Chapter S. Adaptive Management and Monitoring

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Executive Summary

Adaptive management and monitoring efforts focused on vegetation, habitat, and wildlife in the sagebrush (*Artemisia* spp.) biome help inform management of species and habitats, predict ecological responses to conservation practices, and adapt management to improve conservation outcomes. This chapter emphasizes the adaptive resource management framework with its four stages: (1) problem definition, (2) outcomes, (3) decision analysis, and (4) implementation and monitoring. Adaptive resource management is an evolving process involving a sequential cycle of learning (the accumulation of understanding over time) and adaptation (the adjustment of management over time). This framework operationalizes monitoring a necessary component of decision making in the sagebrush biome. Several national and regional monitoring efforts are underway across the sagebrush biome for both vegetation and wildlife. Sustaining these efforts and using the information effectively is an important step towards realizing the full potential of the adaptive management framework in sagebrush ecosystems. Furthermore, coordinating monitoring efforts and information across stakeholders (for example, Federal, State, nongovernmental organizations) will be necessary given the limited resources, diverse ownership/management, and sagebrush biome size.

Introduction

In natural resource management, monitoring provides information about how resources change through time in response to management or whether resource objectives are met following a management action. Well-designed monitoring for specific conservation problems begins with clearly articulated objectives, often with input from multiple stakeholders. There are many conservation challenges facing the sagebrush (*Artemisia* spp.) biome, and thus, there are a myriad of monitoring approaches or programs. This chapter describes monitoring efforts focused on vegetation, habitat, and wildlife. Collectively, the existing natural resource monitoring in the sagebrush biome (and potentially other future monitoring efforts) can help inform management of species and habitats, predict ecological responses to conservation practices, and adapt management to improve conservation outcomes (Nichols and Williams, 2006; Lyons and others, 2008). Monitoring may also help maximize efficiency of conservation spending so that limited resources are spent on the right things, in the right places, and at the right time.

Types of monitoring used in natural resource management include implementation, effectiveness, and validation (Wiechman and others, 2019), all of which can inform adaptive management if implemented within the appropriate framework (fig. S1). Implementation monitoring evaluates the successful execution of a planned management action, such as whether seeded species germinate and emerge in the first growing season. Effectiveness monitoring evaluates changes in condition and progress toward meeting a management objective, such as stabilizing soils following wildfire rehabilitation or increasing bird populations after restoring wildlife habitats. Validation monitoring uses an experimental approach to determine if the observed outcome is caused by a management action. Some view this latter approach as hypothesis-driven research and thus outside the realm of monitoring for adaptive management. This includes most short-term, local research projects conducted by agencies and universities, including those that evaluate alternative management options.

Given the uncertainty in the management of natural resources, monitoring needs to be integrated into all management systems to maximize effective decision making and sustain conservation efforts. Examples of approaches for integrating monitoring data into decision making frameworks include: (1) Systematic conservation planning to answer the "what to do" and "where to do it" questions; (2) Structured decision making (SDM) to integrate stakeholder objectives, alternative management actions, data models and tradeoffs; (3) Adaptive resource management (ARM) that extends SDM processes to include effectiveness monitoring over time; and (4) Strategic habitat conservation that integrates the principles of conservation planning and ARM at the landscape level (Wilson and others, 2009; Marcot and others, 2012; Millard and others, 2012; Williams and Brown, 2012; Drum and others, 2015).

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Although monitoring is often given considerable attention in conservation and management policies and plans, it is often treated as an afterthought in conservation and management action. Monitoring data are inadequately used in adaptive management because of a lack of consistent understanding among those tasked with addressing all or some of the steps required for effective adaptive management. Adaptive management operationalizes monitoring as a necessary part of decision making, and as such, this chapter outlines the use of vegetation and wildlife monitoring in sagebrush ecosystems within the construct of adaptive management.

Adaptive Management

Adaptive management is a structured approach to decision making. Adaptive management essentially means learning by doing and adapting management strategies based on what has been learned (Williams and others, 2009). In all cases, adaptive management is seen as an evolving process involving a sequential cycle of learning (the accumulation of understanding over time) and adaptation (the adjustment of management over time). This feedback between learning and decision making is the central feature of adaptive management (Williams and others, 2009; Williams and Brown, 2012). It is important to recognize that adaptive management is the actual process of implementing a conservation program, not a part of the program to be initiated upon failure to attain an objective. Although adaptive management is not conceptually complex or operationally intricate, successful implementation of the process requires long-term perspective, commitment, and dedication, and it can be expensive (Williams and others, 2009; Williams and Brown, 2012). However, given the uncertainty surrounding the proactive management of sagebrush habitats coupled with the need to pursue innovative management approaches to achieve landscape-scale conservation goals in these habitats, the process of how conservation programs are implemented may be as important as the actual management and conservation actions pursued. Strictly adhering to adaptive management principles can inherently facilitate the application of this conservation strategy and the ecological principles described herein, thereby increasing the likelihood of attaining conservation success.

Structure of the Adaptive Management Process

The ARM framework proceeds in four stages involving (1) problem definition, (2) outcomes, (3) decision analysis, and (4) implementation and monitoring (Hammond and others, 2002; Marcot and others, 2012). Although monitoring is an essential component of ARM, it must be integrated within the management context to measure progress toward achieving management objectives (Nichols and Williams, 2006; Lyons and others, 2008).

The first stage of ARM is a clear articulation of the conservation problem to be solved and involves framing the problem, defining objectives, and establishing criteria by which alternative solutions can be evaluated (Marcot and others, 2012; Nichols and others, 2012, fig. 1). The articulation of the problem statement is an indispensable aspect of the ARM framework. Problem structuring involves identifying the responsibilities of decision makers, recognizing necessary tools and information, determining appropriate levels of investment, and ensuring the right problem is being solved (Marcot and others, 2012). Problem framing and objective setting stems from the policy, legal, and social dimensions of the management context and reflects the values of decision makers and stakeholders. Because natural resource management often involves multiple and potentially competing objectives, the development of objectives often benefits from workshops involving social scientists and experts in human dimensions to elicit the values of decision makers and stakeholders (Marcot and others, 2012). Objectives play the central role in ARM because they drive the other aspects of the process.

Second, the outcome analysis stage of ARM entails defining the full range of alternative management options, estimating their potential consequences, analyzing tradeoffs, and identifying key uncertainties (Marcot and others, 2012). Defining alternative management options may involve input from stakeholders, but the remainder of the decision analysis involves confronting management alternatives with mutually agreed-upon objectives developed in the problem-definition stage. Evaluating consequences involves predicting the outcomes of each alternative management action in terms of measurable objectives (Marcot and others, 2012). Quantitative modeling of existing data is often used to predict outcomes for each alternative management option. However, existing data may be of little use if not relevant to the objectives. Hence, not all existing monitoring data can be retrofitted or repurposed for new or future objectives.

Methods of addressing uncertainty in an ARM context often involve assessing the value of information relative to the predicted outcomes, thereby establishing the extent that information discriminates between management decisions (Canessa and others, 2015; Maxwell and others, 2015). In cases where the expected value of information is high or important, such as monitoring trends in populations of a species of concern to inform Endangered Species Act of 1973 (ESA; 16 U.S.C. 1531 et seq.) listing decisions, then it may be appropriate to implement research to reduce uncertainty prior to making management decisions. However, this is not always realistic within management timeframes or budgets. There is no advantage in gathering additional information if the expected value of information or the power to reduce uncertainty is likely to be low (Marcot and others, 2012). The concept of uncertainty in decision making differs from uncertainty in a scientific context. In many cases, reducing scientific uncertainty about predicted outcomes may not reduce uncertainty relative to the best course of action. Nevertheless, uncertainty can influence model predictions for the effects of management alternatives (Marcot and others, 2012), and several approaches have been developed to deal with uncertainty concerning resource conditions, consequences of management options, uncontrolled environmental variation, and dynamic processes (Williams and Johnson, 2013).

Third, decision analysis involves the selection of an alternative policy, conservation plan, or management option (Marcot and others, 2012). A decision can be thought of as an irrevocable allocation of resources, and may be a choice between strategic directions, such as land and resource management within a given region or area, or project-level decisions involving specific management actions. Several decision analysis frameworks are available for the transparent ranking of management alternatives using available science, values, and preferences of decision makers, and considerations raised by stakeholders (Marcot and others, 2012).

Fourth, implementation and monitoring describe a process of land and natural resource management where monitoring is integrated with the implementation of the preferred management alternatives (Marcot and others, 2012). Within the ARM process (fig. S1), the learning or adaptive phase is represented by the monitor and model components, whereas the optimization or management phase is represented by the model and decide components (fig. S1; Nichols and others, 2012). The state variables to measure and the scale of monitoring should be directly linked to the management context with a clear understanding of how the information gathered will be used to evaluate the management objectives (Marcot and others, 2012). To ensure the feedback necessary for ARM, the iterative, cyclic nature represented by the arrows in figure S1 is critical for sustainable conservation.

Adaptive resource management is a promising framework for managing sagebrush ecosystems (Kachergis and others, 2013; Hardegree and others, 2018), but the full potential of the adaptive framework has yet to be realized. In many respects, the term “adaptive management” has become a catchall phrase meaning something different to conservation planners, land managers, and research scientists (Williams and Brown, 2012). Despite considerable progress in conservation planning, management, and science in sagebrush ecosystems (Davies and others, 2011; Miller and others, 2011; Christiansen and Belton, 2017), separate frameworks for land management and conservation science developed in isolation may ultimately impede learning (Williams and Brown, 2012). In addition, monitoring to inform management in an informal or indirect way is often assumed sufficient to close the feedback loop in adaptive management (Williams and Brown, 2012). Attempts to develop adaptive frameworks in an ad hoc way often overlook key steps in the process and have been termed “adaptive management lite” (Ruhl and Fischman, 2010). These ad hoc approaches often suffer from the lack of clearly defined objectives, monitoring thresholds, and actions triggered by thresholds, and are better characterized

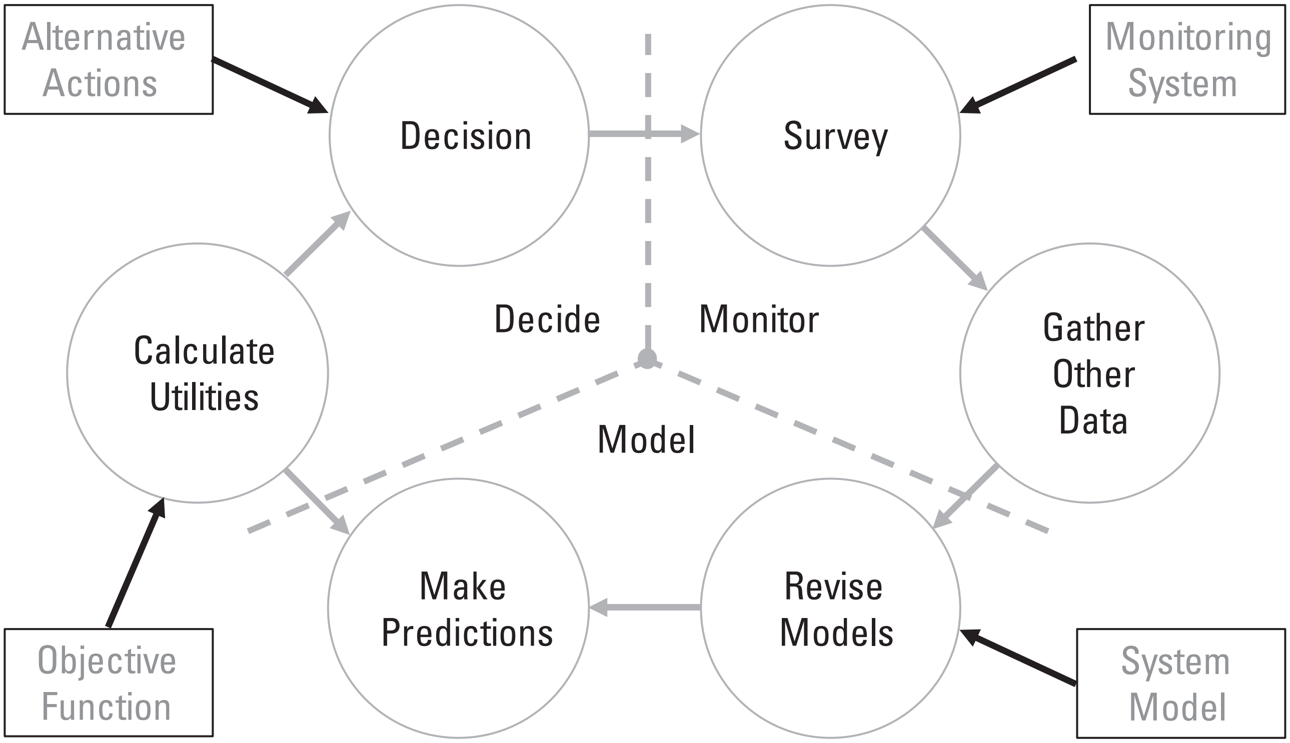

Figure S1. Monitoring in an adaptive resource management framework. Modified from Nichols and others, 2012.

as contingency planning based on monitored conditions than adaptive management (Fischman and Ruhl, 2016). Because legal proceedings have overturned several applications of adaptive management lite, adopting the adaptive management process as defined in the literature (fig. S1) may improve transparency, stakeholder participation, and accountability in the management of resources in the public trust (Fischman and Ruhl, 2016).

Vegetation Monitoring

Vegetation monitoring in sagebrush ecosystems ranges from local efforts on grazing lands to regional efforts designed to understand trends in rangeland health and wildlife habitats. Tracking changes in vegetation parameters of interest can be difficult and sometimes requires specific methods and sampling designs that allow for statistical analyses. The ability to detect changes in habitats over time depends on methods that provide precise estimates at each time interval so that meaningful differences can be detected (Seavy and Reynolds, 2007). In addition, sample sizes need to be large enough to maintain sufficient power—that is, to detect a difference when one exists (Taylor and Gerrodette, 1993).

Most vegetation monitoring methods quantify different measures of abundance. These include cover, biomass, frequency, and density, all of which can be used to derive dominance, and, indirectly, species composition (Bonham, 2013). These methods typically involve sampling using fixed-area plots of varying sizes. Vegetation within plots is sampled with multiple quadrats, belt transects, lines, or points (that is, subsamples). Measurements from these subsamples are then summarized as proportions (for example, percent cover) or as some measure of central tendency (for example, average cover) to represent the vegetation within the plot. Data are often summarized by species, lifeform, or functional group. In addition, ground cover (for example, bare ground, litter, rock) or canopy gap data may be collected. Careful comparisons among methods by researchers (for example, Stohlgren and others, 1998; Seefeldt and Booth, 2006; Godínez-Alvarez and others, 2009; Pilliod and Arkle, 2013) have enabled monitoring data that were collected using different methods to be combined. However, all methods have sampling biases and different levels of precision; these should be considered carefully when combining datasets.

Two common vegetation sampling methods are associated with line transects (Elzinga and others, 2001). The line-point intercept method tallies the number of intercepts (“hits”) along a transect, usually at evenly spaced intervals. Multiple transects are usually placed in a plot, often parallel to each other or in a spoke design (for example, Herrick and others, 2009). Alternatively, the line-intercept method measures the length of a line that is intercepted by vegetation.

Several methods are associated with area sampling within fixed-area plots or subplots. The quadrat method uses multiple small sampling frames placed on the ground, typically along multiple transects within a macroplot (Elzinga and others, 2001). Vegetation cover in the quadrats is either visually estimated or counted systematically at intercepts of grid points (that is, grid-point intercept). Biomass is usually quantified in quadrats by clipping and weighing current year’s growth. Density (the number of units [individual plants or stems]/sample area) is typically recorded in either quadrats or belt transects. Belt transects are like quadrats but elongated, often along a transect tape (for example, 1 meter [m; 3.3 feet {ft}] x 25 m [82 ft]). Finally, plotless methods or distance measures (for example, point-center quarter, nearest neighbor) can also be used to estimate density of plants that are randomly distributed or occur at low densities, and time- or area-constrained visual searches are useful for detecting rare plants (Elzinga and others, 2001).

Frequency is the presence (or absence) of a species (for example, lifeform, functional group member) rooted within a fixed area plot or quadrat. It is reported as the percentage of all possible plots/quadrats within a sample area in which a species is present. Plot or quadrat size strongly affects the percent frequency; selecting the appropriate size depends on the size and distribution pattern of the vegetation. Frequency has been used to infer abundance, but it is not the same as cover. However, in areas that are grazed, it is commonly used in lieu of cover estimates because, in theory, herbivory should not influence species presence as much as species cover. This holds at least until heavy or repeated herbivory begins to eliminate species when both metrics converge towards zero.

Finally, a well-designed, random (but representative) sample offers the best opportunity for detecting relevant trends in resources with maximum inference for areas of interest (Urquhart and others, 1998). In the sagebrush biome, which is heterogeneous owing to soil, topography, and climate, sampling designs often require spatial stratification to improve meaningful representation of resources or environmental conditions. This approach to rangeland vegetation monitoring is increasingly being implemented across multiple spatial scales and by many agencies and organizations (Herrick and others, 2010; Toevs and others, 2011; Barker and others, 2018). Nonrandom monitoring and convenience sampling still occurs but has limited inference and is difficult to roll up for multiscale assessments.

Examples of Vegetation and Habitat Monitoring Programs

Several monitoring programs have been developed by Federal agencies to address status and trends of resources on public and private lands. The U.S. Department of the Interior, Bureau of Land Management (BLM) Assessment Inventory and Monitoring (AIM) and the U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS), National Resources Inventory (NRI) both use core indicators and standardized protocols. The U.S. Department of Agriculture,

Nested, Hierarchical Adaptive Management

The focus for this Sagebrush Conservation Strategy is on a nested, hierarchical adaptive management construct:

Local Scale

- Build adaptive management construct into local sagebrush conservation strategies;
- Orient around the goals of all relevant stakeholders,
- Predict what is needed or what actions to take (for example, restoration) to meet resource, objectives (for example, forage, security cover) explicitly described;
- Assess progress through onsite monitoring; and
- Model pathways and feedback loops explicitly.

Midscale, Ecoregional

- Focus on major drivers to the system and actions needed to meet ecoregional goals, set ecoregional quantitative goals with respect to major drivers and evaluate through monitoring (for example, trends in annual grass infestation, conifer encroachment, restoration of major fires);
- Evaluate progress toward goals by summing number of projects, acreage treated, success, or other variables of local scale management actions by monitoring (most likely remotely) the extent and coverage of sagebrush, multiyear trends in invasive plant species distribution, fire frequency, acres burned, and more;
- Incorporate ecoregional-level monitoring of sagebrush-dependent species as a metric for assessing the success of sagebrush conservation strategies and efforts; and
- Incorporate explicit metrics into ecoregional models to iteratively evaluate whether and where additional conservation efforts are needed or whether assumptions or goals need to be changed at local scales.

Biome Scale

- Similar to the ecoregional scale but with biome-wide goals and assessed through monitoring at biome-wide levels (for example, remotely monitoring the extent and coverage of sagebrush, multiyear trends in invasive plant species distribution, fire frequency and acres burned, across all ecoregions);
- Incorporate biome-wide trends in sagebrush-dependent species by aggregating ecoregional monitoring as a metric for use assessing the success of sagebrush conservation strategies and efforts; and
- Incorporate explicit metrics into biome-wide models to iteratively evaluate whether and where additional conservation efforts are needed or whether assumptions or goals need to be changed at ecoregional scales.

Example

The ARM theory is well-developed. However, implementation, especially at broader scales, has not paced theoretical development. There are State and State/Federal collaborative adaptive management programs that primarily target game species for which harvest or other removal is potentially a factor limiting populations of these species. Examples include harvest management under the North American Waterfowl Management Plan (U.S. Department of the Interior, Environment Canada, and Environment and Natural Resources Mexico, 2018), big game management programs within State wildlife agencies, and the Mourning Dove Harvest Strategy coordinated by the U.S. Fish and Wildlife Service. These programs all include monitoring of population levels and trends, usually through modeling supported by indices of abundance, and feedback to adjust harvest or removal rates in support of larger population goals. A major weakness of all these adaptive management constructs is that while they provide feedback to regulate harvest, there is little to no monitoring of habitat and no feedback of habitat data to influence land use decisions affecting habitat.

Forest Service, Forest Inventory and Analysis (FIA) program uses a different set of indicators but also uses standardized protocols. Although FIA and NRI/AIM use different sampling methods, their sample designs allow for combined analyses of pooled data so that periodic assessments can be rolled up across spatial scales of interest using a nested hierarchy (Patterson and others, 2014). Each program is described below, with more information in appendix S1 (table S1.1).

NRCS National Resources Inventory Rangeland Resource Assessment

The NRCS NRI rangeland resource assessment provides information on the trends of land soil, water, and related resources on the Nation's non-Federal lands (accessible at https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/technical/nra/nri/results/?cid=nrcseprd1343025). A spatially balanced, randomly located sampling design provides land area estimates for qualitative and quantitative indicators related to rangeland health. Quantitative indicators include bare ground, plant species cover and composition, gaps between plant canopies, and soil stability according to the standard methods in Herrick and others (2009). The qualitative indicators of rangeland health (Pellant and others, 2005, 2020) are also assessed at each site. Results are reported to Congress as part of the Resource Conservation Act Appraisal (RCA;16 U.S.C. 2001–2009) and are increasingly used for other applications including research (for example, Herrick and others, 2010).

BLM Assessment, Inventory, and Monitoring Strategy

The BLM monitors public rangelands as part of the AIM strategy (Toevs and others, 2011), which provides a consistent and repeatable monitoring methodology to collect detailed quantitative information on rangeland vegetation condition. The AIM Strategy informs the BLM of resource status, condition, and trend at multiple spatial scales ranging from management units (for example, grazing allotments or treatments) to national-level assessments (Karl and others, 2016). Standard indicators (MacKinnon and others, 2011) are measured using the same methods as the NRCS NRI (Herrick and others, 2009). Many AIM efforts employ a stratified, randomized sample design to enable a statistically valid extrapolation across different spatial scales and reporting units, with greater sampling intensity in areas where issues have been detected or treatments are being monitored. Plots are resampled at 5-year intervals to detect trends over time. The AIM data are captured and managed electronically, which helps ensure data quality and facilitates centralized data storage, analysis, and reporting.

USDA Forest Service Forest Inventory and Analysis

The USDA Forest Service FIA is a national program for collecting and reporting information on status and trends in forest ecosystems. Forested vegetation data are collected across all land ownerships. The FIA programs also consistently collect data on nonforested land on National Forest System lands in California, Idaho, Montana, North Dakota, and parts of Oregon, Utah, Washington, and Wyoming. Because this covers most of the sagebrush distribution, the FIA dataset can be useful at broad scales. Canopy cover is estimated on the four most dominant species within a lifeform that are present within each (of the four 169 square meter [m^2] [1/24-acre]) subplots (within the -plot primary sample unit) that have at least 3-percent cover. In addition, line-point intercept is conducted to quantify ground cover (bare soil, rock, basal vegetation, and litter) composition for each of the four subplots.

Habitat Assessment Framework

The Sage-Grouse Habitat Assessment Framework (HAF; Stiver and others, 2015) is a multiscale assessment of sage-grouse (*Centrocercus* spp.) habitat suitability. The HAF is the primary assessment method used to evaluate the wildlife standard in the BLM land health evaluation process and is used by other Federal and State agencies to characterize sage-grouse habitat suitability. National forests and grasslands implementing the joint BLM/Forest Service sage-grouse land use plan amendments also use HAF to assess sage-grouse habitat. The HAF rates sage-grouse habitat suitability across four spatial scales: rangewide (first order), population (second order), subpopulation (third order), and seasonal habitat areas (fourth order). The second and third order HAF assessments evaluate the availability and continuity of sagebrush habitat at a landscape scale. At the seasonal habitat (fourth order) scale, HAF uses standardized monitoring data from AIM plots, as well as supplemental indicators, to rate sage-grouse habitat suitability across seasonal habitat areas based primarily on vegetation composition and structure. These monitoring indicators are summarized into overall suitability ratings at each plot, which are aggregated across seasonal habitat areas to determine sage-grouse habitat suitability. This coordination effort addresses two critical challenges that Federal land management agencies face today: (1) field capacity to complete monitoring data collection and (2) the ability to share and combine data to conduct data analysis across administrative boundaries.

Interpreting Indicators of Rangeland Health

Interpreting Indicators of Rangeland Health (IIRH) is a qualitative assessment protocol for rangelands (Pellant and others, 2005, 2020). The IIRH provides a preliminary evaluation of the current status of three attributes of rangeland health: soil and site stability, hydrologic function, and biotic integrity. This assessment is conducted by an interdisciplinary team observing and rating 17 indicators related to rangeland ecosystem functions. The IIRH is not meant as a stand-alone tool for monitoring rangelands or determining trend, but it is often used either prior to or in conjunction with quantitative monitoring efforts including BLM AIM and NRCS NRI.

Project-Level Monitoring

Project-level monitoring, including measures of condition and of change following disturbance, occurs throughout the sagebrush ecosystem at local scales and for a variety of purposes. Capturing the extent and diversity of those efforts is beyond the scope of this chapter; however, the individual efforts often provide critical guidance to subsequent management actions, in an adaptive management context, at the project scale. A good example is postfire Emergency Stabilization and Rehabilitation (ESR) monitoring associated with the 2015 Soda Fire in southwest Idaho and eastern Oregon. Led by BLM, this ESR monitoring mostly focused on implementation of many treatments, but collaboration with scientists at the U.S. Geological Survey (USGS) has included effectiveness and validation monitoring (for example, Germino and others, 2018; Davidson and others, 2019).

Project-level and postdisturbance monitoring can take many forms, from quantifying vegetation composition at the species or functional group level to photo points taken at certain time intervals. Project-level monitoring also occurs through programs like the NRCS Sage Grouse Initiative (SGI), where ranch-scale monitoring tracks condition, allows the individual producer to see firsthand the benefits of conservation practices, and provides the mechanism for long-term conservation. This monitoring instills in the producer the benefits of sustainable grazing systems in their operation and to sage-grouse conservation. Many other agencies and entities conducting restoration treatments in the sagebrush ecosystem also collect monitoring information, and some agencies require some posttreatment monitoring as part of their reporting to receive grant funds. Project-level monitoring also occurs as part of long-term research programs designed and carried out by scientists to track changes in vegetation and the biological response of sage-grouse populations to conservation practices.

State Agency Vegetation Monitoring Efforts

Many State agencies collaborate with the BLM to apply HAF for assessing sage-grouse habitat in their States. In addition, many States have developed habitat quantification tools (HQTs) that are used for mitigation programs. These tools are used to measure habitat function to quantify gains in sage-grouse habitat resulting from activities that restore, enhance, or preserve habitat, as well as losses resulting from activities that disturb, fragment, or eliminate habitat. Some States have also adopted individual monitoring and assessment protocols to address sagebrush vegetation and sage-grouse habitat quality; two examples follow.

The State of Oregon adopted simplified state-and-transition models, referred to as threat-based models (Johnson and others, 2019), as a framework for identifying and addressing the primary ecosystem threats to upland sagebrush ecosystems. Vegetation condition is described by ecological states that indicate current vegetation composition and the level of risk from major ecological threats like fire, conifer encroachment, and invasive annual grasses. Transitions between categories may be caused by natural disturbances (for example, drought or wildfire) or by management actions (for example, grazing, juniper [*Juniperus* spp.] removal, prescribed burning). Ecological states are described in easily understood terms, from “A” or “B” for relatively good condition with minimal threats expressed, to “C” for moderate conditions that require management changes to address threats, and then to “D” or “E” for poor conditions with high threat levels. Threat-based models are central to the 2015 Oregon Sage-Grouse Action Plan (Sage-Grouse Conservation Partnership, 2015), forming the basis of the State’s HQT and applied at scales from individual mitigation projects and U.S. Fish and Wildlife Service (FWS) candidate conservation agreements to statewide mapping and assessment of state wildlife action plan effectiveness. Although they have been used for sage-grouse planning in the State, they are ecosystem models that are not species-specific and can be used alongside species-specific methods, such as HAF, to paint a fuller picture of the ecosystem threats affecting sagebrush-obligate species.

In Nevada, the Department of Wildlife monitors approximately 2,000 plots across the State and into the California side of the Bi-State sage-grouse priority management units. Monitoring began in 2011 with the goal of evaluating the effectiveness and efficiency of habitat projects for sage-grouse. With validation in mind, most plots are placed in specific projects that allow for comparisons between treated and untreated areas. Monitoring methods mostly follow the AIM protocol, although the State has partnered with the Forest Service to implement HAF in some areas.

Remote Sensing and Geospatial Data for Monitoring

The use of remote sensing and geospatial datasets can provide tools for monitoring at multiple spatial scales. The increasing availability of remote sensing imagery has offered the potential to characterize and monitor conditions of sagebrush-dominated ecosystems at broad spatial and temporal scales (Kennedy and others, 2014). Given that satellite imagery, such as Landsat, dates back to the 1970s and 1980s, these technologies can provide a consistent approach across the sagebrush biome to monitor implementation of management activities and changes to habitat attributes, such as extent and condition of sagebrush and factors that contribute to habitat degradation.

Continuous remote sensing of vegetation has been available through the USGS Landsat Program since 1972 (U.S. Geological Survey, 2016). Landsat and other satellite, aerial, and ground-based sensors provide standardized metrics for evaluating vegetation productivity (Rouse and others, 1974) and other characteristics (Jensen, 2005). Use of these data products enabled the implementation of thematic vegetation mapping and laid the groundwork for many of the current monitoring programs. The Interagency Greater Sage-Grouse Monitoring Framework (Interagency Greater Sage-Grouse Disturbance and Monitoring Subteam, 2014) outlines standardized protocols for using LANDFIRE (U.S. Geological Survey, 2013b) and other map products to track loss and shifts in landscape attributes and vegetation characteristics that are critical for sagebrush-associated wildlife. Multiple remote sensing products are now available to characterize and monitor rangeland vegetation, including continuous cover maps of rangeland vegetation such as trees, shrubs, sagebrush, total herbaceous, and invasive annual herbaceous vegetation (see app. S2). Remote sensing can also be used to monitor other threats to sagebrush ecosystems. Fires are mapped annually through the USGS Monitoring Trends in Burn Severity (MTBS) program (Eidenshink and others, 2007), the Geospatial Multi-Agency Coordination (GeoMAC) wildfire application (https://www.geomac.gov/GeoMACTransition.shtml), and other programs. Sagebrush loss through agricultural conversion and urban development can also be monitored through programs like the USDA National Agricultural Statistics Service and Multi-Resolution Land Characteristics consortium (multiagency).

As technology has advanced, the capabilities and capacity of agencies and organizations to rapidly develop information to track changes in ecosystem condition have increased dramatically. However, applying remotely sensed maps as part of a monitoring program can be challenging. Although all datasets have limitations, a full understanding of the assumptions, error sources, scale, and limitations of each product is especially important for remotely sensed maps. While mapping technology has improved dramatically, localized errors (for example, inability to precisely reproduce spatial patterns at fine scales) and other accuracy issues (for example, overall bias of predicted values such as an inability to predict where a condition is absent) can limit the ability for mapping vegetation condition, particularly at smaller spatial scales. Most applications of remotely sensed products in rangeland monitoring use products at broad scales (for example, rangewide analyses such as the Interagency Greater Sage-Grouse Monitoring Framework [Interagency Greater Sage-Grouse Disturbance and Monitoring Subteam, 2014] or statewide assessment of habitat condition). Remotely sensed maps hold great promise for tracking changes over time across large landscapes, but accounting for map error is needed for robust change detection analysis. Maps can also be difficult to interpret along with other sources of information, including vegetation plot data, other datasets, and expert knowledge, and there is a need for examples of how to apply maps to management applications at finer management-relevant scales such as grazing allotments. However, technology in remote sensing and computational processing is rapidly evolving, and maps should continue to improve over time.

Additional Datasets for Monitoring and Adaptive Management

As agencies collect and compile spatially referenced data in the course of their functions, these datasets could offer opportunities to study and monitor management across landscapes. For example, the Land Treatment Digital Library (LTDL) has compiled thousands of land treatment records dating back to 1940 from BLM field and district offices across the western United States (Pilliod and others, 2017b). As this dataset is developed and maintained, the LTDL could provide a systematic record of land treatments that could serve a variety of applications including adaptive management and retrospective analyses (for example, Pilliod and others, 2017b; Copeland and others, 2018). Another data source is the FWS's Conservation Efforts Database (CED), which maintains records of conservation and restoration actions on private and public lands targeting sagebrush habitat (Heller and others, 2017). Other useful records relate to livestock grazing on public lands (Veblen and others, 2011; Monroe and others, 2017). The BLM maintains records each year of the reported livestock use (billed use animal unit month [AUM]) and the maximum number of AUMs authorized (permitted active use) in each allotment. These data represent one of the most complete and widespread records of livestock across the western United States and may provide insights into the relationships between the timing of grazing and rangeland condition or sage-grouse population trends (for example, Monroe and others, 2017).

Challenges and Opportunities for Vegetation Monitoring

Vegetation monitoring in sagebrush ecosystems has evolved through time and improved as natural resource managers have adopted inferential sampling designs and standardized methods. However, there remain gaps in vegetation monitoring approaches. One area of improvement is the frequency of monitoring and the length of time following restoration or other types of land treatments. Vegetation monitoring programs, such as AIM, frequently struggle to balance the costs of revisit frequency (for example, yearly, every other year, every fifth year) against increased spatial coverage (that is, more plots). Most management actions provide insufficient funding to perform monitoring for more than a few years, and thus, most project-level monitoring falls into implementation monitoring and not effectiveness monitoring. Some restoration outcomes take years to discern, so a commitment to longer term monitoring efforts is often needed. Monitoring programs used by different agencies, and sometimes within the same agency, are rarely integrated. This integration could increase inference and power, but also cost efficiency. Ultimately, monitoring programs, whether distributed across the sagebrush biome or at the project level, are constrained by limited funding. Perhaps the most practical way to alleviate this constraint is to increase efficiency through better partnerships and data sharing. Both approaches require communication, standardization of methods, and a commitment to value monitoring data as a source of information for adaptive management.

Wildlife Monitoring

The use of monitoring data in the conservation and management of wildlife populations requires a foundation of well-articulated monitoring objectives (Sauer and Knutson, 2008; Lindenmayer and Likens, 2010). For example, management and conservation objectives from the U.S. North American Bird Conservation Initiative (NABCI) are to (1) determine the status and trends of populations, (2) inform management and policy to achieve conservation, (3) evaluate conservation efforts, (4) inform conservation planning, (5) set population objectives and management priorities, and (6) determine causes of population change (U.S. North American Bird Conservation Initiative Monitoring Subcommittee, 2007). Monitoring long-term trends in occupancy, abundance, or demography provide some of the most useful data for the conservation planning process to prioritize and assess the vulnerability of wildlife species (Rosenberg and others, 2017). However, population trends without reference to monitoring objectives have limited utility for evaluating species responses to conservation and management (Nichols and Williams, 2006).

Population density or abundance metrics are essential for wildlife conservation and important for estimating the effect of management actions on wildlife species (Nichols and others, 2007; Smith and others, 2013). For example, a conservation objective for sage-grouse is to maintain annual counts of male sage-grouse at leks within a desired range or relative to a baseline. The State lek monitoring programs can be used to estimate sage-grouse abundance, population trends (McCaffery and others, 2016; Coates and others, 2018) and regional population size (Shyvers and others, 2018). These monitoring data can then be used in the adaptive management process to predict sage-grouse population responses to management alternatives and to determine which management alternatives attain the population size objective. Of course, the development of conservation objectives for sage-grouse at multiple scales will require careful deliberation among decision makers and stakeholders in the problem-definition stage of the adaptive management process (Coates and others, 2017d). Another potential objective could be to maintain population size above a threshold (Martin and others, 2009), and this must be considered in tandem with socioeconomic objectives in the region. Abundance may be a useful state variable for other sagebrush species of conservation concern, although occupancy may be more realistic given the challenges of monitoring most species. One exception appears to be population density of sagebrush birds, which can be quantified using point-count methods and evaluated with respect to management alternatives, such as conifer removal (Holmes and others, 2017) and prescribed grazing (Golding and Dreitz, 2017). Estimating abundance, however, requires larger sample sizes than site occupancy (Joseph and others, 2006; Noon and others, 2012) and may be more appropriate for well-studied, abundant, and conspicuous species, such as birds and native ungulates.

Monitoring population parameters, including movement and demographic or vital rates, provide mechanistic explanations for population change in response to management over time (Sandercock, 2006). Demographic or vital rates include the annual estimates of survival, production, and recruitment that are the ultimate cause of population dynamics. These parameter estimates are a powerful way to assess species responses to habitat management actions in sagebrush ecosystems (for example, Zeoli and others, 2008; Taylor and others, 2012; Doherty and others, 2014; Pilliod and Scherer, 2015; Dahlgren and others, 2016b; Coates and others, 2017d). The costs involved with monitoring population parameters with respect to management alternatives can be considerable because they often require mark-recapture methods, telemetry, or direct observation (for example, nest monitoring). The cost of obtaining this level of information needs to be weighed carefully against the value or necessity of the information to determine if the effort is necessary. As previously stated, the value or necessity of the information is determined when objectives are established by stakeholders and assessed relative to the degree of acceptable uncertainty in the population parameters (Canessa and others, 2015; Maxwell and others, 2015).

Site occupancy is an alternate state variable for wildlife conservation involving the extent of occurrence or geographic range of species (MacKenzie and Nichols, 2004; Noon and others, 2012). Multispecies occupancy models provide a community framework for monitoring the responses of individual species to management alternatives, with species richness summarized across the individual species' responses (Zipkin and others, 2010; Sauer and others, 2013). For example, an objective for the adaptive management of multiple sagebrush species of various taxa can be developed to maximize species richness as the cumulative occupancy of the species (Sauer and others, 2013). Objectives for occupancy dynamics include estimating local extinction and colonization to provide greater understanding of range expansion or contraction in response to management actions (Bled and others, 2013). Species richness of sagebrush wildlife may be best evaluated in an umbrella species framework (Nicholson and Possingham, 2006), with the objective of maximizing species richness when population size or population growth of a representative species is above an acceptable threshold. The sage-grouse has been suggested as an umbrella species for sagebrush wildlife species (Rowland and others, 2006), although there is disagreement over the effectiveness of this approach (Hanser and Knick, 2011; Norvell and others, 2014; Carlisle and others, 2018b; Runge and others, 2019; Timmer and others, 2019; chap. Q, this volume). The ability of adaptive management to accommodate multiple objectives will allow an evaluation of individual species' responses to management alternatives, and this will provide a framework for learning about the linkage between objectives for multiple sagebrush wildlife species and sage-grouse. Although adaptive management often involves directly evaluating the effectiveness of management alternatives (Nichols and Williams, 2006; Lyons and others, 2008), objectives based on habitat relationships can be used to indirectly predict species' responses to changes in habitat structure in response to vegetation management (Marcot, 2006; Aldridge and Boyce, 2007). Objectives defined by habitat relationships present an opportunity to monitor the performance of management alternatives in terms of vegetation responses to management. However, because habitat relationships are correlational rather than causal, effectiveness monitoring may be necessary to validate and update the predicted responses to changes in vegetation structure (Marcot, 2006).

State variables for rare and cryptic taxa with limited data can still be developed using a combination of qualitative data and expert opinion (Nyberg and others, 2006; Choy and others, 2009). For example, occurrence objectives for data-deficient species can be developed from range and distribution maps derived from opportunistic data (NatureServe, 2019), and expert opinion can be used to predict species responses to management alternatives (Kuhnert and others, 2010). Objectives initially formulated with qualitative data and expert opinion are justifiable on the basis that, rather than wait for definitive data, it is preferable to start the adaptive management processes with limited data and uncertain responses to management with the understanding that monitoring the relative performance of management alternatives and updating model results will reduce uncertainty over time (Williams and Brown, 2012; Neckles and others, 2015).

Adaptive Management and Monitoring of Nongame Species

There are relatively few national, regional, or State-level adaptive management or monitoring programs for nongame species in sagebrush ecosystems with the exception of songbirds. The distribution and status of most nongame mammals are rarely assessed, although interest in lagomorphs (for example, pygmy rabbits [*Brachylagus idahoensis*]) and bats has increased recently in sagebrush ecosystems. Reptiles and amphibians tend to be data-deficient, even though some species garner attention (chap. I, this volume).

Monitoring programs for songbirds provide our best example of nongame monitoring. The North American Breeding Bird Survey (BBS; Bystrak, 1981) and the Integrated Monitoring in Bird Conservation Regions (IMBCR; Pavlacky and others, 2017) provide data sources for estimating the site-occupancy and population size of sagebrush-obligate bird species. The primary objective of the BBS is to provide an index of abundance that can be used to estimate population trends and relative abundances at various geographic scales. The BBS covers the entire sagebrush biome, but some intermountain regions in Montana and Nevada have low numbers of routes. The IMBCR program provides defensible estimates of avian abundance and occupancy, designed to meet the NABCI goals for improving avian monitoring and is well suited for addressing multiple management and conservation objectives (U.S. North American Bird Conservation Initiative Monitoring Subcommittee, 2007). In addition, IMBCR accommodates a stratification scheme for effectiveness monitoring of habitat restoration, as well as local-scale habitat associations for predicting species responses to vegetation management (Pavlacky and others, 2017). The IMBCR program currently covers the eastern portion of the sagebrush ecosystem and has recently expanded to include Utah and BLM-administered lands in Nevada and Oregon. The BBS and IMBCR programs can both incorporate remotely sensed data to evaluate objectives for multiple species with respect to management alternatives such as conifer removal (Donnelly and others, 2017).

Amphibian monitoring is organized under USGS's Amphibian Research and Monitoring Initiative, although with less emphasis in the sagebrush biome. Most amphibian monitoring in sagebrush ecosystems is used to determine the status and trends of species petitioned for listing under the Endangered Species Act of 1973 (ESA; 16 U.S.C. 1531 et seq.). Examples include the Columbia spotted frog (*Rana luteiventris*) and western toad (*Anaxyrus boreas*). Monitoring these species involves visual encounter surveys of wetlands to document occupancy and evidence of reproduction.

Sometimes a few focal populations are monitored more intensively using mark-recapture methods to estimate population size and vital or demographic rates. Nevada employed all these strategies in a 10-year monitoring effort for the Columbia spotted frog in 2015 ahead of a not-warranted decision by the FWS (McAdoo and Mellison, 2016).

Adaptive Management and Monitoring of Game Species

Game management provides a useful example of adaptive management (see "North American Waterfowl Management Plan" sidebar). However, game management does not include quantification of habitat quality metrics. Game management aims to monitor annual population changes based on abundance data and hunter success data (estimates rely on data collected from surveys of hunters). As an example, upland game harvest success data are based on a random sample of hunters that purchased upland game hunting licenses. General surveys have inherent bias, such as nonresponse bias associated with higher survey return rates from successful hunters. Most State agencies have reduced reporting bias by increasing survey effort via permits, phone interviews, or web-based surveys, producing a random sample of species-specific hunters (for example, sage-grouse hunters).

As an example of partial adaptive management for a game species, sage-grouse harvest monitoring includes abundance monitoring based on lek counts, hunter surveys, and in some States, wing returns. Analysis of grouse wings provides ratios of males to females, ratios of chicks to females, and potentially nest success information. These ratios can provide productivity estimates to assess habitat quality across time but only at large scales. Counts of adult male sage-grouse on leks during the spring are the primary source of information used to assess populations and set appropriate regulations for the following hunting season. Unfortunately, there is a mismatch with the estimated population size to be hunted because productivity occurs in between the population assessment timeframe and when harvest occurs in the fall. Generally, lek trends are used to recommend season regulations by hunting unit, including season start date, season length, bag and possession limits, and areas open for hunting. Public input is also solicited in this process. Hunting season closures may occur in response to major habitat disturbances (for example, wildfire) or following outbreaks of disease (for example, West Nile virus), or when small populations decline to management triggers.

Most western States use some variation of adaptive harvest management (AHM) to manage big game populations. Not unlike vegetation components of the sagebrush ecosystem (of which several State-trust game species intersect), game resources require careful and increasingly intensive management to accommodate the many and varied public demands and growing impacts from people. Ideally, management of big game populations follows a "management by objective" approach. The primary objectives are based on how many animals should exist in a hunting unit and what is the desired sex ratio for the population (for example, the number of males per 100 females). The selection of

Bird Conservancy of the Rockies—Decision Support Tool

In an example of integrating monitoring and management for nongame species, the Bird Conservancy of the Rockies and partners developed a prototype web-based decision making tool (Bird Conservancy of the Rockies, http://rmbo.org/DST) to answer key management questions surrounding livestock grazing on privately owned or leased sagebrush rangelands (Cagney and others, 2010), as well as conservation objectives for greater sage-grouse (*Centrocercus urophasianus*; Manier and others, 2013) and sagebrush-dependent songbirds (Knick and others, 2003). The objectives of the tool are to maximize the (1) occurrence of sagebrush-dependent songbirds, (2) suitability of greater sage-grouse nesting habitat, and (3) forage production for sustainable livestock production. The tool evaluates alternative U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) practices for prescribed grazing and brush management to improve nesting habitat for greater sage-grouse (U.S. Fish and Wildlife Service, 2010). The tool is based on existing management and planning methods, and includes State wildlife habitat evaluation guides, NRCS state-and-transition models, and important ecological site descriptions for greater sage-grouse. The predicted responses of sagebrush-dependent songbirds to the management actions were based on local-scale habitat relationships and landscape-scale distribution models from the Integrated Monitoring in Bird Conservation Regions (IMBCR) program (Pavlacky and others, 2017). In addition, the tool is compatible with ongoing conservation initiatives in the range of the greater sage-grouse and was designed to input preproject vegetation data collected by NRCS resource inventories. Finally, the tool integrates stakeholder objectives, conservation practices, and data-driven predictions to identify win-win solutions for sustainable livestock production and multispecies conservation of sagebrush birds. The management tool can be easily extended to adaptive management by including data for postproject effectiveness monitoring (Nyberg and others, 2006).

North American Waterfowl Management Plan

As an illustration of adaptive management in action, U.S. Department of the Interior’s Adaptive Management Applications Guide (Williams and Brown, 2012) describes how the Harvest Management Working Group uses adaptive management to inform waterfowl harvest regulations. The adaptive harvest model (AHM), better described as a process rather than a model, incorporates waterfowl population data collected annually into population models to inform development of hunting season regulations. Each year, monitoring activities such as aerial surveys and hunter questionnaires provide information on population size, habitat conditions, and harvest levels. Data collected from this monitoring program are analyzed each year, and proposals for duck-hunting regulations are developed by the flyway councils, States, and U.S. Fish and Wildlife Service (FWS). After extensive public review, the FWS announces a regulatory framework within which States can set their hunting seasons.

Adaptive Harvest Model Components

- A limited number of regulatory alternatives that describe Flyway-specific season lengths, bag limits, and framework dates;
- A set of population models describing various hypotheses about the effects of harvest and environmental factors on waterfowl abundance;
- A measure of reliability (probability or “weight”) for each population model; and
- A mathematical description of the objective(s) of harvest management (that is, an objective function) by which alternative regulatory strategies can be evaluated.
- Components are used in a stochastic optimization procedure to derive a regulatory strategy that specifies the appropriate regulatory alternative for each possible combination of breeding population size, environmental conditions, and model weights. The setting of annual hunting regulations then involves an iterative process:
- Each year, an optimal regulatory alternative is identified based on resource and environmental conditions and on current model weights;
- After the regulatory decision is made, model-specific predictions for subsequent breeding population size are determined;
- When monitoring data become available, model weights are increased to the extent that observations of population size agree with predictions and decreased to the extent that they disagree; and
- The new model weights are used to start another iteration of the process.

The AHM approach explicitly recognizes that the consequences of hunting regulations cannot be predicted with certainty and provides a framework for making objective decisions in the face of that uncertainty. The process is optimal in the sense that it provides the regulatory choice necessary, each year, to maximize management performance. The process is adaptive in the sense that the harvest strategy “evolves” to account for new knowledge generated by a comparison of predicted and observed population sizes. Inherent in the adaptive approach is awareness that management performance can be maximized only if regulatory effects can be predicted reliably. Thus, the AHM approach relies on an iterative cycle of monitoring, assessment, and decision making to clarify the relationships among hunting regulations, harvests, and waterfowl abundance. Despite its limits, the AHM is considered one of the most successful wildlife management programs in North America (Williams and Johnson, 1995; Johnson and Williams, 1999; Williams and others, 2002).

population and sex ratio objectives drive important decisions in the big game season setting process, namely, how many animals need to be harvested to maintain or move toward the objectives, and how are hunting seasons managed to achieve the harvest objective. Most big game AHM constructs lack any explicit habitat component in their modeling approaches. Consequently, they are limited in their ability to respond when harvest management is not an effective tool, for instance when populations are chronically below objective because of long-term declines in habitat quality, quantity, or both.

In summary, game management programs are good examples of adaptive management because they start with broad strategic and population-level management plans which describe quantitative population and performance (for example, doe/fawn ratios) objectives that are based on scientific underpinnings (ongoing monitoring data and models). Annual objectives (for example, harvest quota) are adjusted in some cases because of other sources of mortality, public involvement, and other factors (for example, to reduce damage to property). Cyclic repetition with annual adjustments and consideration of uncertainty and stochasticity represent an AHM approach. Below is an example for waterfowl management that could easily be applied to sage-grouse, for example (see “North American Waterfowl Management Plan” sidebar). However, game management AHM approaches could be improved by the addition of an explicit habitat component that would illustrate the nature and extent of habitat improvements needed to achieve objectives.

Challenges and Opportunities to Implement Adaptive Management for Wildlife

The gaps in wildlife monitoring approaches are often identified when setting priorities for measurable objectives in the problem definition phase of adaptive management. The objectives must be established ahead of the management interventions and before monitoring designs are developed (Lyons and others, 2008). When setting objectives for wildlife, rather than anchoring on the availability of existing data, it is preferable to develop objectives to solve the most pressing conservation problems in sagebrush ecosystems. However, the development of measurable objectives and monitoring designs are an iterative process that often involves evaluating the cost and feasibility of monitoring. Data gaps for the response of wildlife species to management creates uncertainty about the consequences of the management actions (Williams and Brown, 2012). Although there is often institutional resistance to acknowledging uncertainty, adaptive management provides a framework for addressing and reducing uncertainty through the process of management itself (Williams and Brown, 2012). Adaptive management can increase the cost-effectiveness of management and monitoring, but because the process requires considerable time investments on the front-end and continuity to monitor management alternatives on the back-end (Williams and Brown, 2012), implementation of adaptive management across the sagebrush biome faces obvious funding constraints.

Although this chapter provides several examples of successful implementation of ARM for wildlife species and populations in North America, existing programs and approaches also have several shortcomings. First, these iterations of ARM are largely single-species approaches that are not likely to effectively conserve the full breadth of sagebrush-associated taxa. Second, the programs described are, for the most part, funded through license fees and dedicated Federal programs such as Pittman-Robertson for single-species management. Those kinds of funding sources are not expected to be available for most sagebrush species, guilds, communities, or whatever target/ecological unit is identified. Existing adaptive management programs are not typically based on random survey designs and are not standardized among all harvest units, among populations, or across governing entities; in some cases, known technical and analytical flaws persist because of institutional or capacity limitations. Standardization of survey techniques and implementation of random survey designs would allow for better inference related to population trajectories across time (for example, Robust Design surveys). These concepts would reduce inherent sampling bias present in current surveys. Furthermore, in most cases, few, if any, other critical factors are used to inform decisions (for example, habitat extent, quantity, or quality). Spatially explicit surveys would allow wildlife monitoring (abundance or indices) to be related to habitat quality by comparison to habitat data derived from field plots or geographic information system analysis. Also, the targets of existing programs consistently have economic value and active user-bases, neither of which may be the case for many sagebrush-associated taxa.

Advances in technology, statistical design, model integration, and shared conservation planning methods provide opportunities to consider and initiate ARM for multiple taxa and ecological systems. Monitoring programs are getting stronger and more robust, including integration of habitat and population modeling. Advances in remote sensing and data management processes now provide opportunities not available before. Policy makers, agency leaders, and biologists are now recognizing that data-driven management with appropriate feedback loops (that is, effective ARM) will help prevent species from being petitioned or listed under the ESA, an event that would further constrain management options.

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Appendix S1. Comparison of Federal Monitoring Programs in Rangelands

Table S1.1. Comparison of Federal monitoring programs in rangelands.

[<, less than; BIA, Bureau of Indian Affairs; NRCS, U.S. Department of Agriculture, Natural Resources Conservation Service; BLM, U.S. Department of the Interior, Bureau of Land Management, USDA, U.S. Department of Agriculture]

Protocol	National Resources Inventory (NRI)	Assessment Inventory and Monitoring (AIM)	Forest Inventory and Analysis (FIA)
Target population	Private- and BIA-managed rangelands (<25 percent tree canopy cover)	BLM-managed rangelands (<25 percent tree canopy cover)	All nonforested (<10 percent tree cover) National Forest System lands
Sample design	Probabilistic	Probabilistic	Probabilistic
Scale	Broad	Broad to fine	Broad
Attributes	Foliar cover by species	Foliar cover by species	Canopy cover by species (reduced species list)
	Ground cover	Ground cover	Ground cover
	Species richness	Species richness	
	Woody plant height	Woody plant height	
	Herbaceous plant height	Herbaceous plant height	
	Plant canopy gaps	Plant canopy gaps	
	Soil aggregate stability	Soil aggregate stability	
	Production	Others locally collected	
	Sagebrush shape		
Method	Line-point intercept, species inventory, height, canopy gap intercept, soil stability kit, clipping and double sampling, sagebrush shape	Line-point intercept, species inventory, height, canopy gap intercept, soil stability kit, clipping and double sampling, sagebrush shape, others locally collected	Fixed area circular plot (1/24-acre) and canopy cover estimation of top four dominant species within a lifeform that have at least 3 percent canopy cover; line- point intercept for ground cover
Standard plot layout	47 meters (150 feet) diameter circle	30 meters (98 feet) diameter circle	
Data availability	Summary reports available from NRCS; very limited site or database data availability	Calculated indicators by site are public; database available by request	Summary reports are available from USDA Forest Service; site and data unavailable

Appendix S2. Remotely Sensed Maps of Rangeland Vegetation Available Across the Sagebrush Biome

Below we provide information about major remotely sensed maps of rangeland vegetation available across all or most of the sagebrush biome (current as of early 2019). Products specific to smaller geographies (for example, individual States) are not included.

LANDFIRE Existing Vegetation Type and Biophysical Setting Maps

Produced by U.S. Department of Agriculture, Forest Service, and U.S. Department of the Interior

Description.—LANDFIRE delivers geospatial data products for vegetation, fuel, disturbance, and fire regimes that are consistent, comprehensive, and standardized across the entire Nation.

Map product(s) available.—Many LANDFIRE products are available, but most applicable to sagebrush monitoring are existing vegetation type and biophysical setting. Other products include fuel maps, fuel models, and vegetation models.

Timeframe.—Products have been produced for multiple timeframes from 2001 to 2016.

Imagery source.—Landsat satellite imagery.

Plot data source.—The public LANDFIRE reference database (https://www.landfire.gov/lfrdb.php) includes plots from several national vegetation monitoring programs.

Web viewer.—Products available on the LANDFIRE webpage through the Data Distribution Site (https://www.landfire.gov/viewer/).

Data download.—The data access page (https://www.landfire.gov/getdata.php) allows download through the web viewer or ArcMAP tool for an area of interest, download of data mosaics for the entire United States, or streaming of web services.

Documentation.—See LANDFIRE webpage (https://www.landfire.gov/vegetation.php).

Reference.—See list of publications (https://www.landfire.gov/lf_methods.php).

National Land Cover Dataset (NLCD) Characteristics Shrubland Products

Produced by Multi-Resolution Land Characteristics (MRLC) Consortium

Description.—The NLCD shrubland map products characterize shrubland vegetation across the western United States by quantifying the proportion of shrub, sagebrush, herbaceous, annual herbaceous, litter, and bare ground, as well as the height of shrubs and sagebrush.

Map product(s) available.—percent shrub, percent sagebrush, percent big sagebrush, percent herbaceous, percent annual herbaceous, percent bare ground, percent litter, shrub height, sagebrush height.

Timeframe.—current maps represent 2016 conditions. Updates are planned every 5 years, and back in time products are in progress.

Imagery source.—WorldView-2 and Landsat 8 imagery.

Plot data source.—High resolution training data and other sources.

Web viewer.—The MRLC Interactive Viewer (https://www.mrlc.gov/viewer/) allows viewing and download of NLCD data layers.

Data download.—Data are downloadable by ecoregion (https://www.mrlc.gov/data?f%5B0%5D=category%3Ashrubland).

Documentation.—Documentation is provided on the NLCD website (https://www.mrlc.gov/data/type/rangeland-basemap) and product metadata.

Rangeland Analysis Platform

Produced by University of Montana and released in 2018 (https://rangelands.app)

Description.—This product provides continuous cover maps of major rangeland vegetation functional groups at yearly intervals from 1984 to 2017 across the western United States. The mapping process merges machine learning and cloud-based computing with remote sensing and field data to provide continuous vegetation cover maps.

Map product(s) available.—Annual forbs and grasses, Perennial forbs and grasses, Shrubs, Trees, Bare ground.

Timeframe.—Yearly maps for all years from 1984 to 2017. Maps will be updated annually in the future.

Imagery source.—Landsat satellite imagery.

Plot data source.—NRCS NRI plots, BLM AIM plots and Landscape Monitoring Framework (LMF) plots.

Web viewer.—A public web viewer (https://rangelands.app/) allows users to view data layers in an interactive map and generate graphs of average values for each year across a user-defined area of interest.

Data download.—Data download can be requested by the authors, or data can be viewed in ArcGIS as a web map tile service.

Documentation.—Documentation is provided on the web viewer and the reference below.

Near-Real-Time Herbaceous Annual Cover in the Great Basin

Produced by U.S. Geological Survey and released in 2018

Description.—Maps provide near-real-time spatial estimates of herbaceous annual vegetation percent cover across the Great Basin at multiple time points each year (May and June/July). Maps are based on Normalized Difference Vegetation Index (NDVI), which provides an estimate of vegetation greenness. Maps are produced each year by late May to help inform fire suppression activities and other management activities, such as application of weed suppressive bacteria, targeted grazing, and other cheatgrass control measures.

Map product(s) available.—Herbaceous annual cover.

Timeframe.—Multiple timeframes from 2017 to 2018. Maps are produced for multiple months within each spring. Updates are planned in early and late spring each year.

Imagery source.—Enhanced Moderate Resolution Imaging Spectroradiometer (eMODIS) imagery.

Plot data source.—High–resolution training data and other sources.

Web viewer.—None.

Data download.—Data download available from Sciencebase (https://www.sciencebase.gov/catalog/item/5b439bf9e4b060350a127028).

Documentation.—Documentation in the publication and ScienceBase.

Tree Canopy Cover

Produced by Colorado State University and released in 2017

Description.—High resolution maps of tree canopy cover (1-m resolution) were produced from Natural Agricultural Imagery Program (NAIP) imagery by using spatial wavelet analysis.

Map product(s) available.—Tree canopy cover.

Timeframe.—Single timeframe representing 2012–2013.

Imagery source.—National Agriculture Imagery Program (NAIP) air photos.

Plot data source.—None.

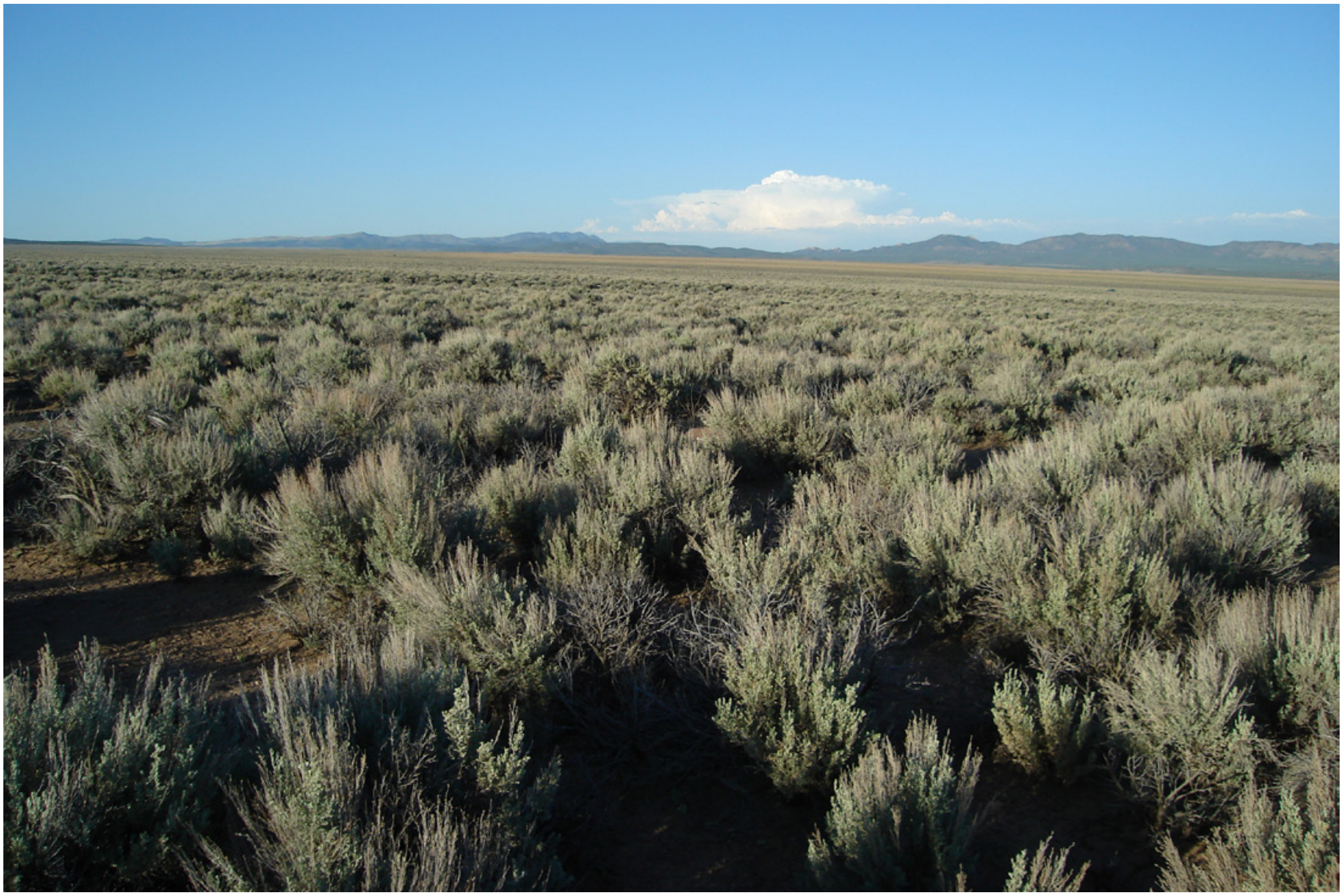
Web viewer.—Map is viewable in an interactive map through the Sage Grouse Initiative Data Viewer (https://map.sagegrouseinitiative.com).

Data download.—Data downloadable by State from the data viewer.

Documentation.—Documentation provided on the data download page and in the publication.

Prepared in cooperation with the Western Association of Fish and Wildlife Agencies, the Bureau of Land Management, and the U.S. Fish and Wildlife Service

Sagebrush Conservation Strategy—Challenges to Sagebrush Conservation



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U.S. Geological Survey

Sagebrush Conservation Strategy—Challenges to Sagebrush Conservation

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