2. ADAPTIVE MANAGEMENT AND MONITORING

Lief A. Wiechman, David A. Pyke, Michele R. Crist, Seth M. Munson, Matthew L. Brooks, Jeanne C. Chambers, Mary M. Rowland, Emily J. Kachergis, and Zoe Davidson

Introduction

Monitoring programs designed to track ecosystem changes in response to both stressors and disturbances use repeated observations of ecosystem attributes. Such programs can increase our understanding of how interactions among resilience to disturbance, resistance to invasive species, and "change agents" including management actions influence resource conditions (or status) and trends and outcomes of conservation and restoration actions. This type of monitoring information provides the basis for adaptive management. The overarching goal of an integrated monitoring and adaptive management program is to reduce the uncertainty in the effectiveness of management actions over time by improving management objectives and strategies to increase the effectiveness of those actions.

An integrated monitoring and adaptive management program includes a series of steps that are repeated over time and are designed to facilitate "learning by doing" (fig. 2.1). A structured decisionmaking process may be useful for developing meaningful objectives, and can aid land managers and stakeholders in examining the context, options, and probable outcomes of decisions through an explicit and repeatable process (Allen et al. 2011; Marcot et al. 2012; Thompson et al. 2013). The first step, **assessment**, involves defining the problem, identifying objectives, and determining evaluation criteria. In the second step, **design**, the alternatives are defined, the consequences and key uncertainties are identified, and tradeoffs are evaluated. Next, the preferred alternative is identified, and the decision is made to **implement** the preferred alternative and management action(s).

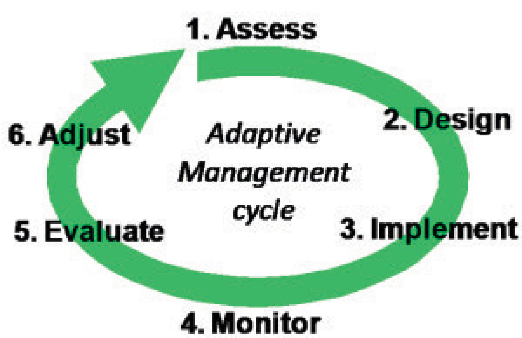

Figure 2.1—The primary components of the adaptive management cycle.

Top left: Assessment, Inventory, and Management (AIM) meeting (photo: Emily Karchergis, USDOI Bureau of Land Management). Middle left: Mark Szcztpinski using telemetry to track the movements of Greater sage-grouse (photo: Kenton Rowe. Montana Fish, Wildlife and Parks). Bottom left: Digging a soil pit and describing the soils (photo: Emily Karchergis, USDOI Bureau of Land Management). Right: Monitoring vegetation (photo: Emily Karchergis, USDOI Bureau of Land Management).

Text Box 2.1—Components of Monitoring Objectives

An example monitoring objective is:

- Maintain sagebrush cover greater than 15 percent and less than 25 percent across 70 percent of the sage-grouse nesting and early brood-rearing habitats in the assessment area.

Monitoring objectives should identify:

- The indicator(s) that will be monitored;
  - In this example, the indicator would be ***sagebrush cover***.
- Quantitative benchmark(s) for each indicator;
  - In this example, a range of values from ***15 to 25 percent*** sagebrush cover across ***70 percent of the sage-grouse brood-rearing habitat*** in the assessment area would be used.
- A timeframe for evaluating the indicator(s);
  - In this example, the timeframe is likely to be determined by the ***life of the management plan or strategy.*** However, projects and treatments may have a finite timeframe.
- The geographic scale(s) (likely local to mid-scale) over which the monitoring results will be reported (e.g., treatment area, land use planning area).
  - In this example, the scale would be ***sage-grouse nesting and brood-rearing habitat*** in the assessment area.

For more detailed information, refer to part B of table 2.1

Monitoring is the fourth step and is key to adaptive management. The information from a long-term monitoring program is used to **evaluate** ecological status and trends and whether or not management objectives are being met. That information is then used to **adjust**, as necessary, the management action(s) to meet management objectives. A well-designed and rigorous monitoring program has many components (table 2.1) Together these components are used to estimate the proportion of an area that is or is not meeting certain objectives or standards, and provide an unbiased estimate of environmental conditions and changes for ecosystems, species, and populations. Describing the likely data analysis techniques can help ensure that the sampling design will produce meaningful results.

Elzinga et al. (1998) describe how to establish a monitoring program for plant populations and Hayward and Suring (2013) describe this process for wildlife habitat monitoring. These sources provide the necessary information for developing monitoring programs for other types of resources. Definitions related to developing a monitoring program are in Appendix 1.

Monitoring is most effective for adaptive management when the objectives are clearly defined and are consistent with the broader management objectives for the resource. Text box 2.1 provides an example of a monitoring objective. To determine whether the objectives are being met, specific indicators are identified that can be measured and can account for changes in the resource within a realistic timeframe and budget given the site potential and spatial scale of the area being managed (table 2.1).

Benchmarks are indicator values, or ranges of values that establish desired conditions and are meaningful for management. Benchmarks are used to compare observed indicator values to desired conditions. For example, achieving a benchmark value of plant density may tell the practitioner that a seeding project was successful; failure to achieve it may prompt a reevaluation of seeding methods.

Benchmarks for a given indicator may vary for sites with different biophysical characteristics and ecological potential (e.g., ecological site types). Thus, it may be necessary to group benchmarks for areas with different characteristics within a project area and to include the proportion of the landscape that is required to meet a given benchmark. Without appropriate benchmarks, such values lack context and cannot be used to assess condition or the attainment of management objectives.

Table 2.1—Components of a monitoring program based on Elzinga et al. (1998) and Goldstein et al. (2013).

A. Complete Background Tasks

1. Compile and review existing information on the ecosystems, species, and populations. Ecological models of the relationships among ecosystem or habitat characteristics, species abundance, and management effects can help in developing monitoring objectives and improve interpretation and application of the data.
2. Review existing planning documents describing management objectives, including benchmarks or desired conditions, and planned management actions.
3. Prioritize the ecosystems, species, and populations to be monitored based on existing assessments. These priorities may require periodic reassessment due to changes in threats, management, conflicts, and the interests of outside parties.
4. Assess the resources available for monitoring, including management support, priorities, and people and equipment available.
5. Determine the scale of interest for the monitoring effort, such as the sagebrush biome, the range of a species, certain ecological types, or local scales (e.g., populations in certain management units).
6. Determine the type and intensity of monitoring based on the management objectives.
7. Ensure adequate review of the proposed monitoring program by higher level management and by individuals working in relevant disciplines. For larger programs or highly controversial ecosystems, species, and populations, a team may need to be assembled.

B. Develop Monitoring Objectives

1. Develop monitoring objectives that are consistent with the management objectives.
2. Select indicators that can be used to identify the status and trends of a resource or the effectiveness of a management action.
3. Identify the indicators that are most sensitive and appropriate for measuring status and trends or change toward the management goals or benchmarks.
4. Specify the amount and direction of change that is desired or that can be tolerated for each indicator. This science-based value may include a percentage change, or a target or threshold value.
5. Specify a biologically meaningful timeframe for monitoring, considering the indicators selected, to measure ecosystem and species responses following a management action.
6. Specify the management responses needed if monitoring indicates that the management objectives have or have not been met.

C. Design the Monitoring Methodology

1. Develop the sampling objectives.
2. Determine and map the area to be monitored.
3. Define the sampling unit for each indicator that will be measured.
4. Determine the method of sampling unit placement within the monitoring area. An unbiased estimate of resource status and trends can be gained by incorporating randomization into sampling designs.
5. Determine biologically meaningful monitoring durations, intervals, and frequencies.
6. Design the data sheets for the indicator to be measured.
7. Describe the likely data analyses for the different indicators.
8. Identify the necessary resources required to implement the monitoring plan.
9. Write a monitoring plan that has sufficient details for the monitoring to be repeated over time.

F. Implement Monitoring

1. Collect the data at specified intervals using trained personnel.
2. Analyze the data that are collected after each measurement cycle.
3. Describe what if any monitoring triggers have been passed, or what if any benchmarks have been met during the monitoring cycle.
4. Evaluate monitoring methods, costs, sample sizes, and relevance after each measurement cycle. Conducting a trial run or pilot study can expose problems and allow adjustments in the methodology to increase monitoring effectiveness.

G. Manage, Store, and Report Data

1. Ensure that the data for each measurement cycle are complete, entered into standardized databases, verified, and backed up.
2. Analyze all data collected over the reporting period.
3. Review the results for potential issues with either the data collection protocols or the amount and direction of change occurring in the indicator variables.
4. Compile the data and analyses into reports. For data collected over longer time periods, reports should be developed at regular intervals.

H. Apply Results of Monitoring in an Adaptive Management Context

1. Use monitoring results to adjust priority areas for programs of work and resource allocation.
2. Use monitoring results to inform revisions of Land Use Plans and Amendments.
3. Use monitoring results to assess the effectiveness of management strategies and treatment methods and to guide revisions in these as needed.

Monitoring benchmarks can be established based on the management objectives and current ecological site potential of the area (text box 2.2). For example, the Bureau of Land Management (BLM) has set a number of benchmarks for sagebrush cover and other vegetation characteristics in order to maintain habitat for Greater sage-grouse (*Centrocercus urophasianus*; hereafter, GRSG) (e.g., Stiver et al. 2015). Ecological site descriptions and state-and-transition models provide information on the current ecological states and the likely effects of stressors, disturbances, and management actions and can be used to help determine appropriate management objectives (see text box 7.2) and set meaningful benchmarks.

Environmental **thresholds** (conditions sufficient to modify ecosystem structure and function beyond the limits of ecological resilience that result in transition to alternative states [Briske et al. 2008]) are necessary to provide a clear path for management options or alternatives under adaptive management. Knowledge, or estimates, of environmental **thresholds** is important for establishing monitoring triggers. **Triggers** are levels of environmental conditions that can provide an early warning of possible thresholds and of management changes that may be necessary to maintain the desired environmental conditions (Briske et al. 2008; Goldstein et al. 2013).

Monitoring of the indicators must be repeated over sufficient, predetermined time intervals to detect changes and trends in resource status at the spatial scale of management interest. After each measurement cycle is complete, the data are entered into standardized databases, verified, and backed up. **Analyzing** the monitoring data to assess whether the management objective has been achieved or any thresholds have been crossed is the fifth step in an adaptive management program.

The final step is either continuing or changing management at the scale necessary to achieve the desired response or condition. Natural resource decisions are often complex and made with uncertainty, yet managers and biologists are expected to effectively justify and communicate their decisions. In the context of Part 1 of the Science Framework (Chambers et al. 2017; hereafter, Part 1), monitoring results can be used to adjust priority areas for programs of work and budget allocation, to inform efforts such as Federal land use plans (LUPs) and State Wildlife Action Plan revisions, to assess the effectiveness of management strategies and treatment methods, and to guide improvements.

Text Box 2.2—Information to Consider for Establishing Benchmarks

Sources of information and data that can be used to develop benchmarks in an interdisciplinary team environment to build consensus include:

- Policy (e.g., sage-grouse habitat standards, State water quality standards)
- Ecological site descriptions or state-and-transition models
- Comparable monitoring efforts (e.g., baseline Assessment, Inventory, and Monitoring [AIM] data)
- Scientific literature (e.g., sage-grouse habitat assessments)
- Predicted natural conditions (e.g., ecological models)
- Best professional judgment (e.g., considering local knowledge and best available science together)
- Paired reference sites

Overview of the Types of Monitoring

Monitoring can be divided into two categories. The first category describes the ecological status and trends of management areas, and the second category evaluates how well management objectives are being met in project areas. For the purposes of this document, we define "treatments" as site-specific management actions that directly influence one or more of the four ecosystem attributes that are defined in the next paragraph (e.g., biotic integrity can be influenced by juniper and piñon removals, fuel treatments, or GRSG population size). "Projects" can encompass multiple treatments and may relate to broader-scale landscape objectives. "Management action" is a general term that includes active treatments, but may also include actions such as changing management of livestock grazing or recreational uses.

Regardless of the category of monitoring, four ecosystem attributes are important to monitor for determining ecosystem status of an individual management unit (local scale), an ecoregion or Management Zone (mid-scale), or the sagebrush biome (broad scale). Because these attributes are difficult to measure directly, they must be tracked through multiple indicators (Herrick et al. 2010, 2017).

Soil Stability and Health. Soil is the basic foundation of terrestrial ecosystems. Thus, the attributes of soil stability and soil health (quality) are critical elements for sustaining plant, animal, fungal, and microbial functions.

Hydrologic Function. Hydrologic function of terrestrial systems is closely linked to soil stability and quality. All land types (upland, wetland, and riparian ecosystems) are important for maintaining the capture, storage, and release of water.

Water Flow and Quality. Lentic (still water) and lotic (moving water) ecosystems have unique functions as basic resources for biotic integrity, but their capacity to function properly (e.g., recharge and discharge of water to or from the soil) may be linked to other attributes such as soil stability (e.g., sedimentation) or hydrologic function.

Biotic Integrity. Biotic integrity of the plant, animal, fungal, and microbial components of the ecosystem, whether on land or in water, is closely linked to resilience to disturbance and resistance to invasion. This may often include composition, structure, and function of the community or ecosystem.

Monitoring Ecological Status and Trends (Condition and Change)

Status and trends monitoring aims to understand the current condition of natural resources (status) as well as changes in resource condition over time (trends). This type of monitoring informs adaptive management decisionmaking by revealing whether any triggers or benchmarks in soil stability and health, hydrologic function, water flow and quality, and biotic integrity have been reached and whether subsequent management actions are necessary. Status and trends monitoring in sagebrush ecosystems can address questions about the quality and quantity of habitat, the spatial distribution of observed changes, and when possible, **why** resource conditions are changing over time (see *Validation Monitoring*). Such monitoring is often a subset of a larger program or inventory aimed at a broad set of resources within a particular land ownership or jurisdiction. Ideally, by using standardized protocols across land ownership or jurisdictional boundaries, data can be aggregated to understand changes at multiple scales (Rowland and Vojta 2013). Monitoring may be intensified in areas where more information is needed such as in high-priority GRSG habitat and areas with low resilience and resistance (table 1.3: cells 3B, 3C). Causal associations between resource conditions and drivers of change, such as land management decisions or climate change, can be determined by evaluating information from status and trends monitoring along with spatial information about those drivers and reference or control sites.

An unbiased estimate of resource status and trends can be gained by incorporating randomization into sampling designs across an area of interest and keeping track of other potential influences on monitoring results, such as different detection levels, observers, and environmental conditions, which can be accounted for in the analysis. Finally, this type of monitoring can provide information at multiple scales of interest.

Several monitoring programs have been developed to address status and trends of resources, including the BLM's Assessment, Inventory, and Monitoring (AIM) and the Natural Resources Conservation Service's National Resources Inventory (NRI), both of which use common indicators and protocols; the Forest Service's Forest Inventory and Analysis (FIA) program; and the national Landscape Monitoring Framework, which is part of BLM's AIM strategy. Although AIM and NRI use different measurement techniques from FIA, the sample designs allow for analyses that cross administrative boundaries, provided that appropriate analytical methods are implemented (Patterson et al. 2014). Regional and finer scale monitoring efforts are also implemented through BLM AIM, the National Park Service Inventory and Monitoring Program, National Inventory and Monitoring Initiative (I&M) managed by the National Wildlife Refuge System, and other efforts. These types of monitoring efforts are the recommended means of understanding status and trends of GRSG habitat (e.g., Stiver et al. 2015; USDOI 2014).

Monitoring to Evaluate Management Objectives

To evaluate whether management objectives are being met, measurements can be conducted at local, mid-, and broad scales. The types of monitoring typically used to monitor management objectives, **implementation**, **effectiveness**, and **validation**, are described next.

Implementation Monitoring

Implementation monitoring determines whether planned management decisions, actions, and treatments have been implemented, and whether standards outlined within planning documents were followed or modified. The BLM and Forest Service report on the actions implemented that are described in their LUPs and that relate to decisions aimed at conserving, improving, or restoring sagebrush habitats (USDOI 2014). Initially, this type of monitoring is conducted by planning units. However, given some consistencies in management objectives across planning unit boundaries, this level of monitoring can often be scaled up to the mid-scale.

Effectiveness Monitoring

Effectiveness monitoring assesses the condition of a management action's outcome. Success is typically achieved by meeting predetermined treatment objectives that can be measured against baseline or reference conditions determined by status and trends monitoring, or another desired condition or benchmark as stipulated in the treatment objectives (table 2.1). As an example, effectiveness monitoring may be conducted at the project scale when expanding juniper and piñon or nonnative invasive plants are removed to restore GRSG habitat. Monitoring indicators, such as landscape cover of trees, and the appropriate benchmarks can be used to evaluate whether the effort has reduced tree cover below the response threshold (e.g., less than X% cover across Y% of the monitoring area, which varies regionally) (Baruch-Mordo et al. 2013). Pretreatment levels (baseline) of nonnative invasive plants can be compared to posttreatment levels of perennial native grasses and forbs (e.g., Chambers et al. 2014). If radio-marked GRSG are being monitored in the area of the treatment, the subsequent space or habitat use can be monitored and used to evaluate the efficacy of the treatment. The effectiveness of multiple projects or treatments within the mid-scale can help determine the effectiveness of the management objectives contained within a LUP or other guiding management document. Appropriate landscape-level indicators tied to project objectives provide the opportunity to assess the effectiveness of efforts in achieving conservation goals at the broad scale. This type of monitoring also lends itself to evaluating the effectiveness of and potential benefit achieved from mitigation efforts.

Validation Monitoring

Validation monitoring uses an experimental approach to determine whether the observed outcome is due to the management action. This requires treating some areas and leaving some areas untreated to serve as "controls" for the treated areas, as is done in research and management projects like the Sagebrush Treatment Evaluation Project (http://www.sagestep.org/). The untreated areas are compared to the treated areas to determine whether they differ in meeting the stated objectives. For example, after a wildfire in a Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) ecosystem with low to moderate resilience and resistance, restoration efforts might focus on seeding Wyoming big sagebrush and native perennial bunchgrasses in a randomly selected sample of potential treatment sites. After X years of monitoring ("X" is equal to the time stated in the objectives statement), cover of native perennial bunchgrasses and stem density of sagebrush are measured to determine whether they are trending toward the desired management objective. If the treated sites have higher cover of native perennial bunchgrasses and stem density of sagebrush than the untreated sites, then the management treatment was successful. If the cover and stem density are similar between treated sites and untreated (or control) sites, then the outcome may be attributed to natural successional processes. Due to its relatively high costs and complexity, validation monitoring is most likely to occur at the local scale rather than at mid- or broad scales.

A combination of these monitoring approaches can ensure that management objectives are achieved at multiple spatial scales and that the observed outcome is due to the treatment. These different types of monitoring provide important feedbacks for adaptive management and thus provide further support for incorporating monitoring strategies into the planning or development phase of any project or treatment, including budget planning. Archiving data collected through implementation, effectiveness, and validation monitoring in tools, such as the Land Treatment Digital Library for the BLM (Pilliod and Welty 2013) and the Conservation Efforts Database (USDOI FWS 2014), and analyzing the status and trends can allow managers to learn from past treatments and decide on appropriate management actions in the future.

Standardization of Indicators and Protocols

Adoption of a standardized set of indicators and protocols for collecting indicator data will allow a wide range of users (i.e., managers, landowners, interested public, and researchers) to compare data collected in different areas and for different objectives. The NRCS and BLM currently use common protocols for national and regional monitoring of many rangeland vegetation and soil indicators (Herrick et al. 2010, 2017; Toevs et al. 2011). The Forest Service recently released protocols for standardized wildlife habitat monitoring (Rowland and Vojta 2013), which rely primarily on existing, commonly used sampling methods and datasets. The Integrated Rangeland Fire Management Strategy (IRFMS) (USDOI 2015) provides guidance for working out some of the differences among protocols and indicators to reduce conflicts.

Measuring standardized indicators with consistent protocols allows ground-based data to be scaled-up from local to mid-scales through ground-truthing and validation with remotely sensed data. Provided that data are collected using a randomized sampling design with known methods of stratification, level of effort, and other parameters, data collected from each location or landscape can be weighted in a statistically sound manner and combined with similar data in other areas to obtain cross-site or cross-landscape comparisons with spatial relevance and known levels of error (Patterson et al. 2014).

Rule sets for making data collection decisions are necessary to ensure precise measurement among different field crews (Rowland and Vojta 2013). Herrick et al. (2005) illustrate how rule sets are stipulated. BLM's AIM and NRCS's NRI both use rule sets to standardize measurement decisions. No one rule set is perfect, but rule sets provide a means for collecting consistent data among different observers.

Linking Resilience and Resistance Concepts and Monitoring

Monitoring landscape heterogeneity over time can provide a clearer understanding of how sagebrush dominated landscapes are changing in response to natural ecosystem processes, anthropogenic disturbances, and management actions. Relative resilience to disturbance and resistance to invasive annual grasses influence the responses of sagebrush ecosystems to threats such as wildfire, land uses, and development. Information on resilience and resistance can provide an additional data layer in monitoring programs that can be used to help understand the changes in ecosystem status and trends and the effectiveness of management treatments at broad, mid-, and local scales. The relationships among resilience and resistance, as indicated by soil temperature and moisture regimes, the predominant sagebrush ecological types, and the responses of those ecological types to both disturbance and management, can be used to inform monitoring designs, to help develop benchmarks and triggers for changes in management, and to determine appropriate changes in management strategies and treatments (Part 1, section 6).

By stratifying monitoring across resilience and resistance categories, the range of potential responses to management actions can be captured. Even if a monitoring program is already in place, including resilience and resistance as a factor in the analyses may still provide useful information and context on the effects of resilience and resistance given adequate sample sizes in the different categories.

Generalized state-and-transition models developed for the dominant ecological types in both the western and eastern parts of the sagebrush biome and GRSG range, provide information on the alternative states for these types, the effects of ecosystem threats and management actions on these states, and the potential restoration pathways (Part 1, Appendices 5 and 6). Examples of how to apply resilience and resistance concepts are provided for areas with different ecological types and threats (Part 1, section 9.2).

Using the Science Framework Approach to Inform Monitoring

The Science Framework, Part 1 gives an approach for prioritizing areas for management and determining effective management strategies based on: (1) the predominant threats, (2) the likely response of an area to disturbance or stress due to threats or management actions (i.e., resilience to disturbance and resistance to invasive annual grasses), and (3) the capacity of an area to support target species or resources.

The geospatial data layers and analyses used in the approach are described in Part 1, sections 8.1 and 8.2, and can be used to help design monitoring programs and interpret monitoring results. Analyses are generally conducted at the mid-scale because of similarities in ecoregional climate, soil properties, resilience to disturbance, and resistance to invasive annual grasses. Key data layers include resilience and resistance as indicated by soil temperature and moisture regimes, GRSG breeding habitat probabilities, habitats of other sagebrush dependent species, and the primary threats for the ecoregions or Management Zones. At the mid- to local scale higher resolution geospatial data that are specific to the assessment area (i.e., the best available data) are used in the analyses. Interpretations of these analyses for monitoring programs, based on the Science Framework approach for GRSG (tables 1.3, 1.4), follow a similar approach and can be used for other species at risk as well as priority resources.

Monitoring areas of high GRSG breeding habitat probability (table 1.3: cells 1C, 2C, 3C) provides information on whether these areas are retaining their composition, structure, and function as GRSG habitat. Protective management is used to retain resilience and resistance in these areas. Monitoring for status and trends and using the Early Detection and Rapid Response approach (EDRR) (USDOI 2016) for nonnative invasive plants can help ensure that invasive plants do not increase and thereby degrade these high value sites. Monitoring areas of low resilience and resistance with high GRSG breeding habitat probabilities is especially important because these areas are at high risk of habitat loss from wildfire and potential for conversion to invasive annual grasses (table 1.3: cell 3C). Regardless of an area's resilience and resistance, implementation and effectiveness monitoring are used to assess treatment outcomes and determine whether follow-up management is needed.

Areas with moderate breeding habitat probabilities are a focus for habitat improvements (table 1.3: cells 1B, 2B, 3B). Treated areas within GRSG habitat are often moderate to high priority for monitoring because habitat improvements resulting from treatments could translate into increased use or improved demographic indices (e.g., population trends, survival), or both, for GRSG. Treated areas typically undergo EDRR, implementation, and effectiveness monitoring to ensure that the treatments were implemented as planned, objectives of the management action(s) are met, and an understanding of the effectiveness of the outcome is gained (Mulder et al. 1999; Noss and Cooperrider 1994).

Monitoring areas with low GRSG breeding habitat probabilities and low resistance and resilience can provide information on continued changes in composition, structure, and function, but is generally lower priority unless other at-risk species or management concerns are identified in these areas (table 1.3: cells 1C, 2C, 3C). Areas of low resilience and resistance and with low breeding habitat probabilities that are currently dominated by invasive annual grasses may be given the lowest priority for monitoring (table 1.3: cell 3A). These areas of invasive annual grasses have gaps in function and structure, which can hinder management efforts toward reference conditions. This reduces the number of adaptive management options.

Monitoring Change in Landscape Status and Trend

Landscape monitoring is an important aspect of land management that provides a way to examine the big picture—it gives information on ecosystem processes, habitat characteristics, and species distributions and movements that operate beyond the scope of management units and land ownership boundaries. This type of monitoring can also provide information on the landscape characteristics of areas with different resilience and resistance and the response of these areas to ecosystem threats and management actions. There are several types of indicators (e.g., indicators developed to map broad spatial patterns for different vegetation types) that can be used to monitor landscapes and evaluate: (1) change in environmental conditions and ecosystem structure, process, and function; (2) cumulative effects of management activities; and (3) crossing of thresholds over broad areas. These indicators can measure physical characteristics on the ground and connect them to ecological processes. They may also be used as surrogates for environmental conditions that cannot be measured directly. Typically, these types of indicators are calculated using spatial data within a specified assessment area (e.g., ecoregion, Management Zone, jurisdictional boundary). The resulting measurements from monitoring these indicators may differ based on the size of the assessment (broad, mid-, and local). Thus, it is important to measure the appropriate indicators at the appropriate resolution and scale to provide comprehensive, integrated monitoring for the scale of interest.

Landscape Indicators

There are certain indicators useful for monitoring and quantifying landscape heterogeneity and change at multiple scales. Examples of indicators that can be monitored and quantified across an assessment area to identify natural and human-caused change over time are: percent cover of the vegetation types occurring across the assessment area, the average cover of all vegetation or habitat patch size, patch size coefficient of variation, the average and range of distance to neighboring patches, vegetation or habitat patch richness, and patch edge contrast or density (Cushman et al. 2008, 2013a,b; Goldstein et al. 2013). These indicators measure various aspects of landscape structure, but when analyzed together can offer a comprehensive evaluation of change in landscape pattern, land cover class conversion, and fragmentation across the assessment area. For example, an aggregate of local-scale monitoring data and remote sensing data (e.g., National Gap Analysis [GAP], Landscape Fire and Resource Management Planning Tools [LANDFIRE], National Land Cover Database [NLCD], Geospatial Multi-Agency Coordination [GeoMAC] Wildland Fire Support Tools) can be examined to quantify sagebrush landscape pattern, heterogeneity, and change over time independently or relative to other landscape class mean patch sizes. These indicators, when evaluated within or across land cover classes, quantified over specific time intervals, provide a measure of how sagebrush patches have changed (expanded or contracted) in response to natural ecosystem processes, anthropogenic disturbances, and management actions over time.

Depending on the management question, distance to neighboring vegetation patches may increase or decrease over time. This indicator combined with other landscape indicators (e.g., change in average sagebrush patch size) will help provide information on whether the assessment area is meeting management objectives and benchmarks and avoiding triggers. For instance, an increase in the average nearest neighboring patch distance along with a decrease in the average sagebrush patch size over time typically indicates an increase in fragmentation of sagebrush across the assessment area. In contrast, a decrease in distance to neighboring sagebrush patches combined with an increase in average sagebrush patch size may indicate successful restoration and a decrease in fragmentation across the assessment area. The landscape indicators monitored should be identified carefully and should address the management objectives. The use of consistent landscape indicators across jurisdictional boundaries will improve our understanding of overall landscape change at the biome scale as well as provide the information needed by land management agencies to understand how management practices are effective in meeting management goals.

Landscape Monitoring of Habitats

Habitats are spatially structured, forming patterns at multiple scales. These patterns may influence wildlife behavior and use of space and influence population dynamics and community structure (Johnson et al. 1992). For all species, habitat must have sufficient size and proximity of resource patches to: (1) support reproduction, (2) facilitate dispersal, and (3) maintain metapopulation structure (if that is a characteristic of the species) (Cushman et al. 2013a). To monitor landscape-level changes within the sagebrush ecosystem with a focus on wildlife-specific species indicator data, landscape indicators can be used to quantify how habitat changes over time in response to management decisions and natural ecosystem processes. For example, much information is available on landscape indicators for GRSG, such as habitat intactness (Aldridge et al. 2008; Wisdom et al. 2011); breeding habitat probability (Doherty et al. 2016); landscape genetics (Cushman et al. 2013b; Row et al. 2015); habitat patch size, habitat connectivity, and networks; ecological minimums (thresholds) (Crist et al. 2015; Knick and Hanser 2011; Meinke et al. 2009); edge effects (Coates et al. 2014; Howe et al. 2014); and distance to water (Donnelly et al. 2016). Goldstein et al. (2013) provide an example monitoring plan for GRSG habitat monitoring at multiple scales, with sagebrush patch size, sagebrush canopy cover, and habitat connectivity selected as landscape-level habitat monitoring indicators. Spatial data from remote sensing efforts (e.g., NLCD, LANDFIRE, GeoMAC, GAP), along with monitoring data collected on the ground, can be used to analyze these indicators and quantify the amount of habitat area and connectivity lost or gained due to habitat conversion or natural succession (Goldstein et al. 2013).

Disturbance, Reclamation, and Restoration

Tracking and measuring the influence of persistent ecosystem and anthropogenic threats, separately and in combination at broad scales, can provide useful information on whether or not management objectives for sagebrush ecosystems are met. Overlaying information on resilience and resistance can aid in the interpretation of management outcomes. For example, the ability to achieve successful reclamation and subsequent restoration will differ for ecosystems with different resilience and resistance. Monitoring can help inform where to prioritize management and conservation actions, what to expect under certain measured conditions, and what the best indicators of overall management effectiveness are.

Classifying habitat restoration, vegetation treatments for fuel management, and other types of vegetation treatments separately from land cover classifications used in vegetation mapping (e.g., Homer et al. 2015) can allow these treatments to be monitored and evaluated over time at the landscape scale. This can provide the basis for determining whether an area has recovered, whether benchmarks (or triggers) at the landscape level (ecosystem or species-specific) have been exceeded, and whether management actions are needed. For example, triggers associated with habitat thresholds, such as mean distance to, and density of, oil and gas wells (Doherty et al. 2008; Holloran et al. 2005; Lyon and Anderson 2003; Naugle et al. 2011; Walker et al. 2007), have guided science-based land use and management decisions in recently amended BLM and Forest Service LUPs, and some State plans.

Recent work has shown variation in threshold responses to disturbance, such as canopy cover and the human disturbance index, across the different sage-grouse Management Zones, indicating that a one-size-fits-all approach to setting thresholds is seldom appropriate (Doherty et al. 2016). These authors (Doherty et al. 2016, p. 23) stated that "when potential for conflict is high and thresholds are extrapolated into novel landscapes, clearly defined adaptive management goals and monitoring systems would be prudent." This recommendation highlights the tension between using research conducted in small parts of the sagebrush biome and the extrapolation of those results to new areas to justify the claim of treatment effectiveness in other parts of the area. This emphasizes the need to have monitoring systems in place to understand whether the results are applicable in the ecological context of the system in which the treatments are occurring. Information on resilience and resistance has provided the means for developing appropriate management strategies based on the likely response of ecosystems to both disturbance and management actions. Monitoring ecosystem threats and land use and development threats at the same time will aid in determining the effectiveness of on-the-ground conservation actions, understanding the reasons for changes in the landscape, and designing more effective management strategies.

Linking Efforts to Identify GRSG Population and Habitat Thresholds

Certain population response thresholds have been defined for managing GRSG habitat within State and Federal plans and in the scientific literature (Doherty et al. 2016; Knick et al 2013; Manier et al. 2014). Disturbance data collected at the project scale can be aggregated within habitat management designations across a landscape. These data can be used to determine whether adaptive management triggers associated with thresholds (such as disturbance caps and limitations of disturbance density specified in the Federal LUPs, and some State plans) have been met or exceeded that prompt actions or decisions by the appropriate agencies responsible for land management. By building on the GRSG Monitoring Framework (IGSDMS 2014) and the Sage-Grouse Habitat Assessment Framework (Stiver et al. 2015), adaptive management triggers tied to population levels or GRSG habitat, or both, have been developed for each LUP. For GRSG, individual and population responses to road densities, oil and gas densities, and other factors (Knick and Hanser 2011; Knick et al. 2013; Manier et al. 2014) are available and can be assessed to gain a better understanding of habitat and GRSG population conditions relative to these specified thresholds as well as offer a more of the landscape-level perspective.

Establishing a robust monitoring program or strategy that informs clearly defined management objectives is paramount to a meaningful adaptive management process. Monitoring the outcomes of management actions allows land managers and resource specialists to gain the necessary knowledge and information to locate treatments and projects in areas where they are more likely to be effective. Monitoring outcomes is essential for understanding the effectiveness of management actions in sustaining sagebrush ecosystems over time. In the aggregate, these efforts can improve resilience and resistance across the sagebrush biome and increase the return on conservation investments.

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