2009).

Historically, rangeland monitoring was limited to determining impacts or maximizing the potential of specific land uses—typically grazing. Because of the recognized heterogeneity of rangelands, uneven distribution of land uses (e.g., grazing), and expense associated with obtaining measurements across large areas, monitoring activities were focused on areas where impacts were either observed or expected (Dyksterhuis 1949; Bureau of Land Management 1996).

Over the past several decades, though, the uses of and disturbances to rangelands have increased dramatically. Historically, grazing, has been a dominant land use on rangelands worldwide. In the United States, though, it is increasingly a minor component in some rangelands compared to other uses such as energy development, recreation, and conservation. Diffuse and widespread disturbances that alter the character and potential of rangelands like non-native plant invasion, woody plant encroachment, and altered wildland fire regimes are prevalent. Additionally, rangelands are increasingly being valued for providing ecosystem services including clean and reliable water supplies, clean air, recreational opportunities, and habitat for many plants and animals, as well as numerous, diverse soil microorganisms (Sala and Paruelo 1997). These changes have altered the need for and character of rangeland monitoring.

The diverse uses and disturbances to rangeland ecosystems are also occurring against a backdrop of global climate change that adds more uncertainty to predictions of future rangeland conditions. The effects of changing climatic conditions on plant community composition and production are expected to be variable regionally (Briske et al. 2015), and increasing inter-annual variability of precipitation (IPCC 2007) and temperature may make detecting management-related changes more challenging (Fuhlendorf et al. 2001). Accordingly there is a need for monitoring data to establish baselines of rangeland conditions and to document changes in condition to both understand impacts of climate change and differentiate those effects from other disturbances or management activities. Monitoring data will also be needed to develop and evaluate climate adaptation and mitigation strategies.

Current multidimensional monitoring needs for rangeland management, however, must be reconciled with realities of costs to collect the requisite data. Monitoring of large rangeland landscapes is complicated by logistical constraints, high variability of rangeland indicators due to inter-annual climate fluctuations and environmental heterogeneity, and costs of monitoring. Despite the fact that it has long been recognized as an important aspect of rangeland management, monitoring often has been perceived as an incidental activity that takes funds away from management actions (Wright et al. 2002). The varied reasons for this include a lack of linkages between monitoring and management decision-making and perceptions of redundant monitoring efforts. Thus the challenges of monitoring rangelands include institutional hurdles to valuing and effectively using monitoring data.

Relative to rangeland management or research, monitoring generally refers to the systematic collection, analysis, and use of quantitative information on rangeland resources over time to support management decision-making (Bedell 1998). Two related activities are assessments (estimating or judging the condition or value of an ecological system or process at a point in time) and inventories (systematic acquisition and analysis of information for rangeland resource planning and management) (Pellant et al. 2005). Whereas there are many specific definitions for these three terms in rangeland management, the ideas discussed here apply across all these activities. Thus, for brevity, we use the term monitoring generically.

Conceptual advances in rangeland ecology that were introduced in the early 1990s and subsequently developed over the past 25 years have facilitated new approaches to monitoring that can support rangeland management's diverse information needs (Text Box 16.1). Additionally, technological advances have broadened the suite of

Text Box 16.1: Knowns and Unknowns "As we know, there are known knowns. There are things we know we know. We also know there are known unknowns. That is to say we know there are some things we do not know. But there are also unknown unknowns, the ones we don't know we don't know".—Donald Rumsfeld, US Defense Secretary (2002).

The quote above was one of the most famous quotes from U.S. Defense Secretary Donald Rumsfeld. It was given in response to a question from a reporter about the existence and veracity of evidence to support the assertion that Iraq possessed weapons of mass destruction. While this quote was almost universally mocked as being an evasion of the question rather than an answer, the idea of known unknowns and unknown unknowns has a longer history (Morris 2014) and is relevant to monitoring of rangeland resources.

Most successful monitoring programs are intended to address the known unknowns. They are built around answering specific questions for which critical data are lacking. These questions should lead to selection of a minimal set of indicators and methods and development of a sampling design to provide

(continued)

Text Box 16.1 (continued)

the identified missing information. This is the classic model of natural resource monitoring, and it has been proven effective when it is applied.

However, one of the hopes when implementing rangeland monitoring is that the data collected will be at least somewhat informative for new resource concerns that arise. In other words, this information can hopefully address the unknown unknowns too. Recently, rangeland managers in the western USA have experienced information shortages related to the status and trend of Greater sage-grouse (*Centrocercus urophasianus*) habitat and the impacts of energy development (oil and gas, wind, solar, transmission lines) on rangeland ecosystems. Many of the existing monitoring programs which were developed around livestock grazing objectives are ill-equipped to inform on these new objectives. The hope, then, is that monitoring programs built around concepts of core indicators and methods and statistically based sampling designs will provide greater opportunities to compile existing monitoring data for new objectives. While it is naive to think that general monitoring programs or compilations of existing monitoring data will address all of the information needs of a new question, robust and interoperable monitoring programs would provide a better foundation from which to begin.

rangeland attributes that can be monitored and the temporal and spatial scales at which they can be monitored. Below we review some of these conceptual and technological advancements and provide examples of how they have influenced rangeland monitoring. We then discuss implications of these developments for rangeland management. We highlight what we see as challenges and opportunities for implementing effective rangeland monitoring, and conclude with a vision for how monitoring can contribute to rangeland information needs in the future.

16.2 Conceptual Advances in the Past 25 Years

Conceptual advances in rangeland monitoring over the past 25 years have been driven by developments in ecological theory, changes in natural resource policies and societal values, and emergence of new technologies. The 1980s and early 1990s were a critical period for development of ecological theories that have proven to be pivotal for rangeland management. During this time scale theory was formally defined (see Wiens et al. 2007) and the field of landscape ecology was founded (see Wiens 1999). For rangeland management, perhaps the biggest conceptual advance was the recognition that rangeland systems are characterized by nonlinear dynamics (Briske et al. 2005; Kefi et al. 2007) and cross-scale processes (Peters et al. 2004) that can produce multiple ecosystem states (Chap. 6, this volume). This change in thinking brought into focus the importance of measuring ecological processes and functions at and across characteristic scales on which they operate (Addicott et al. 1987; Peters et al. 2004; Nash et al. 2014).

Rangeland Reform '94 (U.S. Bureau of Land Management and U.S. Forest Service 1994) was the first attempt by federal agencies in the USA to change how rangeland under Bureau of Land Management (BLM) and U.S. Forest Service (USFS) management would be evaluated since the environmental policies of the 1970s (e.g., Federal Land Policy and Management Act of 1976, National Forest Management Act of 1976, Public Rangeland Improvement Act of 1978 BLM and USFS 1994). Two goals of Rangeland Reform '94 were to bring the two management programs closer together and more consistent in conducting ecosystem management and to accelerate the restoration and improvement of public rangelands to proper functioning condition. The changes brought forth in Rangeland Reform '94 were strongly influenced by the National Research Council (1994) report on rangeland health. Each state developed standards of rangeland health that reflected the need to monitor not just plants important for livestock grazing, but biological diversity, soil stability, hydrologic functioning, energy flow, and nutrient cycling (Veblen et al. 2014).

As part of the goal to bring agencies together in their management of rangelands, the USDA Natural Resources Conservation Service, USFS, and BLM entered into a Memorandum of Understanding in 2005 to define and describe rangelands using a standard classification system, ecological sites (Caudle et al. 2013). This resulted in federal and non-federal rangelands being classified using the same process where soils, landforms, and climate describe potential plant communities and their production. This led to common terminology and similar metrics for determining rangeland status and trends. Standardized terms and metrics position land managers to take advantage of new technology that cross-cuts management and political boundaries through remote sensing and database access (Chap. 9, this volume).

Technological advances in the past quarter century have dramatically increased efficiency of monitoring data collection and analysis as well as opened new possibilities for synoptic rangeland monitoring. The development of robust mobile computing technologies has encouraged electronic capture of data in the field, reducing the potential for recording and transcription errors. The ubiquity and reliability of global positioning system (GPS) technologies not available two decades ago makes it easy to accurately locate (and relocate) monitoring areas. Also during this time period, many of the imaging sensors and analytic techniques that have made remote sensing a staple part of monitoring were developed.

The changes described above—theoretical, policy, and technological—have had a significant impact on how rangelands are monitored and how those data can be used for management decision-making. The following are some of the major conceptual advances to rangeland monitoring from the last 25 years.

16.2.1 Monitoring Land Health Instead of Land Uses

Governments throughout the world have shifted from monitoring plant community responses to a single land use (usually livestock production), to documenting and understanding changes in land health (i.e., the degree to which the integrity of soils, vegetation, water, air, and ecological processes are sustainable, Bedell 1998) in response to multiple land uses. In Australia, Landscape Function Analysis (LFA) was developed to more effectively document and monitor changes in the "leakiness" of water- and nutrient-limited rangeland ecosystems (Ludwig et al. (2004). In the United States, NRCS and BLM have both adopted a suite of measurements that were selected largely because they generate indicators of ecosystem function, while also providing more traditional indicators of plant community composition. These were designed to complement the Interpreting Indicators of Rangeland Health (IIRH) assessment protocol which, like the new BLM and NRCS monitoring systems, was developed in response to the recommendations of the National Research Council and Society for Range Management (National Research Council 1994; Adams et al. 1995). Monitoring systems promoted by private consultants, and NGO's have also taken a more holistic approach, including those directly or indirectly associated with "Holistic Management" such as LandEKG (http://landekg.com) and Bullseye (Gadzia and Graham 2013). These changes have been driven by a number of synergistic factors, including (a) an increasing number of uses of rangelands, in both developed and developing countries, (b) climate change, (c) a more profound understanding of rangeland ecosystem processes and their interactions, and particularly (d) how land uses contribute to transitions in plant communities.

Rangelands that had been exclusively managed for livestock production are increasingly used for energy and crop production and for recreation. Each of these uses introduces novel disturbances, with often unpredictable effects. This has required the development of monitoring systems that are sensitive to the impacts of both current known land uses and unknown future ones. Monitoring the health of the fundamental properties and processes upon which rangelands depend provides managers with the confidence that they will be able to detect the impacts of land uses that don't even yet exist. For similar reasons, climate change has also driven a shift to monitoring land health (Chap. 7, this volume). Because of uncertainty around how climate will change at specific locations and how these changes will affect ecosystem structure and processes, monitoring systems designed to reflect general changes in land health are more likely to detect climate change impacts than those that are narrowly designed to reflect changes in plant community composition in response to grazing.

Arguably the most important conceptual development contributing to the transformation of rangeland monitoring programs has been the increased awareness of threshold transitions and the potential for development of alternative stable states. Previous conceptual models of change in rangelands had been based on linear processes of succession and retrogression that focused primarily on changes in plant community composition in response to preferential livestock grazing of "decreaser" species and avoidance of "increaser" species (Dyksterhuis 1949). As a result, these models largely failed to account for how changes in soil properties and especially soil hydrology can accelerate and even precede more visible changes in plant community composition (see "Developing and measuring soil indicators" below). Land health necessarily requires a broader and more holistic focus (Herrick et al. 2012).

16.2.2 Functional Indicators of Land Health

An indicator is an aspect of an ecosystem or process that can be observed or measured and provides useful information about the condition of the system being monitored (Suter 2001; White 2003). Indicators may be direct measures of an important ecosystem attribute or service (e.g., vegetation biomass is a direct measure of ecosystem productivity) or indirect measures that are correlated with an ecosystem feature or process that is difficult to measure directly (e.g., wind erosion is related to vegetation height and bare ground amount). In either case, to be useful for monitoring, an indicator must be both measurable and related in a known way to the structure and function of the ecosystem being monitored (Suter 2001). For example, the amount of bare ground on a site and its arrangement can be an indicator of risk of soil erosion, soil nutrient loss, decreased water infiltration, and species invasion if the site's potential is known.

In the past, rangeland monitoring focused on measuring a few indicators specific to the impacts of land uses (primarily indicators related to forage production and utilization). The shift to focusing on measuring and monitoring rangeland health and the need to consider how different land uses affect land health have triggered a shift toward monitoring indicators that are functionally related to ecosystem processes. West (2003b) suggested that "… the recent switch to functional attributes rather than singular utilitarian variables is likely to assist in staying the course longer in future monitoring efforts. It is also easier for range professionals to interact with other disciplines and multiple land owners when more general structural and functional attributes of ecosystems are used as proxies for more practical ones." Several useful frameworks for selecting functional indicators for ecosystem monitoring have been developed (Breckenridge et al. 1995; Tegler et al. 2001; Fancy et al. 2009).

Noon (2003) observed that a lack of ecological theory or logic to justify the selection of indicators may explain why monitoring programs historically have failed to provide useful information for natural resource management. A significant advancement in land management from the past 25 years that has helped in this regard is the development and use of conceptual models of rangeland structure and function to identify and interpret suitable functional indicators for monitoring (Noon 2003; Miller et al. 2010).

Conceptual models document what is known about the important components of an ecosystem, the nature and strength of interactions among them, and attributes that characterize different states of the ecosystem (Noon 2003; National Park

Service 2012). Conceptual models illustrate, commonly through visual and narrative summaries, how ecological processes, disturbances, and management actions affect an ecosystem. While not necessarily statistical or predictive in nature, conceptual models are useful for supporting a monitoring program because they document the known (or hypothesized) impacts of management and other disturbances on plant communities and soils (Fig. 16.1). This knowledge identifies the aspects of the system that should be measured (i.e., indicators) and provides an understanding of how to interpret observed changes in those indicators. Conceptual models can also highlight knowledge gaps in ecosystem structure or function (Karl et al. 2012c).

16.2.3 Core Indicators and Methods

A common criticism of rangeland monitoring (in fact, natural resource monitoring in general) is that there is little consistency among monitoring programs in the indicators that are monitored and the methods used to monitor them. This may hinder the ability of data to be used to address multiple resource concerns or combined across projects or jurisdictions. Examination of almost any monitoring methods text (e.g., Elzinga et al. 1998; Bonham 2013) shows myriad quantitative and qualitative methods for measuring almost any indicator. Additionally, the rangeland profession has not adopted a routine practice of validating new methods before they are implemented in monitoring programs (West 2003a).

Although the root causes of method proliferation in rangeland monitoring are diverse (e.g., isolated nature of monitoring programs historically, perceived need for quick and easy to implement methods, methods developed in one region that do not work well in other regions), the effect has been extreme difficulty in combining measurements among monitoring programs and significant challenges in assessing or monitoring rangeland resources above local scales. West (2003a) claimed that "Lack of consistent and comparable monitoring procedures within and between the federal management, advisory, and regulatory agencies has made it impossible to conclude reliably what the overall condition and trends in conditions of our public rangelands are." In their report on resource conditions in the United States, the Heinz Center (2008) concluded that the lack of consistent indicators collected using standardized methods precluded all but a cursory assessment of natural resource conditions. Even for rangelands managed by a single agency and land use, the BLM used five types of data (frequency, cover, production, utilization, and photos) from 15 different methods to monitor range trend plots across 310 allotments in six states (Veblen et al. 2014).

A consistent, minimal (i.e., core) set of standard indicators and methods for rangeland monitoring offers several potential advantages. First, it provides the ability to combine datasets from different monitoring programs (e.g., across jurisdictions). Second, it allows for data to be scaled up to support inferences to areas of larger extent. Third, standard indicators give an opportunity for data to be reused for different purposes. For example, when a new management concern arises, existing

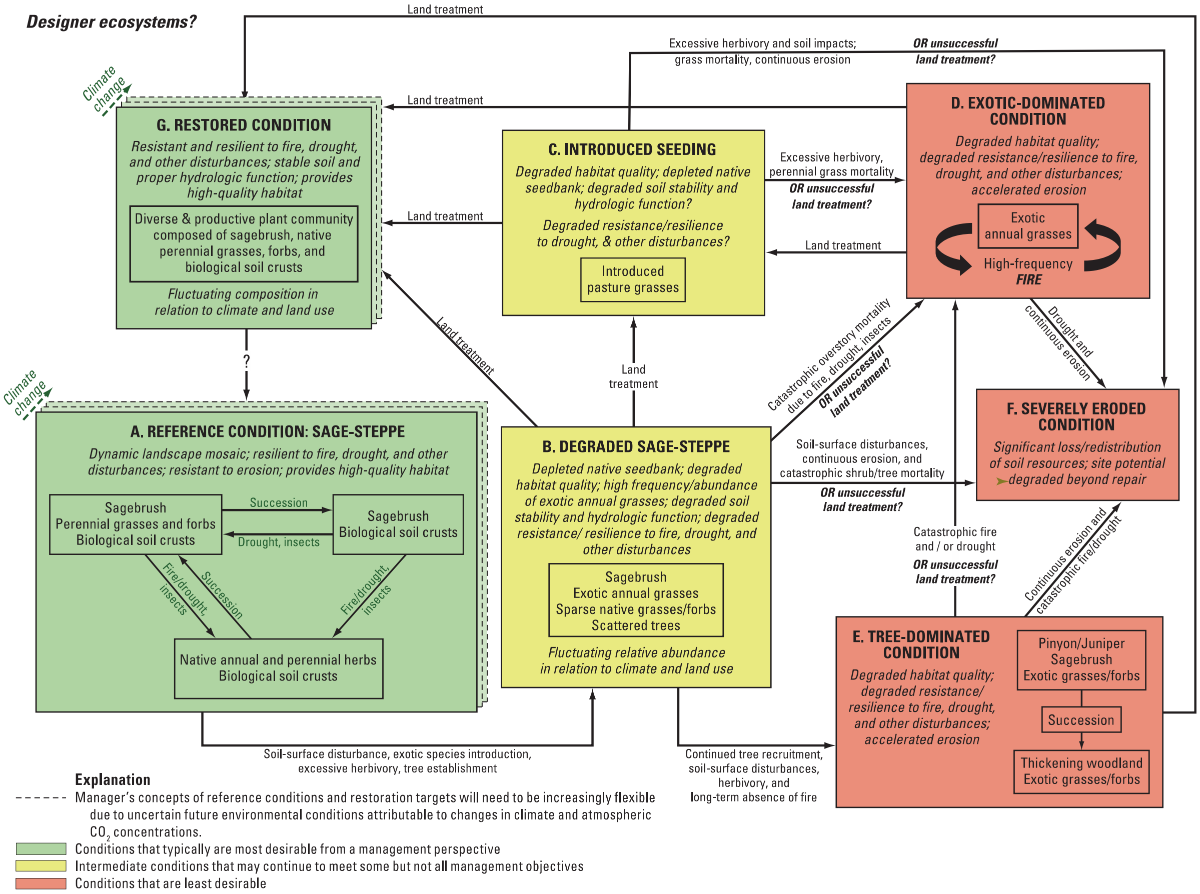

Fig. 16.1 Conceptual models are synthetic depictions about what is known or hypothesized about how an ecosystem is organized and functions. This information can be useful in identifying indicators for monitoring, thresholds or reference ranges for those indicators, and interpretations of indicator changes. The state-and-transition conceptual model above is one example of how a conceptual model for a sagebrush steppe ecosystem in the Great Basin, USA, could be organized. Model reprinted from Miller et al. (2010). General structure follows Bestelmeyer et al. (2003) and Stringham et al. (2003)

monitoring data may be available to provide initial estimates of resource conditions and trends. These potential benefits stem from core indicators resolving incompatibilities between data types used to describe rangeland ecosystems. West (2003a) summarized this need as "… there remains some desirability in choosing at least a short list of variables and means to monitor and in presenting their responses across as wide array of rangelands as possible so that the user could say that a generally approved approach had been employed."

The idea of a minimum set of standard ecosystem indicators and methods for measuring them has been suggested before (West 2003b, H. John Heinz III Center for Science 2008). However, it has only been recently that terrestrial indicators have been actually implemented (e.g., Herrick et al. 2010; Mackinnon et al. 2011; Toevs et al. 2011).

The concept of core indicators is not without criticism. One argument against standardized core indicators is that each region or area has a unique set of ecosystem and management properties and is constrained by historic events, therefore each monitoring program (including selected indicators) must be designed for its specific system (White 2003; Fancy and Bennetts 2012). While this is undoubtedly true, there are indicators that are informative over large regions (e.g., amount of bare ground, woody plant cover) and larger scale questions that can be asked (e.g., what proportion of rangelands have more than 15 % cover of annual grasses?) if core indicator data are available. Also, current implementations of core indicators (e.g., Mackinnon et al. 2011) provide for additional, supplemental indicators to meet local needs.

Another argument against standardized core indicators is that the need to maximize efficiency of a monitoring program (e.g., to minimize costs or to achieve a desired sample size) should encourage strict parsimony in selecting the most informative indicators (White 2003). This argument assumes that enough is known about an ecosystem when designing a monitoring program to select informative indicators, and there will not be need in the future to measure additional indicators. It also takes a narrow view of efficiency—i.e., efficiency is maximized only within a single objective and not among a suite of management information needs. The development and adoption of rangeland core indicators, however, is currently being driven by the need to find efficiencies in monitoring at larger organizational levels. Monitoring data that can be used to address more than one management objective and answer questions at more than one scale are more efficient in terms of cost than data that cannot.

Such a set of core indicators—measurable ecosystem components that are applicable across many different ecosystems and informative to many different management objectives—would be the basis for national-level monitoring programs and comprise a minimal set that should be measured in all monitoring programs. While it is not possible to select a set of indicators that will satisfy all management information needs across scales, the criteria listed in Table 16.1 are useful for considering which core indicators to select.

Core indicators provide no utility for rangeland monitoring without an accompanying set of standardized core methods for measuring them. Seemingly minor

Table 16.1 Criteria for selecting core indicators for rangeland monitoring

Criteria	Description
Relevant to ecosystem structure or function*	Indicators must relate in a known way (e.g., documented in a conceptual model) to the structure or function of an ecosystem of interest.
Usability*	Sufficient documentation exists to select appropriate methods and calculate indicators from measurements or observations.
Cost-effectiveness*	Cost of collecting indicator data is lower than for other competing indicators.
Cause/effect*	A clear understanding exists of how changes in ecosystem attributes will result in changes to the indicator.
Signal-to-noise ratio*	Changes in indicator values are primarily related to the intended ecosystem attribute and not natural variability or other factors.
Quality assurance*	Quality assurance and control procedures are available and adequate.
Anticipatory*	Indicator provides early warning of widespread ecosystem changes.
Historical record*	Information on the indicator has been collected over a period of time such that a reference set of data exist.
Retrospective*	Provides information about historic conditions (e.g., tree rings), over extended time periods (e.g., soil carbon), or can be applied to previously collected data (e.g., remote-sensing imagery).
New information*	Provides new information (i.e., not redundant with other indicators).
Minimal environmental impact*	Collection of information for measuring the indicator causes the least amount of disturbance to the environment.
Used by other monitoring programs	Priority should be given to indicators that are in use by other (especially regional to national) monitoring programs to facilitate cross-program data combination.
Easy to understand and explain	Indicators that are intuitive are likely to be more effective at informing and influencing management decisions.
Applicable to policy and management	Indicators that relate to aspects of an ecosystem that can be managed or that are tied to range management policies should be prioritized.

* denotes criteria proposed by White (2003) for selecting environmental monitoring indicators in general. While it may not be possible to meet all criteria when selecting indicators, priority should be given to the indicators that satisfy as many as possible

differences among methods can result in incompatible data (Bonham 2013). For instance, differences in definitions between soil and rock can cause one method to produce higher estimates of an exposed soil indicator relative to another method. Similarly, for plant-cover indicators, foliar cover methods usually yield different estimates than total-canopy cover methods (Toevs et al. 2011). Core methods represent a minimal set of information that should be collected in almost all monitoring efforts and are intended to encourage combination and “scaling-up” of monitoring datasets.

In selecting core methods, the repeatability, quality, and objectivity of data that the method provides should be considered. The attributes of a method that should be

Table 16.2 Desired properties of core methods for monitoring rangeland ecosystems

Property	Description
Quantitative	A method should record measurements or direct observations of a site's biophysical features.
Repeatable and efficient	Measurements should be repeatable within a stated margin of error and should be able to be collected at minimal cost.
Low potential for non-sampling error	Methods that minimize sources of error (e.g., inter-observer variability) and perform consistently across a wide range of environments.
Objective	Methods should minimize the opportunity for observer bias to influence the results.
Established and validated	Methods implemented for monitoring programs should be well documented and tested. Quality assurance and quality control procedures should be well defined.
Implementable with minimal training	Ideally methods should be able to be learned quickly and reliable data collected by individuals without extensive experience. Comprehensive training and calibration programs should accompany any method implemented in a monitoring program.
Can be used to calculate many indicators	The more indicators that can be derived from a method's data, the more value it can offer as a core method.
Used in other monitoring programs	Methods that are already implemented in other (especially large-scale) monitoring programs should.

prioritized when selecting core methods are similar to those for core indicators (Table 16.2). Selection of core methods is an exercise in optimizing these attributes in combination with a set of selected core indicators.

In some cases, monitoring objectives may not be able to be addressed through the core indicators. In these cases, it is appropriate to specify additional *supplemental* indicators to meet management and monitoring objectives. Supplemental indicators can be specific to land uses (e.g., grazing), programs (e.g., off-road vehicle management), or management actions (e.g., restoration following a fire). For example, the core indicators provide information for assessing impacts of grazing (e.g., cover of forage plants, amount of bare ground). However, this information is sometimes not sufficient to evaluate the effectiveness of grazing management actions. Supplemental indicators, such as forage production, utilization, or residual cover, may be selected in addition to the core indicators to inform grazing management. Where only residual cover is required, it can be easily calculated using data from whichever core method is used for monitoring vegetation cover and composition, eliminating the need for a supplementary method. Supplemental indicators are often intended to meet local management needs, so there may be little expectation to combine or share these indicators across management boundaries.

However, standard methods should be applied whenever possible (i.e., caution should be used in selecting supplemental methods that duplicate indicators that can be calculated from the core methods). Additionally extra expenses of implementing supplemental methods should be justified. In selecting supplemental indicators, the same criteria apply as in selecting core methods.

16.2.4 Statistical Sampling Designs and Monitoring at Appropriate Scales

Given the increasing number of land uses, disturbances, and contention over management of rangeland resources, statistical approaches to sampling designs that can support monitoring for multiple objectives and scaling up and down of monitoring data are necessary. While the shift in emphasis from managing pastures to landscapes has occurred primarily in the last 25 years, rangeland managers have long recognized the need to combine site-level monitoring and management with landscape-scale observations relative to grazing. The key area concept, monitoring of selected areas in an allotment or pasture that are indicative of typical grazing use, was developed in an effort to determine grazing impacts across a landscape when the distribution of livestock was not consistent across the area (Standing 1938). The key area concept originally was stated as a livestock expected use area within which monitoring locations would be randomly selected (Stoddart and Smith 1943, see also Holechek et al. 2001). In practice, however, key areas have often been located subjectively, usually based on best professional judgment, in areas that would receive the most typical grazing use and avoid areas that saw unusually heavy livestock use (e.g., around water access points) or areas that received no use (e.g., too far from water, or too steep) (e.g., Bureau of Land Management 1999; Schalau 2010). Key areas typically maintain key species, those species used by livestock, are abundant and productive, and are representative throughout the area. Key species generally do not include highly desirable species that livestock may overuse, nor do they include species that may have the potential to grow on the area, but were eliminated by past use (Holechek et al. 2001). Key areas and species were thought to be an efficient means for assessing rangeland conditions relative to grazing in order to quickly detect changes with the fewest number of monitoring plots possible.

Key areas (or any other subjective or haphazardly selected sets of monitoring locations), however, have several disadvantages that significantly limit their utility for rangeland monitoring. First, selection of key areas is often a subjective process. The validity of a key area for monitoring grazing impacts in a larger landscape can be contested because of differences of opinion on what it means to be representative (Gitzen et al. 2012). Second, indicator values from key areas, when the key area has been subjectively or haphazardly selected cannot be statistically extrapolated to larger areas (Lohr 2009). Therefore indicator estimates from subjectively selected locations cannot be scaled up to larger reporting units (West 2003b). Third, assuming that key areas can be selected to be truly representative of the conditions in an area, a set of key areas will underestimate the variance of any indicator because they are a sample of only the average conditions in the area. As a result, confidence intervals will underestimate the uncertainty in the indicator estimates, and statistical tests will tend to show significant differences more than is warranted (i.e., inflated Type I errors). Finally, key areas are often representative of a single land use. Because the spatial distribution of different land uses and resource concerns vary across a landscape, a set of key areas selected for monitoring livestock impacts may not be representative for other objectives. Additionally, the ability of a key area to represent the land condition also may change over time as conditions within a landscape change (e.g., new roads are created or range improvements installed).

A statistically valid sample of a resource has several properties (Thompson 2002; Lohr 2009). First, the estimates of an indicator for that resource are unbiased. Unbiased in this context means that there is nothing inherent in the sampling design approach that would result in systematically over- or underestimating the indicator values. This is accomplished through explicit and careful definition of the study area (i.e., population) and sampling units (Table 16.3). The use of randomization techniques in selecting sampling units for monitoring allows the uncertainty about indicator estimates to be characterized and confidence intervals to be constructed around monitoring results. Uncertainty estimates (often expressed as a standard error or confidence interval, or used as part of a statistical test) are not direct measures of the variability of an indicator, but a reflection of how close an indicator estimate is to the actual indicator value in the study area.

Table 16.3 Descriptions of the basic components of a sampling design following the definitions of Thompson (2002) and Lohr (2009)

Sampling design component	General definition.
Element	An item upon which some type of information is collected (i.e., observation or measurement).
Sampling unit	A unique set of one or more elements that can be selected for being included in a sample. In rangeland monitoring, a sampling unit is often an area (e.g., a plot). The sampling unit may contain zero elements.
Sampling frame	The complete set of sampling units within the geographic area of the target population (e.g., the list of all plots available to be selected for sampling).
Sample population	All elements associated with the sampling units listed in the sample frame. Ideally this coincides with the target population, but constraints (e.g., safety, accessibility) may limit sample population to less than the target population.
Target population	All elements of interest within some defined area and time period.
Sample	A selected set of sampling units. Measurements or observations from the sample are used to draw inferences about the target population.

Successful rangeland monitoring efforts carefully consider and explicitly define each of these components. Table adapted from Beck et al. (2010, see also Strand et al. 2015)

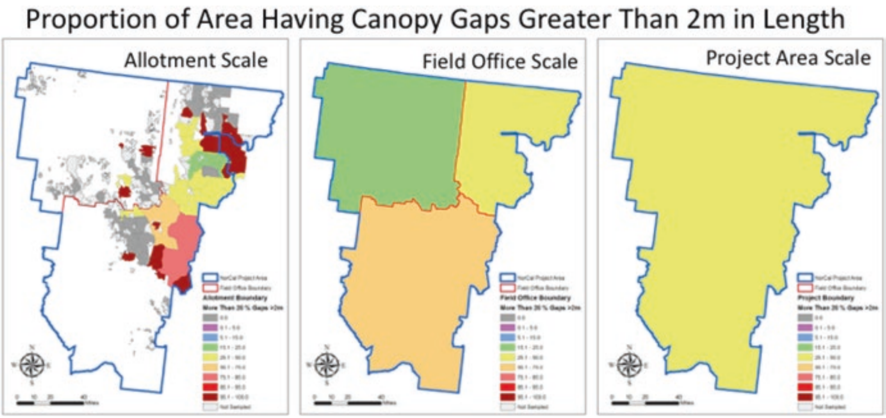

Fig. 16.2 A stratified random sampling design for three Bureau of Land Management (BLM) Field Offices in Northern California, implemented in 2013, allows for statistically valid estimates of indicators to be generated at multiple scales within the project area. Uncertainty of the indicator estimates is also calculated at each scale. Figure by S. Lamagna, BLM National Operations Center (unpublished data)

In a statistically valid sample, the area that each sample location represents can be quantified. It then becomes possible to "scale up" monitoring results to other reporting units or to combine similar monitoring datasets to make better predictions for a monitoring area (Fig. 16.2). Note that a statistical sampling design and consistent indicators and methods are necessary for this to be possible (Toevs et al. 2011).

16.2.5 Summary

The past 25 years has seen a rapid increase in the uses of and disturbances to rangelands that has taxed our ability to monitor these ecosystems with traditional techniques. However, the same time period has brought about conceptual developments that lay a foundation for more effective, and ultimately more efficient, rangeland monitoring. The cornerstones of this foundation are an understanding the nonlinear, cross-scale dynamics of rangeland ecosystems, and the development of functional indicators of critical ecosystem processes. The standardization of indicators (and measurement methods) to the extent possible and adoption of statistically valid and scalable sampling designs will help ensure monitoring data that not only satisfies initial objectives, but also is able to be combined with other datasets and analyzed for other or larger scale purposes.

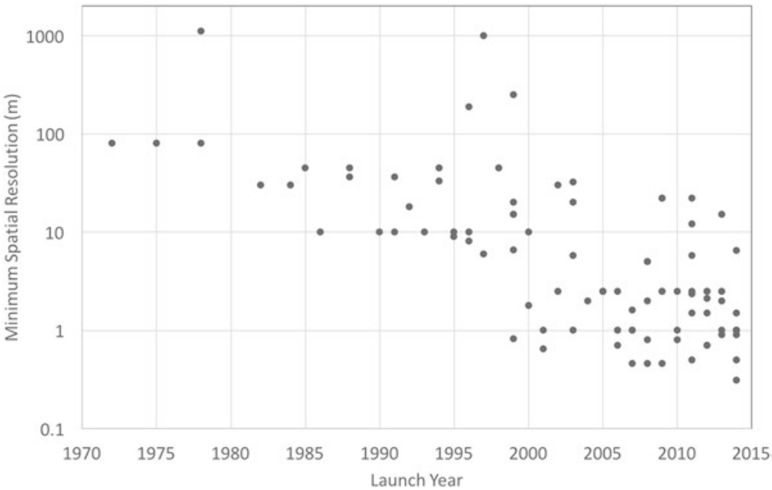

Fig. 16.3 Satellite-based sensors have become more numerous and higher-resolution over time. This increases opportunities for remote-sensing applications in rangeland monitoring. *Source* https://directory.eoportal.org/web/eoportal/satellite-missions (accessed April 20, 2015)

16.3 Remote-Sensing Developments for Monitoring

The widespread application of remote-sensing technologies to natural resource inquiries has been one of the most significant developments of the past 25 years. Several seminal papers have discussed the role and potential of remote sensing for rangeland monitoring. Hunt et al. (2003) provided an overview of the many ways in which remote sensing had been applied in rangeland management to that point. Booth and Tueller (2003) propose a framework for integrating remote sensing into rangeland monitoring and management. Washington-Allen et al. (2006) provide a technique for using remote sensing to understand past changes in rangelands. In the time since these papers were published, however, new applications, sensors, and methods have increased markedly. Here we briefly survey some of these developments, but a thorough review of remote-sensing developments in rangeland monitoring is beyond the scope of this chapter.

In 1990, there were only a handful of publicly available sources of satellite imagery, and this imagery was expensive and difficult to process (Fig. 16.3). Satellite imagery was generally panchromatic or multi-spectral only and of moderate (e.g., 30-m) or coarse (e.g., ≥1 km) resolution. Aerial photography was largely analog (i.e., on film) and challenging to incorporate into emerging GIS technologies. Contrast that to 2015 where there are now over 100 sources of satellite imagery (https://directory.eoportal.org/web/eoportal/satellite-missions, accessed April 20, 2015), many of them free and delivered in near real-time, and the emergence of inexpensive and autonomous unmanned aerial vehicles (UAVs) has caused a renascence of aerial photography research and applications.

16.3.1 Developments in Remote Sensors

The launch of the Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor in 2000 ushered in a new era of remote sensing due to its ability to image large swaths of the earth on a daily basis. The synthesis of MODIS imagery into high-quality, standard products available every 7, 8, or 16 days has greatly facilitated the use of satellite imagery for looking at changes in rangeland landscapes among and within years. Reeves et al. (2006) predicted aboveground green biomass from MODIS net photosynthesis estimates throughout the growing season and characterized inter-annual variability in grassland vegetation. Wylie et al. (2012) used MODIS time series data from 2000 to 2008 to develop expected annual greenness profiles for rangelands in southern Idaho to detect significant departures due to management changes or disturbance. Browning et al. (in review) related a time series of MODIS normalized difference vegetation index (NDVI) to changes in overall plant biomass across years and to changes in plant functional group responses within years.

Hyperspectral imaging—collection of many, narrow contiguous spectral bands through the visible and infrared portions of the electromagnetic spectrum (Govender et al. 2009)—has also seen increasing application in rangeland monitoring. Hyperspectral imaging has been used to detect and monitor infestations of non-native, invasive plants (e.g., Ustin et al. 2004; Glenn et al. 2005; Mundt et al. 2005). Weber et al. (2008) used hyperspectral data to map biological soil crusts in South Africa.

Light detection and ranging (LiDAR) is a remote-sensing technology for mapping elevations from laser impulses reflected off a surface. LiDAR has been used in rangelands to estimate shrub height and crown area (e.g., Streutker and Glenn 2006; Glenn et al. 2011; Mitchell et al. 2011) and for mapping fine-scale topography to monitor processes like shrub invasion, dune formation, and soil erosion (e.g., Perroy et al. 2010; Sankey et al. 2010). LiDAR has also been used in conjunction with other remote-sensing products (e.g., multispectral or hyperspectral imagery) to improve the accuracy of vegetation classifications (e.g., Mundt et al. 2006; Bork and Su 2007).

Interest in the use of unmanned aerial systems (UAS)—small remotely piloted or autonomous aircraft—for rangeland monitoring has increased as imaging sensors have become smaller and software for processing large amounts of digital imagery improves. With a UAS, it is often possible to acquire imagery at resolutions <5 cm and with more flexibility than traditional aircraft (Rango et al. 2009). For example, Laliberte et al. (2012b) used 6–8 cm UAS imagery to map vegetation types in Idaho and New Mexico rangelands. Breckenridge et al. (2012) found that estimates of vegetation cover and bare ground from UAS images agreed well with field-based measurements. d'Oleire-Oltmanns et al. (2012) used overlapping UAS images to monitor gully formation and soil erosion in Moroccan badlands.

16.3.2 Developments in Remote-Sensing Techniques

Over the past 25 years many new remote-sensing techniques have been developed and applied to rangeland monitoring. In some cases (e.g., digital photogrammetry, object-based image analysis) these new techniques were made possible by computing advances that have enabled faster and more efficient processing of large amounts of imagery. In other cases (e.g., multi-temporal image analysis), new approaches were developed around a new type or increased availability of remote-sensing products. Below are four techniques that have changed how remote-sensing imagery has been applied in rangeland monitoring.

Manual interpretation and grid-point cover estimation methods for aerial photographs were some of the first remote-sensing analysis techniques. While these approaches have gone out of vogue in favor of statistical classification algorithms for many remote-sensing applications, the recent increase in easily obtainable very-high resolution (VHR, <5 cm ground sampling distance) digital imagery from piloted aircraft, UAS, or even pole-mounted digital cameras has brought about a resurgence in image interpretation techniques. Booth et al. (2006) developed SamplePoint, a computer application for quickly and easily estimating vegetation cover from VHR aerial photography via point sampling. Many studies have looked at the accuracy and efficiency of image interpretation compared to field techniques and have found comparable results for estimating cover of functional groups (e.g., shrubs, perennial grasses) (e.g., Booth et al. 2005; Cagney et al. 2011; Duniway et al. 2011; Pilliod and Arkle 2013). Image interpretation of VHR images has also been used to estimate other rangeland indicators like canopy gaps (Karl et al. 2012b) or to evaluate wildlife habitat quality (e.g., Beck et al. 2014). Duniway et al. (2011) and Karl et al. (2012a) explored how VHR image interpretation could be employed in large-scale rangeland monitoring programs. A distinct advantage to VHR image interpretation techniques is that they can be employed by rangeland management staff with minimal expertise in remote sensing.

The increase in availability of VHR imagery from piloted aircraft or UAS has also spurred an interest in using digital photogrammetric techniques to create three-dimensional representations of rangeland sites from pairs of overlapping VHR images. Advances in photogrammetry software have made this process much easier, more accurate, and less expensive. Gillan et al. (2014) used stereo aerial photographs to model shrub heights in the Mojave Desert. Gong et al. (2000) created digital surface models from VHR stereo imagery to monitor changes in crown closure and tree height in a hardwood rangeland. Marzolff and Poesen (2009) used 3D digital surface models from digital photogrammetric techniques to monitor the gully development. Gillan et al. (2016) mapped soil movement following experimental juniper removal treatments by differencing digital surface models from before and after treatments. Recently, a new photogrammetric technique called structure from motion (SfM) has estimated three-dimensional surfaces from sequences of VHR images (Turner et al. 2012; Fonstad et al. 2013). An advantage of SfM is that, unlike traditional photogrammetric techniques, accuracy of surface elevation models increases with the number of overlapping photos. Genchi et al. (2015) used SfM

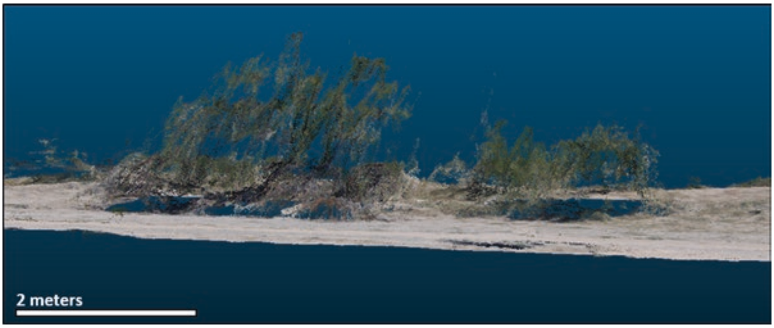

Fig. 16.4 Structure from Motion (SfM) is a new photogrammetric technique that estimates the structure and height of three-dimensional objects from a sequence of two-dimensional images. The SfM algorithm was applied simultaneously to a set of downward-looking and oblique images to produce a point cloud of the canopy structure of creosote (*Larrea tridentata* (DC.) Coville) and soil surface elevation below the shrub canopy in the Chihuahuan Desert, New Mexico (J. Gillan, unpublished data)

with images acquired from a UAS model soil surfaces and cliff faces to estimate soil excavation and nesting habitat for birds. Another benefit of SfM is that it can accommodate both downward-looking (i.e., nadir) and oblique images together to produce "LiDAR-like" point clouds. This provides an opportunity to estimate canopy structure and ground surfaces below vegetation—something that is possible from ground-based (e.g., Greaves et al. 2015) and aerial (e.g., Streutker and Glenn 2006) LiDAR but not traditional photogrammetry (Fig. 16.4).

Traditional remote-sensing algorithms analyze and assign meaning to the individual pixels of an image. While these techniques have been used successfully for many rangeland applications, pixel-based approaches are challenged in many rangeland landscapes because of inherent heterogeneity and patchiness. In these situations, the variability within and context of patches at different scales is an important trait for their correct identification or description. Object-Based Image analysis (OBIA) groups adjacent pixels in an image together based on their similarity and then treats the resulting "objects" as analysis units rather than the individual pixels (Burnett and Blaschke 2003). With OBIA, additional measures of variability, patchiness, and juxtaposition within and between patches can be factored into classifications or models. By changing the amount of variability acceptable within an object, objects of different sizes (i.e., scales) can be created for the same area. It is possible to define optimal analysis scales with OBIA that maximize the accuracy of a remote-sensing product (Feitosa et al. 2006; Laliberte and Rango 2009; Karl and Maurer 2010a). The OBIA technique has shown to yield more accurate classifications of rangeland vegetation than pixel-based techniques in many cases (Karl and Maurer 2010b; Dingle Robertson and King 2011; Myint et al. 2011; Whiteside et al. 2011). The OBIA technique has been applied for quantifying rangeland vegetation cover and distribution at both fine (e.g., Luscier et al. 2006; Laliberte et al. 2012a; Hulet et al. 2013, 2014a) and coarse (Laliberte et al. 2006) scales. Karl (2010) used OBIA in predictions of three rangeland indicators in a southern Idaho study area. Laliberte et al. (2004) used an OBIA method to detect shrub encroachment in southern New Mexico rangelands using historic aerial and current high-resolution satellite imagery.

Several satellite sensors (e.g., AVHRR, Landsat, MODIS) have now been operational long enough to provide a reliable record of change in rangeland ecosystems. For example, Homer et al. (2004) developed a National Land Cover Dataset for the United States from 2001 Landsat imagery that has been subsequently updated to assess change over time (Xian and Homer 2010; Jin et al. 2013). Homer et al. (2013) quantified annual and seasonal changes in bare ground and cover of shrubs, sagebrush, herbaceous plants, and litter using Quickbird and Landsat imagery. Additionally, sensors like MODIS are providing image products at a temporal resolution (e.g., MODIS NDVI composites are available on 8-day cycles) that was not previously available for rangeland studies. This combination of temporal extent and resolution has spawned a host of multi-temporal remote-sensing techniques for rangeland monitoring. Wylie et al. (2012) used 9 years of MODIS NDVI data to construct estimates of expected production for a southern Idaho study area and detect departures from this expectation. Sankey et al. (2013) used MODIS and AVHRR NDVI time series as a proxy indicator for post-fire recovery in rangelands. Brandt et al. (2014) used a combination of SPOT-Vegetation, Landsat long-term data record, and MODIS NDVI products to assess degradation and vegetation biomass changes in the Sahel region of Africa from 1982 to 2010. Maynard et al. (in review) demonstrated that significant seasonal and between-year breaks in a MODIS NDVI time series decomposes using the Breaks for Additive Season and Trend (BFAST) algorithm (Verbesselt et al. 2010) correlated to changes in biomass and functional group composition in a Chihuahuan Desert rangeland.

16.3.3 Modes of Remote-Sensing Implementation for Monitoring

Three general modes of applying remote sensing have emerged in rangeland monitoring. The first mode is to use remote-sensing technologies and products to replace field measurements. Numerous studies have shown that interpretation or classification of high-resolution imagery can match or outperform many field-based measurements of certain attributes (e.g., Booth et al. 2005; Seefeldt and Booth 2006; Cagney et al. 2011; Hulet et al. 2014b). Land cover classifications or predictions of vegetation attributes (e.g., cover) have been used for landscape-scale rangeland assessment and monitoring (e.g., Hunt and Miyake 2006; Marsett et al. 2006; Homer et al. 2013). Regression models (e.g., Homer et al. 2012) or geostatisical techniques (e.g., Karl 2010) are used to predict rangeland indicators over landscapes from a set of field samples. In these cases, it is more important that the field sample locations represent the range and extremes of the indicators being predicted than to be randomly selected (Gregoire 1998). Historic analysis of rangeland condition is also possible using archives of aerial photography (e.g., Tappan et al. 2004; Rango et al. 2005) or satellite imagery (e.g., Washington-Allen et al. 2006; Malmstrom et al. 2008).

The second mode of remote-sensing application is to supplement or augment field-based activities. For example, high-resolution aerial photographs may be acquired at field sample locations and at nearby, similar sites for use in a double-sampling approach (see Duniway et al. 2011; Karl et al. 2012a). Another example of this mode of remote-sensing application is model-assisted inference which uses a statistical model developed between field measurements and remote-sensing products (e.g., NDVI) to improve indicator estimates in larger areas (Gregoire 1998; Opsomer et al. 2007; Stehman 2009). This mode of remote sensing can also be employed to make improved spatial predictions of indicators such as vegetation cover (Karl 2010). Gu et al. (2013) used biomass models developed from MODIS NDVI to remove artifacts from rangeland productivity estimates due to administrative boundaries (i.e., state and county lines).

Finally, remote-sensing techniques can be used to generate new or synthetic indicators of rangelands that are difficult or impossible to characterize through field techniques. For example, Ludwig et al. (2007a) defined a "leakiness index" to characterize the ability of water to move through a rangeland site and increase soil erosion. Cocke et al. (2005) defined the differenced normalized burn ratio as a measure of the extent and severity of wildland fire. Kefi et al. (2007) used changes in vegetation patch-size distributions as an indicator of impending desertification. Nijland et al. (2010) mapped soil moisture at depths to 6 m using electrical resistivity tomography. While the diversity of new indicators available from remote-sensing techniques is increasing, a challenge with this remote-sensing mode for rangeland monitoring, however, is translating the remote-sensing-derived indicators into statements of rangeland quality or health.

16.3.4 Summary

Remote-sensing technologies and applications for rangeland monitoring have burgeoned in the past 25 years. Rapid advancements in sensor technologies and analytical techniques coupled with decreasing costs of remote-sensing products have resulted in myriad examples of the utility of remote sensing to quantitatively monitor rangelands in ways previously not possible. Integration of remote-sensing techniques as replacements for and supplements to existing field-based monitoring efforts will continue. However, development of novel remote-sensing-specific indicators will quicken, spurred in part by the increasing availability (e.g., frequency of imagery, ease of access) and flexibility (i.e., ability to control image acquisition parameters and timing) of remote-sensing products.

16.4 Societal Implications of Conceptual Advances

The conceptual advances described above have influenced how rangeland monitoring is conducted and have increased the utility of monitoring data for management decision-making.

16.4.1 Increases in Monitoring Program Efficiency

The shift of focus to land health and the adoption of core indicators and methods has led to increases in the efficiency of monitoring programs. In the past, monitoring efficiency was gained through optimizing an individual monitoring program relative to its specific objectives. One form of this optimization was minimizing the number of required sample sites by restricting sample populations, employing specialized sampling designs, or resorting to subjective sampling. In highly heterogeneous rangeland systems, this drove monitoring to selected areas that were considered representative of a larger landscape (Stoddart and Smith 1943; Holechek et al. 2001), and emphasized the need to maximize the value of individual observations. This approach, however, is only efficient if a single monitoring objective or indicator is being considered. It is an inefficient approach if a separate monitoring program is needed for each management objective. Additionally, monitoring programs designed tightly around a single objective (e.g., monitoring of grazing use impacts) may be inappropriate for informing other management objectives.

Overall efficiency of monitoring programs increases as the number of questions that can be answered with a dataset increases, and if data from multiple efforts can be combined. This is because monitoring data that have been collected for one purpose can be reused to answer other objectives. For example, data collected since 2004 (NRCS) and 2011 (BLM) by the National Resource Inventory (NRI) program are designed to generate regional and national estimates of rangeland status and trend. As of 2015, many of these data were being used to support the development and revision of ecological site descriptions. In the future, it is anticipated that they will be combined with local to regional monitoring data to address more specific questions, such as habitat suitability for wildlife species or for use in developing remote-sensing products provided restrictions regarding confidentiality of data can be overcome.

Combining datasets is only possible, however, if indicators and methods are consistent between programs and if the datasets were based on a probabilistic sampling design. Although combining different datasets is not always straightforward statistically (e.g., for monitoring over large landscapes or when sample size requirements are high due to variability in an indicator), it can be worth the effort.

16.4.2 Cross-Jurisdictional Monitoring

Another benefit of the recent adoption of core indicators and methods is that it opens up new opportunities for monitoring conditions across boundaries of ownership or administration. Land owners or agencies that use core methods and statistically based sampling designs can interchange and combine datasets to address management questions related to the context of a management unit in a larger landscape or pertaining to resources or disturbances that cross boundaries. This can be particularly useful in rangelands where ownership is fragmented, and can be applied at all scales from local to national.

For example, monitoring the status and condition of seasonal habitats is necessary for the conservation of greater sage-grouse (*Centrocercus urophasiuanus*) across its range. Approximately 52 % of the current greater sage-grouse distribution occurs on land managed by the BLM, whereas the remainder is managed by private (31 %) or other (17 %) federal and state agencies (U.S. Fish and Wildlife Service 2010). The mixed land ownership has resulted in multiple sage-grouse habitat mon-

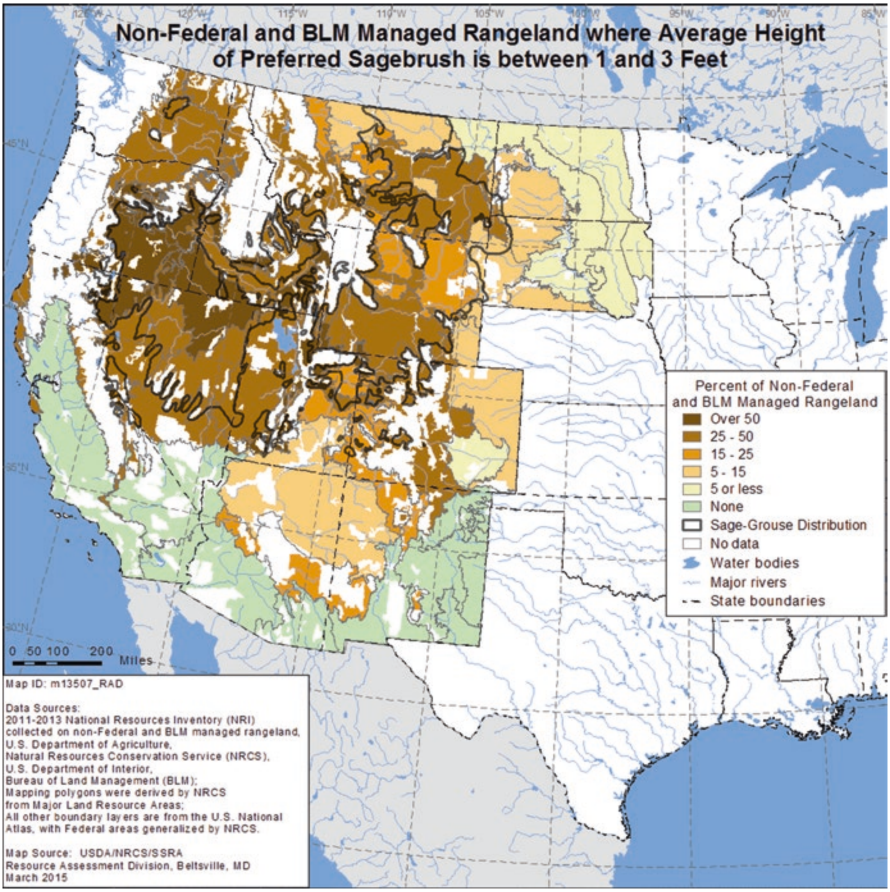

Fig. 16.5 Use of consistent indicators and methods and statistically valid sampling designs permit aggregation of data across jurisdictional boundaries. This map shows an example of how habitat suitability indicators for greater sage-grouse can be calculated from the National Resources Conservation Service's National Resources Inventory (NRI) and the Bureau of Land Management's (BLM) Landscape Monitoring Framework (LMF) for all non-federal (e.g., private, state, tribal) and BLM-managed rangelands in the western USA. These results are based upon NRI rangeland data collected in the field on 3658 non-Federal and LMF data from 2876 BLM rangeland sites during the period 2011 to 2013

itoring programs. Knowledge of the condition or trend of greater sage-grouse on lands managed by one agency or land owner may be informative for some questions relative to the affairs of that organization. However it provides an incomplete picture of habitat for the species as a whole. Because the BLM Landscape Monitoring Framework and the NRCS National Resources Inventory both adopted the core indicators and methods, these datasets have been combined to produce estimates of greater sage-grouse habitat indicators across private, tribal, and BLM lands from a sample of over 6500 locations between 2011 and 2013 (Fig. 16.5).

16.4.3 Effectiveness Monitoring

Monitoring the effectiveness of specific management actions is important and sometimes mandated. Current philosophies of rangeland management are built upon the concept of adaptive management (Walters and Holling 1990) where management actions, developed as a result of best-available knowledge, are treated like hypotheses to be evaluated by data collected following implementation of actions. This learning phase of adaptive management is essential for translating data on treatments and management adjustments into further management actions. However, this step of adaptive management has often been short-circuited (Moir and Block 2001; Walters 2007).

Effectiveness monitoring of a single project or action provide information on whether a project met an objective. Yet projects or site-specific actions and their corresponding effects carry with them environmental variability that may sometimes lead to failures merely by chance. Adaptive management requires across-project comparisons where projects are implemented over multiple time frames under different environmental conditions to determine the likelihood of success under future conditions. If all projects use the same core indicators for addressing common management objectives, then decisions on future management actions will likely be more successful if adaptive management adjustments are applied to future decisions.

For example, Arkle et al. (2014) and Knutson et al. (2014) used the same core indicators to monitor long-term plant responses with and without revegetation after wildfires to address multiple objectives: did revegetation (1) increase perennial plant cover; (2) reduce annual grass cover; and (3) provide greater sage-grouse habitat? They found that higher elevation and mean annual precipitation of locations related to meeting objectives of perennial and annual plants and to providing herbaceous cover, but not shrub cover for greater sage-grouse. They were able to identify potential levels of elevation and precipitation below which objectives would not likely be met. They were also able to point to potential changes in techniques to enhance shrub cover for greater sage-grouse. These results are available for adapting post-fire revegetation to better meet these objectives where possible. In addition, this information is available during the decision process after fires to determine if the likelihood of success is worth the expense of a revegetation project.

16.5 Future Perspectives

16.5.1 Developing Functional Indicators at Broad Scales

Much of the advancement in developing functional indicators for rangeland management has been at the site scale owing to the fact that most research has been conducted at this scale (Peters et al. 2015). In some cases these site-based indicators can be scaled up meaningfully to larger (e.g., landscape or regional) scales (Peters et al. 2004). For example, cover of invasive annual grasses at a site is meaningful for local management, and the proportion of sites in a region having some minimal amount of the invasive grass is also useful for decision-making.

However, interactions between monitoring objectives and rangeland resources are scale-dependent, and informative indicators (and appropriate methods) may be different at different scales (West 2003b). Some site-based indicators such as those that need to be referenced to land potential to be interpreted (e.g., bare ground amount, shrub cover) or those tied to attributes that exhibit strong cross-scale interactions (Peters et al. 2004) or threshold effects (Briske et al. 2006), may not scale up meaningfully. For example, average shrub cover in a region is only marginally meaningful because the region contains many areas with different potential to support shrubs. Additionally, indicators derived from site characteristics can be informative of the overall conditions in a larger summary (i.e., reporting) unit, but do not capture the distribution or pattern of indicators within those areas.

A major challenge in developing effective monitoring programs and applying monitoring data to rangeland management is the paucity of functional indicators of ecosystem processes at landscape to regional scales. This is due in part to a critical knowledge gap: we simply don't understand how the relationships between ecosystem properties, processes, and functions vary across space and time. Principles of landscape ecology state that characteristics like connectivity, patch size and shape, and habitat diversity are critical to sustaining ecosystem processes. But quantifiable indicators and specific thresholds tied to these ecosystem attributes are not common in monitoring programs. The lack of broad-scale indicators may be limiting the utility of remote sensing in many monitoring programs, relegating it to a pattern description.

There are some examples, however, where specific indicators related to ecosystem processes have been developed at fine and broad scales. Greater sage-grouse habitat has been described at four distinct scales and habitat suitability indicators defined for each scale (Connelly et al. 2000; Doherty et al. 2010; Stiver et al. 2015). A regional decision matrix has been proposed (Chambers et al. 2014) and is being tested in these regions for greater sage-grouse management. It is based on landscape cover of sagebrush (i.e., percent of pixels classified as sagebrush using a 5-km^2 moving window), an indicator of greater sage-grouse lek longevity, in combination with soil temperature and moisture as a surrogate for ecosystem resistance to invasive annual grasses and resilience to fire. Ludwig et al. (2004) defined landscape functional integrity indicators to assess grazing effects on Australian rangelands at fine to coarse scales using cover and bare ground indicators within and between vegetation patches. Bertiller et al. (2002) described changes due to cattle grazing in plant composition, patch structure, and vegetation cover at different scales in Patagonian Monte rangelands.

16.5.2 Developing and Implementing Soil Indicators

Monitoring ecosystem functions should reflect changes in soil processes (Chap. 4, this volume). While it is not always, or even usually, the case that "monitoring vegetation has to take a backseat to monitoring soils" (West et al. 1994), directly monitoring soil degradation and recovery may provide better information for rangeland management decisions. In systems where vegetation cover and composition either do not reflect, or lag behind, fundamental changes in water and nutrient cycling and the energy flows upon which ecosystem services ultimately depend, soil indicators are appropriate. For example, soil compaction can increase runoff, and increased soil surface disturbance can increase soil erodibility and drive declines in soil organic matter. Both of these changes can occur without causing detectable differences in plant cover (e.g., Herrick et al. 1999; Bird et al. 2007).

Despite the recognized value of soil indicators, they are rarely included in monitoring programs. There are multiple reasons, including cost and measurement consistency. Even where sufficient financial resources and trained personal are able to ensure consistent measurement of a sufficient number of samples to detect change, the logistical challenges of collecting, processing, transporting, and storing samples for laboratory analysis quickly overwhelm institutional capacities. For this reason, only a field measurement of soil aggregate stability was selected for measurement in US national rangeland monitoring system.

The future, however, is bright as new field soil sensors and remote-sensing techniques are being rapidly developed and deployed. For example, Pastick et al. (2014) mapped soil organic layer thickness in interior Alaska from Landsat ETM+ and ancillary data. Field spectroscopy, in particular, appears to hold a high level of promise for predicting soil organic matter and other variables that are related to spectral properties (Shepherd and Walsh 2007).

16.5.3 Accounting for Inter-annual Climate Variability

A perennial challenge in monitoring rangelands is dealing with climate differences during the intervals between measurement periods. Because many rangeland ecosystem indicators (e.g., cover, production, and recruitment of herbaceous plants) are sensitive to yearly fluctuations in timing and amount of precipitation, it can be difficult to determine whether observed differences are due to management or disturbance, climate variability, or an interaction of the two. Conventional approaches to this problem have included comparing only like years, sampling across several years to encompass both dry and wet periods (West 2003b), or selecting indicators that are less sensitive to climate fluctuations (e.g., woody plant cover, density, perennial grass basal cover).

Advances in remote sensing, specifically the increasing availability of high-frequency remote-sensing products (e.g., MODIS NDVI), offer several new opportunities for addressing this challenge (e.g., White et al. 2005). This can be accomplished by constructing indicator ranges from different climate years and analyzing for departure (e.g., Wylie et al. 2012; Rigge et al. 2013). Alternatively, remote-sensing-derived indicators can be analyzed directly for trends over time or used as a covariate to analyze or interpret field observations (e.g., White et al. 2005; Dardel et al. 2014; Brandt et al. 2014). Finally, remote-sensing time series can be decomposed and inter-annual variability "factored out" to isolate management changes. Effective strategies for using remote-sensing products to account for inter-annual climate variability in rangeland monitoring still need much development and research.

16.5.4 Operationalizing Remote Sensing

Despite the advances in remote-sensing technologies and the potential uses for monitoring, adoption of remote sensing in many formal rangeland monitoring programs has been slow. Reasons for this are diverse and include historically variable performance of remote-sensing products (especially in rangelands), misunderstandings of what remote-sensing indicators actually mean in a rangeland context, and high skill and computing requirements to produce and use remote-sensing products (see Kennedy et al. 2009). Nevertheless, substantial incorporation of remote sensing into monitoring programs is necessary to meet the information needs of rangeland management in the future (Booth and Tueller 2003).

Operational use of remote sensing in rangeland monitoring programs requires not only clear articulation of the monitoring objectives but also analysis of remote-sensing options, desired accuracy requirements, and costs (Kennedy et al. 2009). Changes in sensor technology, data availability, and processing techniques also must be considered. In many cases remote-sensing-based indicators will not be adequate on their own and an integrated field and remote-sensing approach will be required (Ludwig et al. 2007b). The sources of error and uncertainty in indicator estimates must also be characterized for remote-sensing products that are used in rangeland monitoring programs to determine whether differences in indicator estimates are likely due to model error, sensor or analytical differences, or real changes on the ground.

16.5.5 Considerations with Evolving Technologies for Measuring Indicators

The conventional wisdom that has been taught to many rangeland management practitioners is that once you pick a monitoring method you should always stick with it. This advice likely stems from the facts that rangelands are heterogeneous, diverse systems and many techniques for measuring rangeland attributes can contain a large degree of imprecision. Thus, the perception is that changing from one data collection technique to another may introduce more noise into the monitoring data and make it even harder to detect differences. This thinking, however, is flawed and has stymied adoption of more efficient and accurate approaches for monitoring rangeland indicators.

The development of new techniques and instruments for making quantitative indicator measurements happens in all science fields, and there are established procedures for phasing new technologies into existing monitoring programs. For example, the U.S. Historical Climatology Network, which tracks temperature averages and trends in the United States, began in the 1980s to shift from liquid-in-gas (e.g., alcohol or mercury) analog thermometers to digital thermistor sensors (Menne et al. 2010). Studies showed that biases and differences in variance could exist between these two different types of thermometers, and methods were developed to reconcile these differences so that analyses of long-term trends could be performed (Peterson et al. 1998).

Decisions to incorporate new measurement techniques into existing monitoring should be a part of ongoing reevaluations of the monitoring program (Lindenmayer and Likens 2009; Reynolds 2012). When considering changes to existing methods, however, it is critical to ensure indicators calculated from the new methods are consistent (in both definition and interpretation) with the original monitoring objectives. It is also important to study the results of both methods relative to each other to understand potential biases and differences in precision (Bland and Altman 1999). New methods should be well defined and documented and then only be adopted in a monitoring program if they (1) provide more accurate or precise data, or (2) bring the program into better alignment with other monitoring programs.

While changes to a monitoring program are possible over time, they should not be taken lightly because changes can be difficult and impose complexity in data analysis. Oakley et al. (2003) proposed a modular approach for defining monitoring protocols so that incremental changes to increase precision or efficiency could be more easily made. It is also helpful in designing monitoring programs to clearly distinguish indicators from methods (Toevs et al. 2011) so that the best available methods can be used to provide indicator estimates.

16.5.6 Collaboration and Sharing Monitoring Efforts and Data

Sharing monitoring data and participatory monitoring offer tremendous opportunities for both dramatically reducing future monitoring costs, and increasing our ability to interpret both historic and future data.

Sharing monitoring data reduces costs by reducing redundancy: individuals and organizations that would have previously each collected their own data to address different objectives can take advantage of others' data, freeing up resources for supplementary measurements, data management, analysis, and interpretation. It also increases the quality of interpretation because a larger reference pool of information, often covering greater areas and time periods, can be used. This can help to address the challenges of accounting for inter-annual climate variability, even if the same methods are not used, provided that generally co-varying indicators, such as foliar and canopy cover, were measured. Where standard methods and statistical designs were used, even greater benefits can be realized through data integration and direct comparisons. In some cases, issues of data confidentiality or proprietary ownership currently impede data sharing. To the extent possible, these issues should be addressed to foster better data sharing.

Participatory monitoring reduces costs and can improve interpretation. Costs may be reduced due to lower labor costs, although these savings are often offset by increased data management costs due to higher quality control costs. Perhaps the most intriguing, and often ignored, benefit of participatory monitoring is for interpretation. Individuals engaged in participatory monitoring often have both local knowledge and information that trained, paid field crews lack. Their knowledge may span both seasons and years, allowing them to identify possible drivers of change, as well as explain anomalous results or outliers.

16.5.7 Defining the Reference: The Challenge of Applying Monitoring to Management?

Perhaps the greatest challenge faced by managers seeking to apply monitoring data to management decisions is defining the reference. The first time monitoring data are collected at a location defines the baseline, but says nothing about where the baseline is relative to short- and long-term potential. Existing global assessments of land degradation are based largely on the opinions of multiple experts (Oldeman 1994), interpretation of satellite-based greenness indices (Bai et al. 2008), or a synthesis of multiple estimates based on one or more of these (e.g., Scherr 1999) to estimate the extent of land degradation. Expert opinion is limited by lack of a clearly defined reference. Greenness indices use spatial and temporal deviations from maximum greenness as the reference. Spatial differences are confounded by soil-based differences in potential productivity, while temporal differences are confounded by weather. Use of both spatial and temporal variability to determine the reference is particularly problematic in rangelands, where an increase in green woody cover often reflects degradation rather than recovery. While nearly all of these challenges can be addressed through the application of fine-scale information of phenology, weather, and vegetation, it is quite difficult to collect and apply this information across large areas

Two steps are required to reliably define reference conditions. The first is to describe the factors that determine land potential, including soil, topography, and climate (Herrick et al. 2013). Where an ecological site classification (Bestelmeyer et al. 2009) is available, identification of the ecological site can substitute for documentation of the individual edaphic, topographic, and climatic variables (Chap. 9, this volume). The second is to define the natural range of variability for response variables (vegetation and dynamic soil properties) for the ecological site.

The USDA National Resource Inventory is one of the few examples in which ecological site-specific references have been defined and applied at the national level to provide a context for assessments and baseline monitoring data (Herrick et al. 2010). Definition of reference conditions is based on the natural range of variability in the reference state of the state-and-transition model for the ecological site, where available, and on a combination of scientific literature, observations and measurements from reference plots, and local knowledge (Pyke et al. 2002; Pellant et al. 2005). These assessments were completed at the same time that quantitative baseline data were collected, providing both a snapshot of current levels of land degradation, and information that can be used to interpret the baseline monitoring data.

16.6 Summary

Rangeland ecology has benefited from recent developments in theory, policy, and technology. These developments, together with the increasing diversity of uses of rangelands, have changed the need for resource monitoring as well as the approaches for how it is carried out. Monitoring data are needed to establish baselines and changes in rangeland condition for documenting the impacts of climate change, disturbances, and management activities. The myriad monitoring needs for rangeland management, however, must be reconciled with realities of costs associated with collecting, analyzing, and using monitoring data. Thus the challenges of implementing useful and efficient monitoring of rangelands include both practical and institutional hurdles.

Traditional approaches to monitoring and management, however, are entrenched in agencies, organizations, and universities and often applied to objectives and systems beyond those for which they were designed. While aspects of this legacy of rangeland management are helpful (e.g., rangeland scientists were pioneers of landscape-scale thinking), relying too heavily on monitoring techniques focused on grazing management will not serve management needs in the future. West (2003b) concluded, "The range profession has put so much of its training efforts into identification of plant species, sampling within plots, and application of conventional statistical analysis that it hasn't had the background to examine other possible ways of answering the questions really being asked." Going forward, monitoring of rangeland resources needs to be grounded in the conceptual and technological advances of the past 25 years.

The recognition that rangelands are nonlinear systems characterized by thresholds and cross-scale processes has led to a realization of the importance of monitoring ecological processes and functions at different scales. This advance translated to a shift in thinking from monitoring plant community responses to land uses to monitoring changes in land health. The adoption of conceptual models as a mechanism for documenting and illustrating how ecological processes, disturbances, and management affect an ecosystem, has contributed to the identification and selection of functional ecosystem indicators. Conceptual models not only identify what parts of an ecosystem should be monitored, they provide insight into how monitoring data should be interpreted and used for making management decisions.

Differences in indicators and measurement methods among monitoring programs has hindered the ability of data to be used for multiple objectives or combined to understand conditions over larger scales. A consistent core set of standard indicators and methods for rangeland monitoring provides the ability to combine datasets from different monitoring efforts, allows data to be scaled up to larger extents, and expands opportunities to reuse data for other purposes. Core methods represent a minimal set of information that should be collected in almost any monitoring effort. When monitoring objectives are not served by the core indicators or methods, supplemental indicators and methods should be added.

Statistical approaches to sampling design for rangeland monitoring are necessary in our era of expanding land uses and disturbances and increasing contention. Conventional approaches that relied on targeted or haphazard sample site selection have disadvantages that severely limit their utility for rangeland monitoring. Most statistically based sampling designs can support monitoring for multiple objectives and scaling up and down of monitoring data. Additionally, randomization techniques for selecting sampling locations guard against bias and allow for characterization of uncertainty in indicator estimates.

The widespread application of remote-sensing technologies to rangeland research and monitoring has been one of the most significant developments of the past 25 years. Technological developments in remote sensing have happened at such a rate that the periodic summaries of remote-sensing applications for rangeland management have become quickly outdated. In addition to new sensors being continually developed, imagery is becoming available at higher resolutions and more frequently while being cheaper and easier to access. These innovations have been accompanied by new analytic techniques that has improved the ability to extract meaningful information from remote-sensing products. In particular, the nexus of inexpensive yet capable UAS with new digital photogrammetric software has led to cheap, easy 3D analysis for rangeland ecosystems.

The conceptual and technological advances in rangeland science and management have important implications for monitoring. First is the potential to increase monitoring efficiency. Historically efficiency was maximized through parsimonious monitoring program design. Under the weight of so many monitoring efforts, however, efficiencies across programs can only come through coordination of monitoring efforts such as adopting core indicators and methods and scalable, statistical sampling designs. Second, coordinated monitoring based on functional indicators of land health opens up opportunities for monitoring conditions across jurisdictional boundaries. This will be crucial for managing large-scale and diffuse disturbances (e.g., invasive species) as well as conservation of landscape-scale species (e.g., greater sage-grouse). Robust monitoring programs also help complete the learning cycle that is often missing from evaluating effectiveness of monitoring actions, and enable comparisons across projects to begin to understand the factors that affect the success of management actions.

Despite the advances of the past few decades, there are challenges but also many opportunities for rangeland monitoring in the future. One set of challenges deals with the development and implementation of monitoring indicators. A significant challenge for rangeland monitoring is developing functional indicators of land health at landscape and regional scales. In many cases empirical research has not been done to understand the interaction of ecosystem components and processes at broad scales. Another challenge is in developing and incorporating indicators of soil degradation and recovery into rangeland monitoring programs when such indicators may provide better or more timely information to managers than vegetation indicators.

A second set of challenges relates to technical aspects of rangeland monitoring. Variability of precipitation and temperature (and thus plant biomass and species composition) on rangelands both within and between years is a perennial challenge for monitoring. Conventional approaches to dealing with temporal variability in monitoring data include comparing only like years or averaging over multiple years. Advances in remote sensing, specifically the increasing availability of high-frequency remote-sensing products (e.g., MODIS NDVI), offer several new opportunities for addressing this challenge. However, despite the promise of remote sensing, its formal adoption in many rangeland monitoring programs has been slow. Operational use of remote sensing for rangeland monitoring will require a clear statement of objectives and roles for remote-sensing products as well as accuracy needs.

For the future, rangeland professionals (both upcoming and current) need instruction on monitoring that focuses on development and selection of functional indicators, monitoring rangelands at multiple scales, and efficiencies of core indicator monitoring with supplementation as necessary. Additionally, effort should be invested to improve our understanding of statistical principles of monitoring design and data analysis and increasing the availability of professionals with the skills to execute these tasks for rangeland monitoring.

Most sources on rangeland monitoring point out that monitoring is worthless if the data are never analyzed, reported, and ultimately used to address the original objectives. At the same time, however, many rangeland monitoring manuals focus almost exclusively on data collection protocols and leave out substantial treatment of data analysis and reporting. Going forward, considerable effort needs to be placed on translating monitoring results into management actions that are supported by analyses and data visualization. It is our experience that in many cases difficulties in sustaining funding for monitoring programs stem in part from the lack of tangible and useful analyses and results from the data that were collected. Monitoring programs can and should be designed to produce interim as well as long-term products that are useful to rangeland managers.

Technologies involved in rangeland monitoring will continue to evolve (e.g., remote sensing will supplant some field efforts), and strategies need to be put in place for adopting new techniques into monitoring programs. Ultimately, selection of technologies and methods for monitoring needs to be based on relevant management questions and a thorough understanding of the processes governing rangeland responses to management and disturbance.

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