

Chapter R. Restoration

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Executive Summary

Vast expanses of the sagebrush (*Artemisia* spp.) ecosystem have been degraded by disturbances, including plant invasions, wildfire, and improper grazing, necessitating restoration efforts to maintain wildlife habitats, reduce future wildfire risks, and recover ecosystem services. Restoration treatments, such as conifer removal, seeding, and herbicide applications, have been extensively applied. However, treatment success has been mixed, and many other acres are degraded or are at risk but have not been treated. A primary objective of restoration in sagebrush communities is to maintain or increase desirable perennials, such as sagebrush and forbs, that are key to wildlife, along with perennial grasses that provide resistance to invasion and resilience to future disturbance. This objective is challenging because of variable environmental conditions, including frequent drought, exotic plant invasions, recurrent wildfire, and inadequate postfire grazing management. Additional challenges include the large extent of areas that need treatments, lack of basic site information, and logistical challenges to treatment application. Moreover, restoration efforts have typically been short-term, single applications. Restoration planning now emphasizes prioritizing areas that need intervention and are likely to have a positive response. Treatment success is likely to improve in the future given prioritization of sites, adaptive management approaches that incorporate learning, and the involvement of multiple stakeholders that allows for repeated interventions over longer time periods. While current research is improving the understanding of factors affecting restoration success and restoration techniques, there are clear opportunities to better incorporate current knowledge into restoration practice.

Introduction

Restoration of habitats that have been altered by anthropogenic and natural disturbance and the introduction of invasive plant species is a significant concern in sagebrush (*Artemisia* spp.) ecosystems. Restoration, broadly defined here to include rehabilitation and reclamation, is most feasible when objectives are clear, residual ecosystem components are present, and environmental conditions are favorable. However, severe loss of biotic diversity and ecosystem functioning creates substantial obstacles for recovery to original or even desirable alternative, stable vegetation states. This is the case for sagebrush habitats, especially those in the warmest and driest regions of the biome. Nearly half of the estimated 651,316 square kilometers (km²; 251,473 square miles [mi²]) of sagebrush habitats in the western United States are now in a disturbed and degraded condition that is undesirable for wildlife, livestock, and other land uses (Miller and others, 2011). Impacts from surface disturbing activities, such as energy development and mining, are often compounded by wildfire, nonnative plant invasions—particularly annual grasses that fuel increased wildfire, and improper grazing in these habitats.

Following European settlement, historical land treatments in the sagebrush biome often focused on shifting vegetation communities from shrub to grass dominance to increase forage production for domestic livestock (Knick, 2011). Prescribed fire, mechanical, and herbicide treatments were used to remove sagebrush and favor seeded bunchgrasses. These bunchgrasses were typically introduced Eurasian species, such as crested wheatgrass (*Agropyron cristatum*) and Siberian wheatgrass (*A. fragile*). Sagebrush removal continued into the late-1970s at low elevations and into the mid-2000s at high elevations until wildfire and wildlife (for example, greater sage-grouse [*Centrocercus urophasianus*]) concerns increased. Since then, managers and researchers have been developing new treatments and seed sources to improve the ecological condition of sagebrush communities with an emphasis on the conservation of native wildlife species. However, documenting the types and locations of treatments and their outcomes has only begun to be standardized and tractable (Pilliod and others, 2017b).

The complex suite of threats to sagebrush communities has led to an increase in the size, number, and type of restoration treatments used by land management agencies, as well as an increased use of sagebrush and other native

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seed in those treatments (fig. R1; Pilliod and others, 2017b; Copeland and others, 2018). To meet restoration challenges, the management and science communities have developed tools for prioritizing resources across sagebrush ecosystems and strived to increase the efficiency and effectiveness of treatments.

Increasing restoration success requires identifying the necessary knowledge, strategies, and tools for implementation. While seemingly straightforward, diverse management objectives, scale issues, and a range of conditions and habitats increase the challenges associated with developing successful strategies for sagebrush habitat restoration. This chapter addresses restoration planning at several spatial scales and provides an overview of approaches and tools for increasing the likelihood of success. Appendix R1 provides additional sources of information on restoration in general and details specific to the sagebrush biome.

While the term “restoration” is often used broadly in sagebrush and other ecosystems, some agencies and practitioners recognize specific meanings for rehabilitation or reclamation. Restoration means bringing an ecosystem back to an original state of structure (for example, native species) and function (for example, nutrient cycling, erosion prevention, and primary production; Bradshaw, 2002). In contrast, rehabilitation aims to reinstate part of the original structure with a focus on recovering ecosystem functions, and reclamation focuses on restoring ecosystem function often with little regard to structure.

Postfire rehabilitation in sagebrush ecosystems has been guided and implemented by the U.S. Department of the Interior, Bureau of Land Management’s (BLM) Emergency Stabilization and Rehabilitation (ESR; (Bureau of Land Management, 2007); see “BLM Emergency Stabilization and Rehabilitation (ESR) Program” sidebar) and the U.S. Department of Agriculture (USDA) Forest Service’s Burned Area Emergency Response (BAER; National Interagency Fire Center, 2020) programs on public lands. The planning and evaluation of BLM ESR and Forest Service BAER treatments typically involve interagency and stakeholder partners. Rehabilitation and restoration actions are also planned and implemented by private landholders, municipalities,

counties, State-level agencies (for example, Utah’s Watershed Restoration Initiative [WRI; <https://wri.utah.gov/wri/>]) and nongovernmental organizations (NGOs). In addition, the USDA Natural Resources Conservation Service (NRCS) frequently provides consultation and support to these groups as well as cost-share funds for affected private landowners. In contrast, reclamation is often regulated by governmental agencies but implemented by single private entities or their contractors.

In general, restoration will be effective, efficient, and engaging if (1) efforts are referenced to native ecosystems and consider their response to broader environmental changes (chap. L, this volume); (2) key ecosystem attributes are identified prior to developing goals and objectives; (3) natural recovery is augmented with assisted recovery when ecosystems are impaired; (4) actions aim towards full recovery; (5) practices are based on all pertinent knowledge, which can be enhanced with science and technology transfer and outreach to restorationists; and (6) efforts genuinely engage stakeholders early and actively in the restoration process (McDonald and others, 2016).

Restoration for Wildlife Conservation

The goal for many restoration projects is improvement of wildlife habitats. Projects aimed at restoring wildlife habitats should include (1) information on species distributions and population abundances; (2) information about baseline habitat conditions; (3) an understanding of the most important habitat features required for species colonization or persistence; (4) specific objectives for focal species and benchmarks that define restoration success; (5) a monitoring plan; and (6) comparisons with nearby unrestored sites, either representing baseline or target conditions (Borgmann and Conway, 2015). Additionally, monitoring wildlife response is crucial. The suitability of restored habitats for wildlife can be influenced by conditions at multiple spatial and temporal scales, as is addressed in more detail in the “Sagebrush Restoration” section of this chapter. Consideration of landscape context, size of restored areas, and time since restoration can assist in

BLM Emergency Stabilization and Rehabilitation (ESR) Program

The ESR program’s objectives are to (1) stabilize fire-damaged sites in order to protect life and property and prevent further degradation of burned areas, and (2) rehabilitate lands that have a low probability of recovering on their own (Bureau of Land Management, 2007). Emergency stabilization may be achieved by repairing structures crucial to public health and safety, minimizing erosion, applying treatments to critical habitat for species of concern, protecting cultural resources, and mitigating invasive plants. Burned area rehabilitation focuses on longer term treatments, such as noxious weed removal, ecosystem recovery, tree planting, and repairing damage to less critical facilities. Proposals must be submitted to the ESR program within 21 days after fire containment and address a broad range of topics including treatment details and cost estimates. In years when many fires occur, budgets may limit the number of treatments that can be implemented in their entirety.

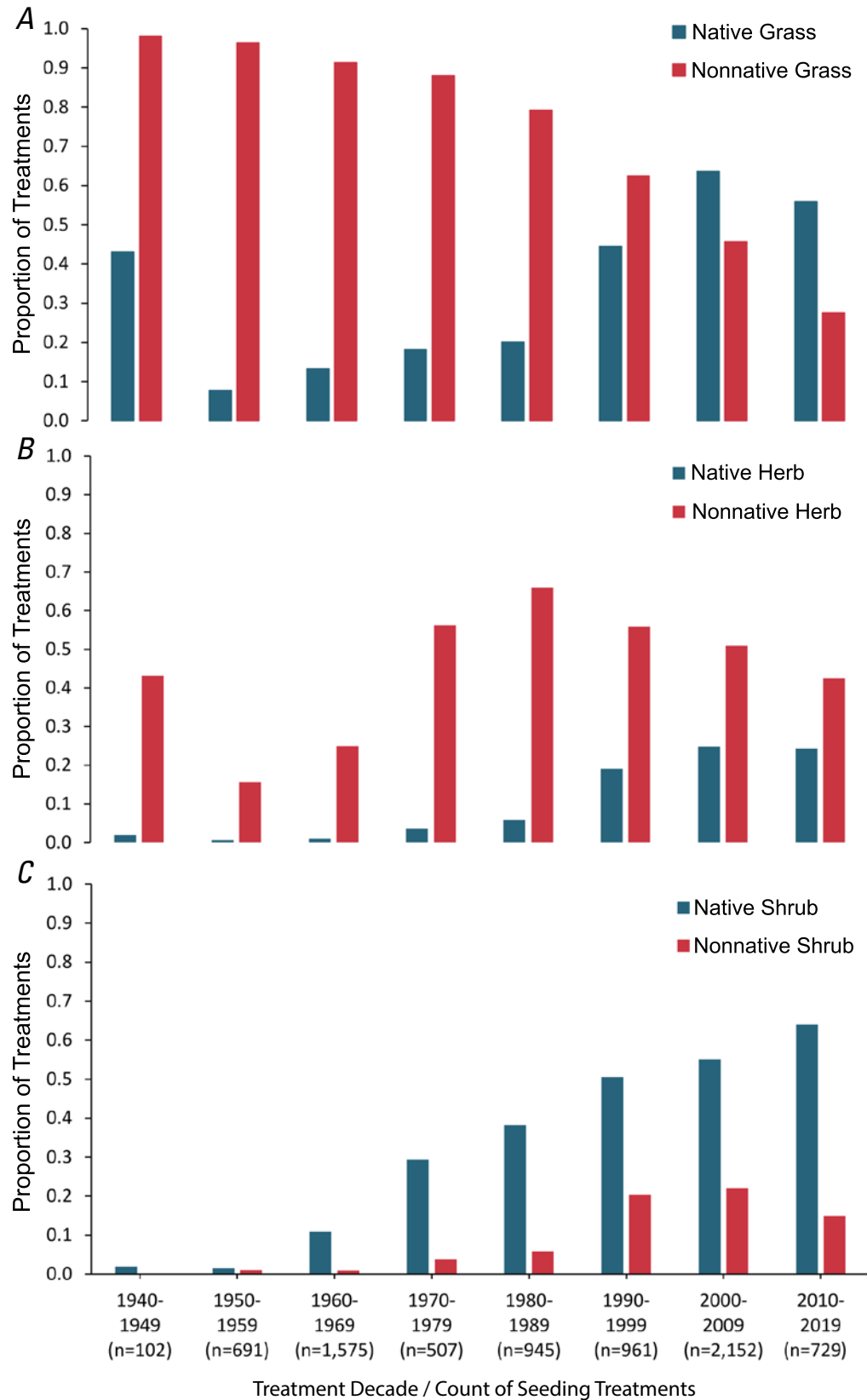


Figure R1. Proportion of seeding treatments on U.S. Department of the Interior, Bureau of Land Management lands with seed mixes that *A*, have at least one native or nonnative grass, *B*, native or nonnative forb, and *C*, native or nonnative shrub (Pilliod and Welty, 2013). This is not a comprehensive sample of all treatments in the area for the entire time period, as not all seeding treatments contain explicit seed lists, and data entry is not yet complete for seedings from 2015 to 2019. n, number.

understanding and predicting wildlife responses to restoration (Ortega-Álvarez and Lindig-Cisneros, 2012). A prioritization process can guide site selection that will result in the biggest gains for focal species (see “Landscape-Level Characterization and Prioritization and Project-Level Prioritization and Planning” sections of this chapter; Pyke, 2011; Reinhardt and others, 2017; Ricca and others, 2018).

A central consideration regarding the value of restoration for wildlife is how best to make habitats functional for a suite of animal species. The umbrella species concept has been invoked for multispecies management, particularly when implementing treatments focused on greater sage-grouse (Rowland and others, 2006; Hanser and Knick, 2011; Carlisle and others, 2018b; chap. Q, this volume). There are species that will likely benefit from this approach solely because some of their needs will be met indirectly by protecting and restoring large areas and providing resources for umbrella species. However, because habitats are inherently species-specific, restoration aimed at providing habitat for one species may not necessarily result in suitable habitat for another species. For example, conifer removal can positively affect

sagebrush-dependent wildlife species (see review of studies by Bombaci and Pejchar, 2016; Holmes and others, 2017; Knick and others, 2017; Peterson and others, 2017; chap. L, this volume) but negatively affect pinyon jays (*Gymnorhinus cyanocephalus*; Johnson and others, 2018). Restoration implemented under the umbrella species concept is mostly applicable at broad scales (Carlisle and others, 2018b), but, at local scales, restoration efforts may need to target particular species or guilds, and species-specific habitat requirements should be considered.

Criteria for successful restoration of wildlife habitats, including measurable changes in habitat structure, proximity of suitable habitat to treatment area, availability of colonists, provisioning of resources for focal species, and the importance of increasing animal productivity and avoiding population sinks or ecological traps, are outlined in Hale and Swearer (2017; fig. R2). Information on wildlife responses to sagebrush restoration are also detailed in Dahlgren and others (2006), Johnson and Chalfoun (2013), Petersen and others (2016), Severson and others (2017a, b), and Smith and Beck (2018).

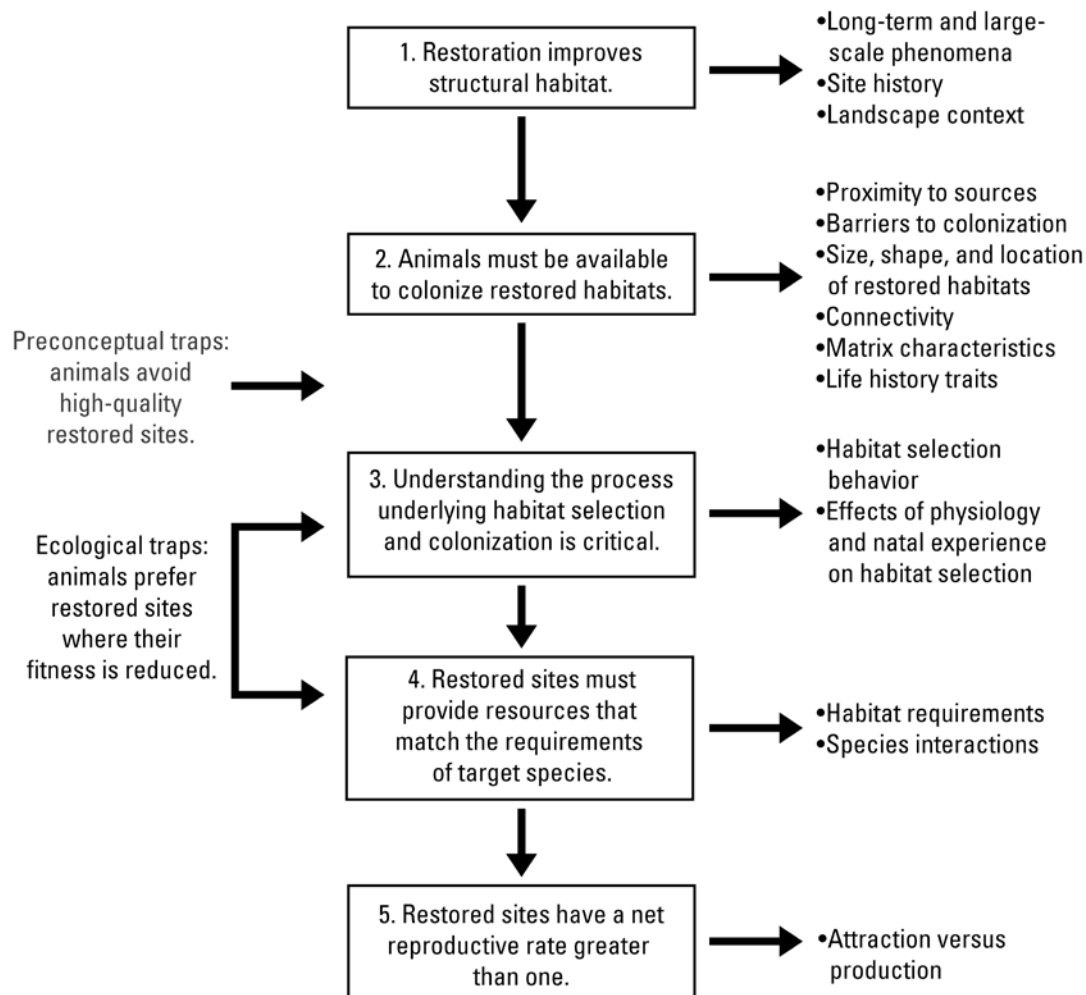


Figure R2. Five critical criteria for ensuring habitat restoration is successful (modified from Hale and Swearer, 2017).

Sagebrush Restoration

The vast extent of sagebrush communities and the limited resources available for restoring degraded sagebrush habitats have led to development of processes and information to help evaluate and prioritize areas for restoration (fig. R3). Prioritizing restoration activities across large spatial extents helps ensure that treatments are placed within the context of the surrounding landscape and maximize their effectiveness. After the landscape is prioritized, individual projects and treatments are prioritized to achieve project objectives and overall landscape objectives. Evaluation of outcomes and implementation of adaptive management throughout this process helps improve the efficiency and effectiveness of restoration actions. The following sections discuss each step of this process, give examples of ongoing activities, and provide resources to help with implementation.

Landscape-Level Characterization and Prioritization

At the landscape scale, fragmentation of large, continuous habitat patches into smaller, discrete units is a significant problem, and restoration investments are critical to reconnect habitat patches or maintain continuous landscapes. Landscape units often differ in merit for investment relative to their wildlife values, need for restoration actions to advance

recovery, and recovery potential. Moreover, a complexity of multiple stressors, jurisdictions, land uses, stakeholders, and economic development investments usually exists. Thus, restoration at the landscape scale (ecoregion to planning unit) requires collaboration with partners across jurisdictional boundaries and addresses: (1) extent and connectivity of sagebrush patches or spatial resilience, (2) resource values such as habitat for wildlife or threatened and endangered species, (3) relative resilience to disturbance and resistance to invasive plants, and (4) disturbances or land uses that may impact restoration outcomes.

Tools and knowledge are increasingly available to help link landscape characteristics, such as vulnerability to invasive plants and resilience to disturbance, to both landscape recovery potential and importance for wildlife populations (Knick and others, 2013; Chambers and others, 2014a, 2017a, b; Doherty and others, 2016; Ricca and others, 2018; Crist and others, 2019). Habitat fragmentation impacts the function of the sagebrush and other ecosystems and ability to recover following disturbance (Holl and Aide, 2011; Knick and others, 2013). Functional connectivity is the ability of a landscape to support movement (that is, dispersal and migration) and is necessary to support local populations (Knick and Hanser, 2011; Crist and others, 2017). Examples include the need for a landscape to contain and support movement of sage-grouse within and between seasonal habitats and the ability of mule deer (*Odocoileus hemionus*) to migrate from summer to winter range. Maps are particularly useful to show the spatial variability in (1) the locations and connectivity of high-value resources and habitats and (2) the resilience and resistance for

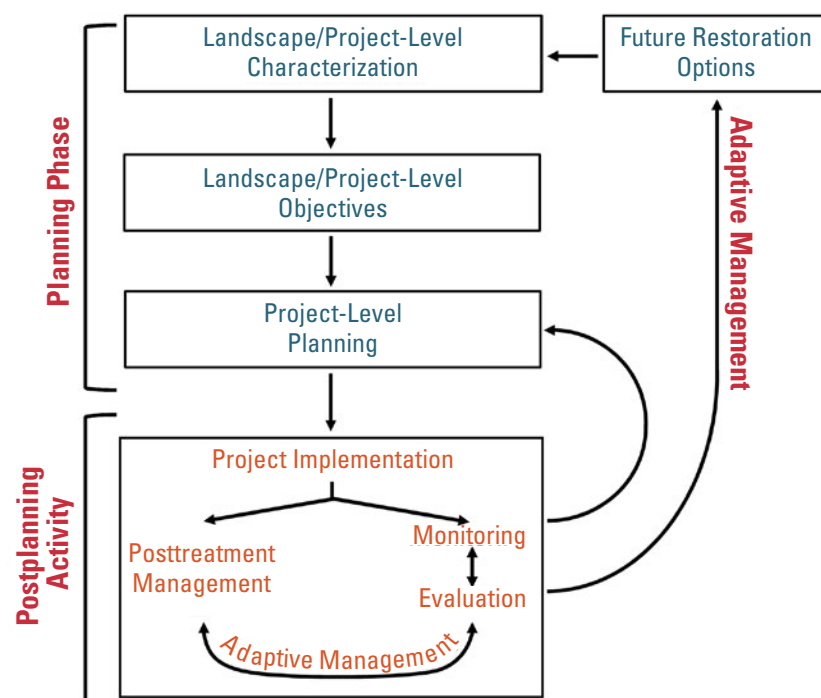


Figure R3. Workflow of an idealized restoration process that includes setting landscape and project objectives, determining monitoring protocols and design, selecting project-level treatments, and then ensuring regulations are met.

prioritization of locations to improve habitat patches, reduce threats to habitat patches, and reduce fragmentation (for example, Chambers and others, 2017a, b; Ricca and others, 2018). Assessing likelihood of successful habitat improvement and prioritization of the investments may lead to increased connectivity and overall functioning of the landscape.

Landscape-scale restoration implementation is often a collaborative or multiproject effort. Only managers of large land units at the watershed or larger scale, such as the BLM or Forest Service, are able to develop large projects solely on lands under their jurisdiction, and even then it may take multiple years to complete provided that agency resources are available. When land ownerships vary, timing and coordination requirements can be difficult to achieve.

Project-Level Prioritization and Planning

At local scales, wildlife habitat suitability is affected by both structural and floristic characteristics of vegetation. Thus, a focus on restoring appropriate vegetation structure and species composition is critical for creating functional wildlife habitats. Structural characteristics of vegetation are important in providing thermal and escape cover (McAdoo and others, 2004; Coates and others, 2017b). Key structural attributes in sagebrush include cover and height of trees, shrubs, forbs, and grasses; plant density; bare ground; and litter depth. Floristic characteristics include species composition, richness,

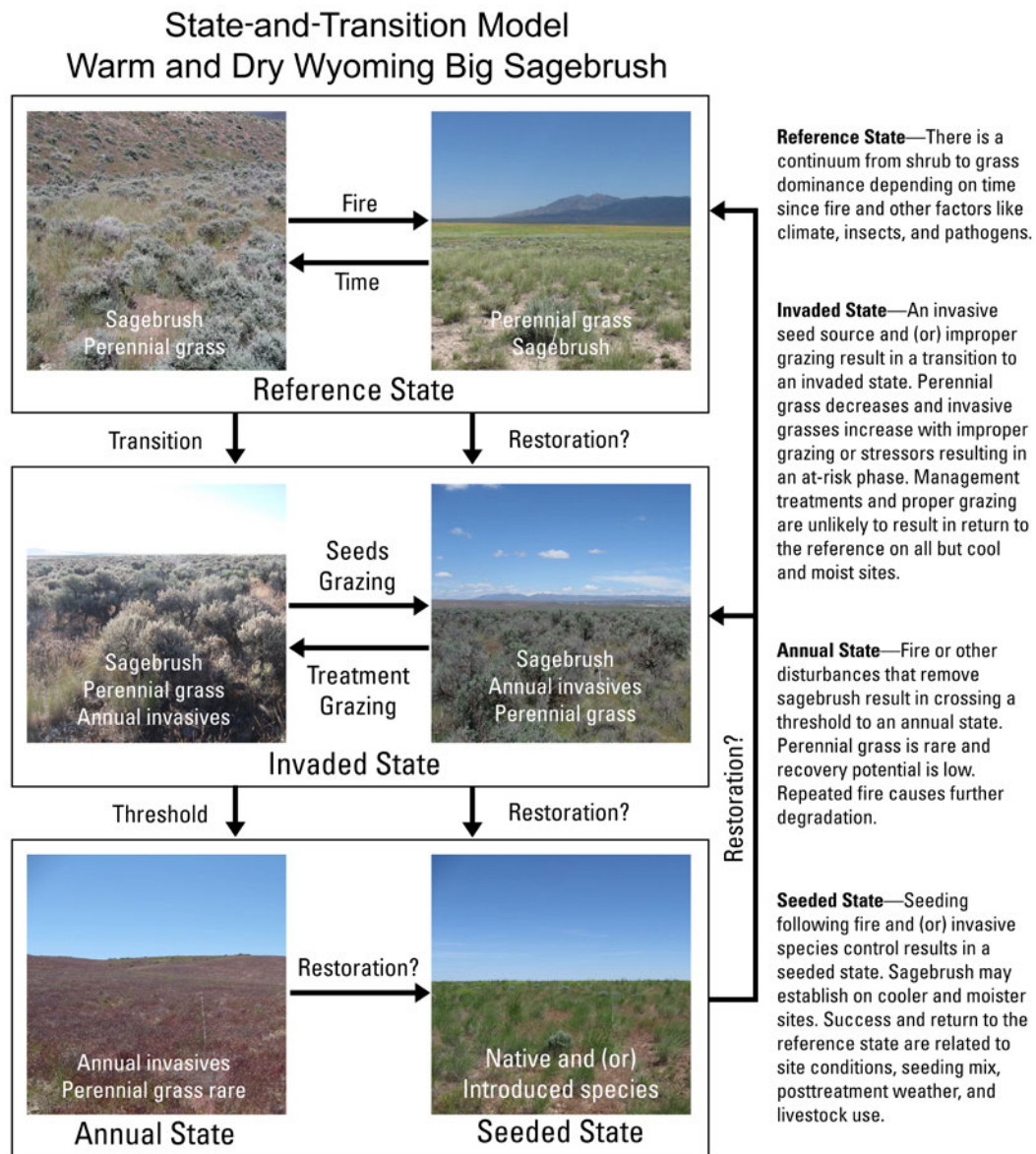


Figure R4. Generalized state-and-transition model for a Wyoming big sagebrush (*Artemisia tridentata wyomingensis*) community. Note that the reference condition or state is dynamic and depends on many temporal factors (modified from Pyke and others, 2015b).

Resilience and Resistance

Sagebrush landscapes differ significantly in terms of their relative resilience to disturbance and resistance to invasive annual grasses (Chambers and others, 2014a, c, 2019b, c). Information on how resilience and resistance differ across landscapes can assist managers in evaluating the recovery potential of an area and thus the magnitude of the investment needed for successful restoration (Chambers and others, 2017a). Areas with high resistance to invasive annual grasses and native plant persistence often have the potential to recover without intervention following fire or other disturbance. Seeding or transplanting of native species following surface disturbance usually results in successful establishment, especially at cooler, moister sites at higher elevations. Areas with moderate resilience and resistance also typically recover unassisted following wildfire, especially if characterized by cooler and moister conditions. Seeding or transplanting success often depends on environmental conditions, and more than one intervention may be required for restoration success in warmer and drier areas. Areas with low resilience and resistance to invasive annual grasses often have low potential for recovery after fire or other disturbance without seeding, especially if the perennial grasses and forbs have been depleted. Seeding or transplanting success depends on site characteristics, the relative abundance of invasive plants, and posttreatment quantity and timing of precipitation. Thus, more than one intervention may be required in these areas.

Soil temperature and moisture strongly influence plant species composition and abundance on a site and are closely related to sagebrush ecosystem resilience to disturbance and resistance to invasive annual grasses (Chambers and others, 2007, 2014a, c). Consequently, soil temperature and moisture regimes that are characterized in soil taxonomic designations (that is, mapping unit) can be used as indications of resilience and resistance at landscape scales in sagebrush ecosystems. Areas with cool to cold and wet to moist soil conditions are typically characterized by high resilience and resistance (see Chambers and others, 2014a; fig. R5). They tend to exhibit less change, recover more rapidly, and are less susceptible to invasion by nonnative invasive annual grasses after stressors and disturbances. In contrast, areas with warm and moist to dry conditions are typically characterized by low resilience and resistance. They tend to exhibit slower ecosystem recovery after stressors and disturbances and may be at greater risk of conversion to alternative states (for example, conversion of sagebrush-perennial grass systems to invasive annual grass systems). In conjunction with information on other landscape threats, such as wildfire risk, this information can be used to help prioritize management actions.

The relative resilience and resistance of a site are closely related to sagebrush ecological types and soil temperature and moisture regimes. Soil moisture availability and plant productivity increase over elevation gradients resulting in greater recovery potential and more competition with cheatgrass. Disturbances that increase soil water and nutrients and reduce competition can decrease both resilience and resistance. Understanding these relationships and mapping them across the landscape (fig. R5) is useful for prioritizing areas for restoration and determining the most effective management strategies (Chambers and others, 2017a).

or diversity within the plant community. Restoring species composition will influence trophic and pollinator relationships to help create functional wildlife habitats and likely result in cascading responses throughout the sagebrush community (Dumroese and others, 2016). Specific sagebrush communities provide food sources for herbivores, especially during fall and winter when herbaceous vegetation is dormant (Campos and others, 2011; Beck and others, 2012; Frye and others, 2013; see chap. D, this volume; chap. E, this volume). Sagebrush species and subspecies of big sagebrush (*A. tridentata*) differ considerably in their height and palatability to sage-grouse, pygmy rabbits (*Brachylagus idahoensis*), and mule deer. Recognizing these differences in habitats is important for successful restoration. Additionally, during the growing season, grasses become an important source of forage for native ungulates, and forbs are a critical feature of diets for ungulates (Scotter, 1980; Mule Deer Working Group, 2009) and greater sage-grouse.

Existing conditions are key factors for consideration when prioritizing at the site scale. Site conditions can be characterized by physical factors such as climate and microclimate, slope, aspect, soil depth, stoniness, restrictive layers, and vegetation factors including the presence of invasive plant species. All of these have the potential to affect treatment success (for example, Germino and others, 2018; Davidson and others, 2019). The potential resilience to disturbance and resistance to invasion of a site (see “Resilience and Resistance” sidebar) are influenced by factors including soil characteristics, elevation and climate, vegetation composition, and disturbance history. Ecological site descriptions (ESDs) and their associated state-and-transition models (STMs; fig. R4) use these factors to provide site-specific information to help determine potentially effective restoration treatments (see “Ecological Site Descriptions, State-and-Transition Models, Species Distribution Models, and other Geospatial Tools” sidebar). Species distribution models (SDMs) and other geospatial tools are also important data sources.

Project-Level Prioritization

Selection of locations to treat within areas prioritized for restoration is influenced by (1) the contribution of an individual site to landscape-scale goals; (2) site conditions, including the site's influence on the landscape and expected responsiveness of the site to restoration intervention; (3) key resources present at the site that impact planning, such as cultural or wildlife concerns or buildings or other infrastructure; and (4) logistics of treating individual sites. If rare or endangered species are present, a protocol of surveillance/detection followed by protection, including avoidance of collateral impacts from restoration treatments such as herbicides and drill seeding, may need to be included.

Designing project-level restoration treatments to meet landscape-level objectives is critical for success and may require considerable analysis and planning. Sites that increase

the overall function of the landscape, such as increasing the size of habitat patches or improving connectivity among existing patches, should be a high priority for treatment. For example, site suitability is improved for greater sage-grouse when large, contiguous, or more connected sagebrush patches occur on the landscape (Stiver and others, 2015). Project-scale treatments can also improve landscape resistance to nonnative species by removing invasive plant species at the edges of otherwise intact and noninvaded landscapes.

Local resources can also constrain the tools available for implementation, particularly when restoring one part of a site requires the temporary disturbance or removal of another part required for a sensitive wildlife species. For example, treatments to increase forb or deep-rooted perennial grass cover may reduce annual grasses but still compete with sagebrush recovery and subsequently influence site value to greater sage-grouse (Davies and others, 2011; Germino and others, 2018).

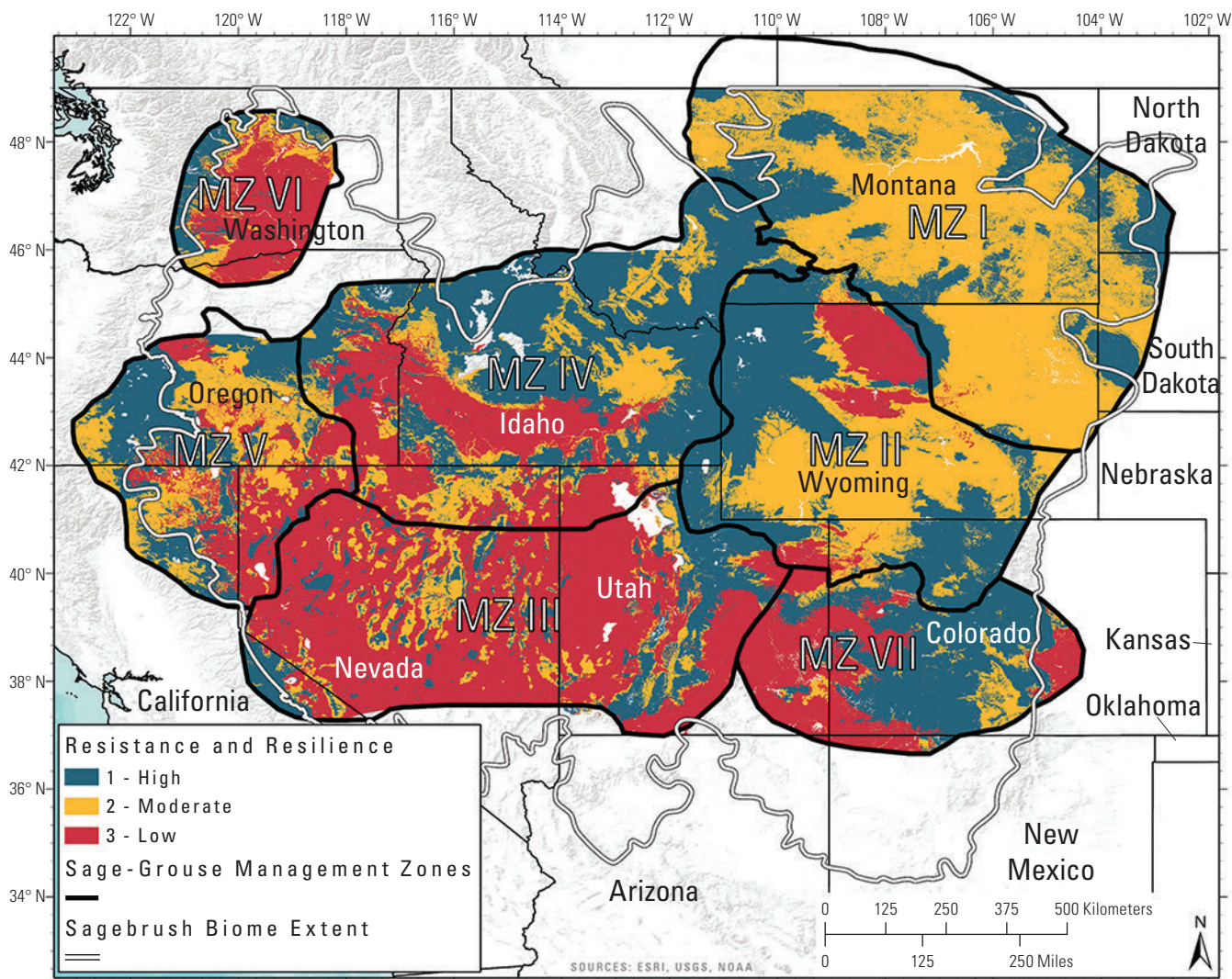


Figure R5. Resistance and resilience classifications in management zones (MZ) for greater sage-grouse (*Centrocercus urophasianus*; Campbell and others, 2016).

Table R1. Resources to help select and prioritize treatments at the project scale.

Topic	Resource
Site-scale planning	U.S. Geological Survey Circular 1426 (Pyke and others, 2017; https://pubs.er.usgs.gov/publication/cir1426) Benson and others, 2011; (https://wdfw.wa.gov/publications/01330) Bureau of Land Management Technical Note 443 (Dunwiddie and Camp, 2013); https://www.blm.gov/documents/national-office/blm-library/technical-note/enhancement-degraded-shrub-steppe-habitats)
Field guide and score sheets to assist selection of mechanical and prescribed fire treatments and postfire treatments	A Field Guide for Selecting the Most Appropriate Treatment in Sagebrush and Piñon-Juniper Ecosystems in the Great Basin (Miller and others, 2014a; https://www.fs.fed.us/rm/pubs/rmrs_gtr322.pdf) A Field Guide for Rapid Assessment of Post-Wildfire Recovery Potential in Sagebrush and Piñon-Juniper Ecosystems in the Great Basin (Miller and others, 2015; https://www.fs.fed.us/rm/pubs/rmrs_gtr338.pdf)
Importance of various structural and floristic components of habitat for sagebrush-dependent species	Birds in a Sagebrush Sea (Paige and Ritter, 1999; https://www.sagegrouseinitiative.com/wp-content/uploads/2013/09/Birdsinasagebrushsea.pdf) Restoration Handbook for Sagebrush Steppe Ecosystems with Emphasis on Greater Sage-Grouse Habitat (Pyke and others, 2015b; https://pubs.er.usgs.gov/publication/cir1416) Bird Habitat Guide: Sagebrush Communities in the Intermountain West (http://abcbirds.org/wp-content/uploads/2015/05/SagebrushGuide.pdf) Guidelines to Manage Sage-grouse Populations and their Habitats (Connelly and others, 2000a; https://www.fws.gov/nevada/nv_species/documents/sage_grouse/connellyetal2000.pdf) Pocket Guide to Sagebrush Birds (Shultz, 2012; https://digitalcommons.usu.edu/sagestep_reports/20/), and McAadoo and others (2004) and Shaw and others (2005)

Logistical constraints also affect project-level prioritization. Ability to complete all regulatory documentation, access constraints, availability of planting materials, or current partnerships may all influence prioritization and the feasibility of project implementation. Spatial factors such as whether restoration equipment can access and operate given the topography of sites or temporal factors such as suitable weather windows relative to plant community recovery are critically important logistical issues. Incorporating the full set of available information into the prioritization process may improve overall project success (table R1).

Project-Scale Restoration Objectives

For each project, it is essential to establish site-scale management and monitoring objectives (Pyke and others, 2017). Management objectives set targets for attaining an ecological condition while monitoring objectives measure the extant ecological condition. Objectives can be improved by ensuring they are “SMART”—Specific, measurable, achievable/accountable, realistic, and time-bound (Pyke and others, 2015a). Specificity refers to the target species or desired ecological conditions, geographical area, attributes or indicators measured, action or directionality of change in the attribute or indicator, level or values of the indicator that will specify success, and timeframe over which the outcome is expected. Additional detail is provided in the Adaptive Management and Monitoring section of Science framework for conservation and restoration of the sagebrush biome, “Linking the Department of the Interior’s Integrated

Rangeland Fire Management Strategy to Long-Term Strategic Conservation Actions—Part 2—Management Applications” (Wiechman and others, 2019).

Objectives should have some degree of precision to the expected response and be measurable using quantitative metrics. Although it may be easy to identify variables to measure (for example, perennial grass cover in treatment and control sites), it is often harder to identify threshold values in the objectives. For perennial grasses, only a few studies provide guidance on what level of perennial grasses will provide resistance and resilience, and the guidance is generalized and approximate (for example, Chambers and others, 2014c). Furthermore, the objectives must be achievable and reasonable based on available capacity. The time needed to meet the objective must be stated and realistic (for example, 20-percent perennial grass cover in 5 years).

Implementation Requirements

Most restoration implementation will require some degree of regulatory review and conformance. Specifics of regulatory conformance depend on the actions taken, the agency or group performing restoration, and resources present in and adjacent to the treatment area (table R2). Early coordination with interested parties (for example, Tribes, agencies, adjacent landowners, and other stakeholders) is critical given that timelines, documentation requirements, and other needs vary by regulation, regulatory agency, and project complexity.

Weather and Grazing—Two Factors that May Affect Project Implementation and Outcomes

Weather

High spatial and temporal variability in soil temperature and moisture make restoration implementation and success in sagebrush and other semiarid ecosystems very difficult. Transitions from undesirable to desirable plant communities require successful establishment of the perennials being restored, along with effective treatments to reduce exotic

annuals. Seed germination, plant establishment, and effectiveness of herbicides are all highly sensitive to weather events (Westoby and others, 1989; Call and Roundy, 1991; Hardegree and others, 2011; James and others, 2011, 2013; Svejcar and others, 2014; Brabec and others, 2017). Long-term patterns of soil microclimate vary with soil type and topography and determine underlying ecological resilience and resistance to annual weed dominance (Knutson and others, 2014). Landscape gradients of resilience and resistance are also correlated with soil microclimate factors that affect seedling establishment in any given year (Hardegree and others, 2013).

Ecological Site Descriptions, State-and-Transition Models, Species Distribution Models, and Other Geospatial Tools

Ecological Site Descriptions (ESDs) are part of a land-classification system that describes the potential of a set of climates, topographic, and soil characteristics and natural disturbances to support a dynamic set of plant communities. ESDs are widely available (for example, <https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/ecoscience/desc/>) but incomplete for some areas within the sagebrush ecosystem. State-and-Transition Models (STMs) describe the possible alternative states of sagebrush ecological sites (for example, reference, annual-grass dominated, or seeded perennial-grass dominated; fig. R4; Pyke and others, 2015b; Chambers and others, 2017a, app. 5). State-and-Transition Models (STMs) are a simplified way of characterizing dominant plant composition of sites and how different drivers (for example, fire, grazing, and restoration) may cause shifts in composition and function. They may be useful both at the site/project level and at the landscape-level where STM simulations help project how vegetation changes on an assemblage of sites may impact the broader landscape.

Evaluating existing site conditions relative to a set of reference conditions can help prioritize a list of potential treatments, although choosing reference sites is not trivial and requires many site-matching considerations (Herrick and others, 2019). The level of departure from reference or desired condition can be visualized using STMs, and site conditions can be classified into relevant states based on field-collected data and soil verification of the ecological site (Pellant and others, 2005), compared to rangeland health standards used by BLM or predicted natural conditions such as LANDFIRE biophysical setting models (U.S. Geological Survey, 2014a).

Geospatial and remotely sensed data are typically more available than field data for supporting restoration project planning and may provide information about potential resources at the project-level. Geospatial and remotely sensed data are best considered a supplement to other sources of information on landscape cover, such as field data and local knowledge of landowners or managers. Digital models of vegetation cover, such as the National Land Cover Database Shrubland Products (Xian and others, 2015) or conifer canopy cover mapping (Coates and others, 2017c; Falkowski and others, 2017) can provide estimates of relative cover and height of important vegetation characteristics useful at coarse scales.

Species distribution models provide information about the potential occurrence or abundance of wildlife and sensitive plant species. Species distribution models can help identify the potential occurrence of important wildlife species or sensitive plants that may trigger follow-on assessment and possible adjustments to the placement of restoration treatments. While general tree cover and water bodies are readily mapped with remote sensing (for example, Sankey and Germino, 2008), differentiating and resolving different plant types or species using geospatial data is relatively difficult to achieve in sagebrush ecosystems. The most important project-level consideration for remotely sensed products and derivative models is that the models have unspecified lower-limits of appropriate and reliable spatial application. Specifically, it is difficult or impossible to know if (or where or when) vegetation cover estimates derived from remotely sensed could provide acceptable accuracy and precision at the scale of a 4,047-hectares (10,000 acres) pasture, for example. At this time, accuracy assessments that use field data collected at the scale of the modeled data (that is, field data that have verified accuracy for entire pixels, over many pixels) are rare or nonexistent, and so the onus is currently on each restoration project to find ways of addressing the uncertainty and error in the model. This uncertainty increases the need for integrated monitoring and adaptive management approaches to assess, design, and implement restoration strategies and to monitor the results and adjust management strategies (chap. S, this volume).

Table R2. Example regulatory needs for different conditions or impacts from potential restoration actions.

[U.S.C., United States Code]

Project elements	Regulatory documentation	Regulation
In or near listed species	Biological assessment or State equivalent	Endangered Species Act of 1973 (ESA; 16 U.S.C. 1531 et seq.) or State equivalents
Applied fire	Burn plan, air quality conformance	Clean Air Act (42 U.S.C. 7401)
Effects to the human environment	Environmental assessment	National Environmental Protection Act (NEPA; 42 U.S.C. 4231 et seq.), State Environmental Protection Act (SEPA)
Herbicide use	Pesticide Use Plan (PUP) Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)	State Department(s) of Agriculture
Cultural disturbance or proximity	Area of Potential Effects (APE), Section 106 report	Antiquities Act (16 U.S.C. 431 et seq.), others

The tools available for understanding vegetation change in sagebrush ecosystems incorporate the impacts of weather variability but provide little guidance for incorporation of weather prediction, variability, and modeling in restoration management planning (Hardegree and others, 2012a, b). These tools include STMs (Briske and others, 2003, 2005; Bestelmeyer and others, 2009), successional planning and management paradigms (Roundy, 2005; Krueger-Mangold and others, 2006; Sheley and others, 2006; James and others, 2010; Davies and others, 2011), and adaptive management strategies (Herrick and others, 2006; Reever-Morghen and others, 2006; Briske and others, 2008; Williams, 2011).

In addition to the soil moisture and temperature regime information described above, data on temporal variability in weather parameters are available from national and local meteorological datasets (table R3). Much of this weather data is limited to areas of high population density or are associated with airports and transportation corridors (Hardegree and others, 2012a). In the Great Basin, the BLM operates the remote automatic weather stations (RAWS) network of rural weather stations, although these sites do not produce data for the whole year and often have a limited period of record. Modeled/gridded weather datasets provide daily weather estimates on a 4 square-kilometer (km²; 1.5 square-mile [mi²]) grid across the sagebrush biome and are available from 1979 to present (Daly and others, 2008; Abatzoglou, 2013). In addition to these tabular and spatial datasets, meteorological data tools are being developed that aid in interpretation of weather conditions by characterizing historical site meteorological conditions and microclimatic constraints to seedling establishment (Moffet and others, 2019). These tools are especially useful when interpreting historical field-treatment data and developing long-term adaptive management scenarios that entail multiple treatments over years on challenging restoration sites.

Grazing

Herbivores can impact vegetation and soil conditions during and after restoration activities and may place ecological constraints on the ability to reestablish plants. Selective herbivory results in direct and indirect effects on plant community composition, vegetation structure, soil nutrients and cycling, and other ecosystem processes (Milchunas and Lauenroth, 1993; Frank, 1998; Jones, 2000; Manier and Hobbs, 2007). In sagebrush ecosystems, native plant diversity and landscape heterogeneity have been shown to increase with livestock exclusion (Anderson and Inouye, 2001).

Grazing deferment is perhaps the most broadly applied tool for restoration of sagebrush ecosystems. Permitted grazing is typically deferred for two growing seasons of rest after disturbance or seeding, although there is increasing recognition that greater flexibility in duration of rest is needed (Bureau of Land Management, 2007; Pyke and others, 2017). In general, grazing should not resume until perennial grasses can maintain productivity, recruit new individuals, and stabilize the site (Veblen and others, 2015). However, few datasets are available to test whether 2 years of rest is the appropriate time period. Further guidance on grazing deferment during and after restoration is found in Archer and Pyke (1991), Veblen and others (2015), Pyke and others (2017), and Wiechman and others (2019).

Management of grazing by free-roaming wild horses (*Equus caballus*) and burros (*E. asinus*; WHB) is often more challenging compared to domestic livestock, and effects of WHB should be considered within the context of co-occurring domestic livestock and large native ungulates (Pyke and others, 2017; Griffin and others, 2019). Effects of WHBs on sagebrush plant communities and associated wildlife are discussed in chapter N (this volume), Griffin and others (2019) and Crist and others (2019). In those areas where WHB occur, the ability to manage their populations to specified appropriate management levels (AML) is a primary consideration in deciding if restoration should be implemented (Griffin and others, 2019). Currently, the primary management tool is the gathering of WHB to reduce numbers to the high end of AML.

Foraging by native herbivores may result in fundamental differences in plant responses and ecosystem states compared to livestock and WHB grazing (Manier and Hobbs, 2007; Veblen and others, 2015). The influence of native ungulates should be considered when implementing restoration projects because excessive grazing by native ungulates may be as detrimental as excessive grazing by domestic livestock (Kay, 1995). Reducing numbers of native ungulates or associated grazing or browsing pressure in sensitive areas may be achieved through exclosures, reduction or relocation of supplemental feeding or irrigated forage, or increased harvest or hunting pressure. More information on the effects of native ungulate herbivores on shrubs, such as sagebrush, and their implications for restoration can be found in Kay (1995) and Wambolt and Sherwood (1999).

Tools for Implementation

Appropriate selection of tools and techniques to implement restoration may increase success and prevent unintended consequences. This section describes the primary tools used by managers and discusses the application of each tool and their potential limitations. Passive restoration using grazing deferment as a tool is addressed in the previous section and not repeated here.

Targeted Grazing

Targeted grazing is the application of a specific type of livestock at a determined season, duration, and intensity to accomplish vegetation or landscape goals (Launchbaugh and Walker, 2006). Targeted grazing differs from traditional livestock grazing given its focus on meeting specific vegetation goals instead of other objectives such as livestock production or watershed protection. Targeted grazing has

typically been applied to control noxious weeds and, more recently, is being tested for efficacy in reducing invasive annual grass fuels and contributing to recovery of perennials (Launchbaugh and Walker, 2006; Frost and others, 2012; Freese and others, 2013; Schmelzer and others, 2014). Strand and others (2014) identified the four fuel characteristics (live/dead fuel mix, biomass composition, fuel amount, and continuity of fuels) that could be influenced by grazing and the factors that must be considered in modifying fire spread, severity, and intensity (fig. R6). Applying targeted grazing in the dormant season is expected to reduce livestock grazing impacts on perennial plants, reduce cheatgrass by removing litter that promotes germination, and partially remove residual fuels. Successful implementation of targeted-grazing programs aimed at reduction of fuels is challenging because of the need to influence invasive annuals over large and diverse landscapes across multiple years while also responding to variable precipitation and plant production.

In the context of restoration, areas where invasive annual grasses have become the dominant vegetation will only benefit from targeted grazing where enough perennial grasses and forbs exist to promote recovery and where grazing does not have negative impacts on the existing perennial grasses and forbs. The effects of this approach will be context specific, but insufficient research currently exists to predict longer term effects on either perennial native grasses or invasive annual grasses in different sagebrush types.

Targeted grazing has recently been used on fuel breaks. A fuel break is defined as a natural or humanmade change in fuel characteristics that affects fire behavior so that fires burning into them can be more readily controlled (Shinneman and others, 2019). The objective on fuel breaks requires spring livestock grazing to remove current year’s growth (Diamond and others, 2009), but there are logistical and ecological challenges to meeting targeted grazing objectives (Shinneman and others, 2018). Demonstration areas, including a robust

Table R3. Sources of weather information.

[RAWS, Remote automatic weather stations; SNOTEL, snow telemetry, PRISM, Parameter-elevation regressions on independent slopes model; -, not applicable]

Data type	Data source	Link	Citation
National and local meteorological datasets	National Centers for Environmental Information	https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets	-
	SNOTEL	https://www.wcc.nrcs.usda.gov/snow/	-
	AgriMet	https://www.usbr.gov/pn/agrimet/	-
	AgWeatherNet	http://weather.wsu.edu/	-
	MesoWest	https://mesowest.utah.edu/cgi-bin/droman/whats_new.cgi	-
	RAWS	https://raws.dri.edu/	-
Modeled/gridded weather datasets	PRISM	https://www.prism.oregonstate.edu/	Daly and others (2008)
	GridMet	http://www.climatologylab.org/gridmet.html	Abatzoglou (2013)
Online tools	Great Basin Weather Applications	http://www.greatbasinweatherapplications.org	Moffet and others (2019)

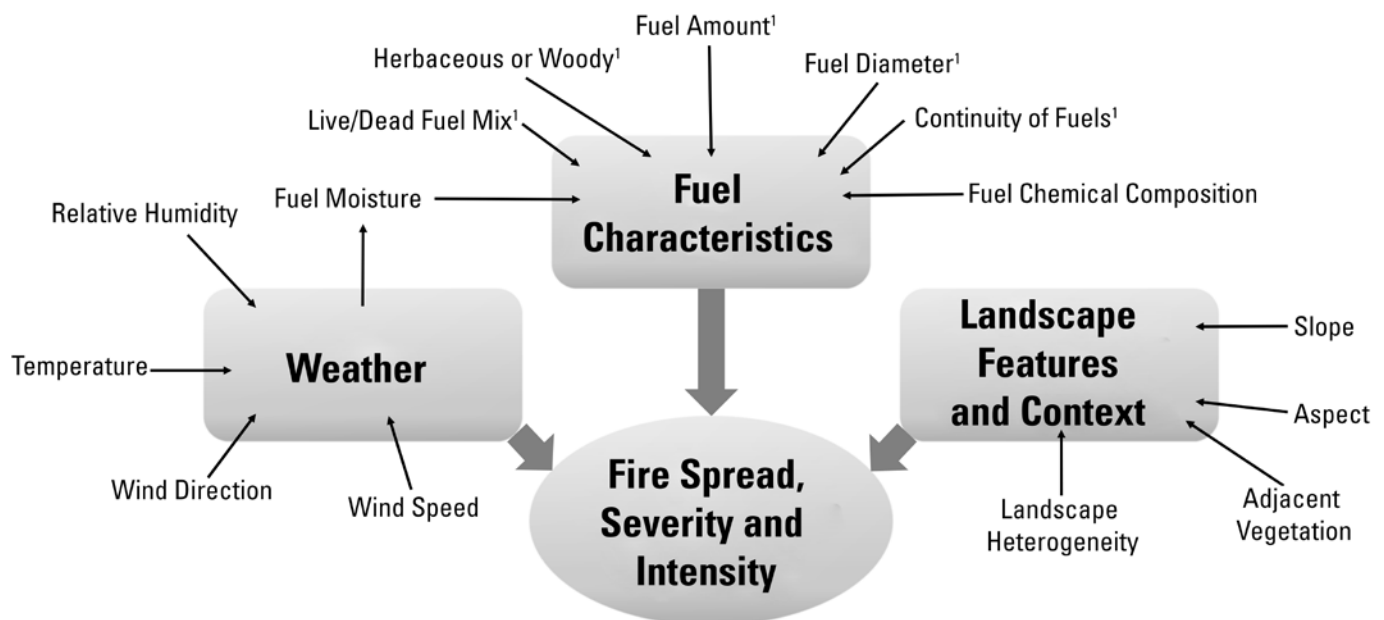
USDA Agricultural Research Service monitoring program, have been established in southwest Idaho and north-central Nevada to attempt to more fully explore the efficacy of targeted grazing to reduce fine fuels on BLM lands (for details, see “Targeted Grazing” at <https://www.greatbasinfirescience.org>). A caveat is that most large fires in sagebrush ecosystems are burning under extreme fire weather conditions. During these conditions, the fuel type has less influence on fire behavior than during low to moderate fire weather conditions (Strand and others, 2014). For this reason, the focus of the BLM program is on strategically reducing fine fuels, primarily cheatgrass dominated areas, near sagebrush-dominated or previously burned and rehabilitated areas.

Mowing or Thinning Sagebrush Stands

Mowing shrubs and grasses with tractor-pulled mowers is common along roadways and other fuel breaks (Shinneman and others, 2019), and mowing of dense grass swards and increasing soil exposure is sometimes also used to prepare sites for herbicide or seeding applications (Brabec and others, 2015). Mowing and herbicides (especially tebuthiuron) are also used to thin sagebrush stands that are deemed too dense. High densities of sagebrush often result from an inadequate abundance of perennial grasses for postfire resistance and resilience and often do not meet wildlife values (McIver and others, 2014). The intent of thinning sagebrush stands is to promote growth of desirable understory herbaceous vegetation.

Herbicides to Control Invasive Annual Grasses

Precise, targeted spraying of postemergent herbicides or release of biocontrol agents are two tools used in the restoration of sagebrush ecosystems. However, these methods are generally not useful for broadly distributed invasive annual grasses. Instead, use of pre-emergent herbicides, such as imazapic, can reduce germination of annuals with minimal harm to perennials by spraying at the appropriate time or within a year or two after fire (Applestein and others, 2018a). The effects of herbicides typically only last for a few years, but the temporary suppression of annuals provides a window for remnant native bunchgrass populations to recover or establish after reseeding. However, perennial grass recovery often requires more than 2 years and necessitates longer acting herbicides, some of which are under development and not approved for use on lands grazed by livestock (for example, indaziflam [Esplanade]). Determining how to phase the application of both pre-emergent herbicide and seeding is an important area of research because there are currently few established guidelines on how to best apply herbicides (Applestein and others, 2018a). Bioherbicides such as the weed-suppressive soil bacteria *Pseudomonas fluorescens* are also in development, although experimental support for their effectiveness is mixed and often shows no effects (Germino and Lazarus, 2020; Lazarus and others, 2020; see also chap. K, this volume).



¹Factors potentially influenced by grazing.

Figure R6. Factors that affect fire spread, severity, and intensity in the sagebrush (*Artemisia* spp.) ecosystem and potential opportunities for grazing to influence fuel characteristics (modified from Strand and others, 2014).

Seeding

Seeding, either using ground-based rangeland drills or aerial broadcast methods, is a common restoration treatment in sagebrush ecosystems (Pilliod and others, 2017b). Seeding decisions require site assessments to first determine if the site is capable of unassisted recovery (Miller and others, 2015). Many factors influence seeding success, including environmental and site conditions favorable for germination and establishment. First, restoration practitioners should ensure there is a proper seedbed with good seed-soil contact, adequate infiltration and nutrient cycling, minimal runoff, and minimal weed seedbanks. Seed beds may be treated mechanically or chemically before or after seeding, for example, using vegetation removal, herbicides, pulling chains or harrows over the ground to redistribute soil over seeds, and soil amendments (Shaw and others, 2005). Wildfire, particularly “clean” burns that leave bare exposed soil, confers benefits for seed germination and initial seedling survival, although with risks of erosion that can be exacerbated by soil disturbances associated with seed bed preparation (Miller and others, 2012; Germino, 2015). Granivores such as small mammals may impact existing seed banks or seeding efforts (Archer and Pyke, 1991), and their impacts to restored areas should be considered.

Selecting the appropriate species and seed source is important for improving success in seeding efforts (Bower and others, 2014), and a number of tools are available to assist with species and seed selection, including ESDs and the Seedlot Selection Tool (for example, <https://seedlotselectiontool.org/sst>; Doherty and others, 2017). However, in practice, compromises must be made because of seed-supply constraints, the narrow timeframes required to plan and acquire seed postfire, and budget limitations. While these points have not been evaluated in publications, the national ESR program typically receives many more proposals than it can fund, and sagebrush seed availability has not been adequate to meet the demand in some years. Weed contamination of seed mixes is a concern, although it is an even greater concern for straw or mulch applied to stabilize soils (Beyers, 2004).

Today, efforts are being made to seed diverse plant communities to establish species important to ecosystem structure, function, and wildlife. The National Seed Strategy (Plant Conservation Alliance, 2015) focuses on the importance of diverse seed mixes. For example, research is focusing on establishing native forbs in seed mixes that provide habitat for pollinators and forage for sage-grouse chicks. Only a small set of species are typically used for seeding because they are common and easily collected, thus readily available as a seed source (Shaw, 2004). The number of species is also limited from lack of knowledge about the species-specific requirements for germination and establishment, seeds of less dominant species are often scarce, and the low availability is compounded by high costs. In addition, seeding diverse mixes is difficult owing to species requirements in seeding depth,

presence of seed appendages, and other factors that complicate application (Shaw, 2004).

Big sagebrush is the most commonly seeded shrub species, is most often seeded in winter, and must be collected just prior to aerial broadcast because of its short longevity in storage (reviewed in Meyer and Warren, 2015). Additionally, sagebrush exhibits high levels of local adaptation to climate conditions such as minimum temperatures (Brabec and others, 2017; Germino and others, 2019). Fortunately, seed-transfer guidelines (Chaney and others, 2017; Richardson and Chaney, 2018) provide a relatively new tool to help match the climate of origin to the seeding sites and may improve seeding success. Some of the population-level diversity of sagebrush is attributed to subspecies, and seeding the correct subspecies to an ecological site is important (Mahalovich and McArthur, 2004). Sagebrush seeding success is also influenced by snow-water abundance (Shriver and others, 2018) and by critical topographic, soil, and plant community properties that create patchiness, or unevenness, in recovery of competing vegetation that may assist in sagebrush establishment (Germino and others, 2018).

Native bunchgrass seed is often readily available and commonly planted in restoration projects in sagebrush ecosystems. Cultivars of dominant native species, such as bluebunch wheatgrass (*Pseudoroegneria spicata*, “Anatone”) and Sandberg’s bluegrass (*Poa secunda*, “Sherman”) and nonnative bunchgrass species, including crested wheatgrass, Siberian wheatgrass, or Russian wildrye (*Psathyrostachys junceus*), are available (Asay and others, 2003). These cultivars, especially nonnatives, have relatively high establishment rates but may tend to dominate at the expense of plant species diversity once established (Fansler and Mangold, 2011). Cultivars may provide site resistance to invasion and resilience to disturbance; however, they may not always provide satisfactory palatability or habitat for wildlife (Ganskopp and others, 1997; Beck and Mitchell, 2000).

Owing to the many challenges involved with seeding efforts, seeding success has been mixed with many cases of failure, especially at lower elevations sites with low resistance and resilience (Knutson and others, 2014). However, new insights on the spatial and temporal factors affecting seeding success are improving our ability to plan successful treatments based on past treatment outcomes. Examples of factors that have been associated with positive treatment outcomes include the influence of soil-surface conditions known as “pedoderms,” which include soil crusts, and the discovery that grasses do not invariably outcompete sagebrush (Germino and others, 2018). Moreover, new seeding technologies are currently being developed that may increase seeding success, including seed coatings that manipulate water availability and hormones that alter germination timing (Madsen and others, 2012, 2018).

Transplants

Transplants, or outplants of nursery seedlings, may be more effective than seedlings in harsh environmental conditions that limit seed germination or seedling survival and subsequent seeding success (Knutson and others, 2014). Transplanting is considerably more expensive and requires greater time and effort than seeding, and thus is only applicable to smaller areas that will provide clear benefits relative to the effort and cost. Transplanting projects often entail a few thousand plants, although larger projects exist (for example, greater than 1 million sagebrush outplants on the 2015 Soda Wildfire). Some areas with high wildlife values receive repeated shrub and forb transplants nearly every year (for example, Birds of Prey National Conservation Area in Idaho).

While the science and practice of using transplants in sagebrush ecosystems is still in its infancy (McAdoo and others, 2013), transplants may be advantageous for species that are difficult to establish via seed in field conditions, attaining rapid soil stability, accelerating the development of wildlife habitats and forage production, and providing windbreaks (Shaw, 2004). Shrubs and forbs are most commonly and successfully transplanted, and while grasses also are successfully transplanted, they are more readily restored through seeding using a rangeland drill compared to forbs and shrubs.

Timing of planting can strongly affect transplant success. Some species and settings may be best planted in spring to avoid freezing-induced mortality. For sagebrush, outplanting in late fall, just prior to the onset of winter freezing and moisture accumulation, is often the most operationally feasible and ensures that seedlings can capitalize on spring moisture and warmth for root growth prior to seasonal drought (Stevens, 2004; Pyke and others, 2017). Modifications to increase soil moisture and nutrient availability, including hydrogels and woody material, may increase short-term survival (Minnick and Alward, 2012; Dettweiler-Robinson and others, 2013). Selection of the appropriate species and genotypes for the ecological site is also considered important (Edwards and others, 2019). However, in complex terrain, environmental factors such as slope, aspect, soil, and the abundance of annual or perennial grasses can be stronger predictors of transplant success than taxonomic/subspecies identity (Davidson and others, 2019).

Common transplant materials in uplands include bare-root or container stock reared in nurseries and plants collected from the field. Cuttings for vegetative propagation may be used with meadow or riparian plants, and some species (for example, willows [*Salix* spp.]) are easily field propagated. Container stock are sometimes more versatile because they have an existing growing medium, are less prone to drying out, and can be stored for longer before transplanting. However, bare-root stock has advantages including rapid establishment, the availability of older plants with stronger roots and shoots hardened to outdoor conditions, and lower

cost compared to container stock (Stevens, 2004). If a local source is available, excavation and transfer of plants collected from wild plant populations to restoration sites has the advantage of already-established microbial communities (Pyke and others, 2017), although field studies have not found mycorrhizae presence to increase transplant survival (Minnick and Alward, 2012; Dettweiler-Robinson and others, 2013).

Transplants may be done by hand or with mechanical planters. Sites may need to be treated with herbicide prior to planting transplants to reduce competition from annual species (Van Epps and McKell, 1983; McAdoo and others, 2013). After transplanting, seedlings may need to be protected from herbivory, although the type of herbivore and timing of herbivory vary in their effects (Austin and others, 1994; McAdoo and others, 2013).

Conifer Removal to Reduce Tree Expansion

Expansion of juniper (*Juniperus* spp.) and pinyon pine (*Pinus* spp.), Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*P. ponderosa*) into sagebrush ecosystems may inhibit wildlife, particularly sage-grouse because trees provide perches for predators and displace sagebrush and associated understory species (Coates and others, 2017a; Miller, R.H., and others, 2017; Severson and others, 2017a). Moreover, the loss of perennial grasses with conifer expansion decreases resilience to fire and resistance to postfire invasion (Miller, R.H., and others, 2017). Thus, conifer removal is an extensive restoration activity in sagebrush ecosystems. The impacts of conifer expansion into sagebrush habitats on ecological processes and wildlife and the benefits of conifer removal are described in chapter M (this volume).

Conifer removal may be implemented by prescribed fire or mechanical methods (Miller and others, 2014a). Mechanical methods include removing entire trees using large equipment (for example, roller choppers or masticators) or cutting individual trees with chainsaws. Cut or pulled trees can be left in place, piled and burned, removed from sites, or mulched; however, each method can have strong effects on herbaceous regrowth (Roundy and others, 2014a; Williams and others, 2017). Where the goal of tree removal is improving sage-grouse habitat, the selected approach should leave no standing tree skeletons. In sites that are susceptible to invasion, ground disturbance should be minimized. Managers should be aware that posttree removal herbicide applications and seeding may be required once niches are opened from mechanical, chemical, or fire treatments (Miller and others, 2014b). There are field guides available for selecting the most appropriate treatments (Miller and others, 2014a) and assessing site recovery potential (Miller and others, 2015).

Frameworks and Tools

The list of frameworks, data, and tools is rapidly expanding to assist managers faced with prioritizing, planning, and implementing projects across large landscapes. Access to data and tools useful for prioritizing areas for restoration at broad, ecoregional scales has also increased dramatically with the development of online web portals. The “Science Framework for Conservation and Restoration of the Sagebrush Biome—Linking the Department of the Interior’s Integrated Rangeland Fire Management Strategy to Long-Term Strategic Conservation Actions—Part I—Science Basis and Applications” (Chambers and others, 2017a) provides a common starting point and contains information and a number of geospatial resources to inform landscape prioritization. Federal agency implementation of these principles has begun through the BLM’s integrated program of work and Forest Service’s fire and invasive assessments and through collaborations between the BLM and the NRCS Sage Grouse Initiative; State programs such as the Utah’s WRI are using these tools more locally.

Several portals and web-mapping interfaces provide a suite of geospatial information and decision support tools to inform landscape-level decision making. The BLM’s Landscape Approach Data Portal is one example providing a curated subset of tools and interagency geospatial data (<https://landscape.blm.gov>), including the data contained in the “Science Framework for Conservation and Restoration of the Sagebrush Biome—Linking the Department of the Interior’s Integrated Rangeland Fire Management Strategy to Long-Term Strategic Conservation Actions—Part I—Science Basis and Applications” (Chambers and others, 2017a). Empirical, field-collected data on plant cover and other land health parameters are available through the BLM assessment, inventory, and monitoring (AIM) program (<https://aim.landscapetoolbox.org/>) and can be analyzed at landscape or smaller spatial scales. The BLM and Forest Service have also classified habitat condition for greater sage-grouse at landscape and smaller spatial scales through the sage-grouse habitat assessment framework (HAF) for many landscapes (Stiver and others, 2015). The U.S. Geological Survey (USGS), BLM, Forest Service, and Western Association of Fish and Wildlife Agencies (WAFWA) have developed SageDAT (<https://sagedat.org>), which allows for sharing and leveraging of data, maps, and map services and facilitates broad participation and transparency in decision making.

The use of emerging technologies will allow Federal, State, and local agencies, as well as NGOs, industry, and private parties to share relevant data and tools while maintaining and preserving control by data owners. Data and tools characterizing conditions at landscape scales are often used to set broad objectives that will improve the overall quantity, composition, or configuration of sagebrush habitats. However, this information often lacks the accuracy or precision to be used for site or project-scale implementation. Often, finer scale or field-collected information is necessary when planning and implementing projects.

Evaluation of Outcomes

Stakeholders, partners, funding programs, and supervisors usually require some level of reporting on outcomes of some restoration projects. On short timeframes, managers require information about vegetation recovery and response to restoration treatments to make appropriate posttreatment decisions, such as allowing resumption of grazing and the need for re-treatment. At broader time and spatial scales, outcomes are evaluated to address accountability and general interest and enable learning and improvement for future investments. Historically, restoration efforts in sagebrush ecosystems were difficult to evaluate and learn from at broader spatial and temporal scales (that is, multiple fires) owing to inadequate documentation of treatment timing, location, and details, in addition to limited data on vegetation and ecosystem responses. Availability of the USGS Land Treatment Digital Library has improved treatment documentation and the ability to evaluate and learn from treatment outcomes (Pilliod and others, 2017b). Most evaluations of restoration focus on one taxonomic or community type. Few evaluations quantitatively consider the whole ecosystem, from plants and biological soil crusts to the higher trophic levels such as wildlife and forage production, and yet integration across trophic levels may offer robust insight on ecosystem functioning.

Key evaluation parts include clear objectives, devising and implementing appropriate monitoring and measurements, data management and quantitative synthesis, and assessment of the quantitative outcomes, including determining whether objectives were met or not. Most restoration projects are best evaluated with many observation points measured in a short period of time, rather than few observation points within heterogeneous landscapes in order to provide adequate inference over the treated area (Applestein and others, 2018b). In many cases, a small number of plots are used to represent the response of large burn areas up to 40,470 hectares (100,000 acres) or more. The likelihood of a few observations representing the average conditions in the landscape is low, and the patches where high or low recovery success are incipient can help inform follow up treatment actions while community recovery is still underway. This need for spatially adequate sampling contrasts the most common measurement approaches and methods described in chapter S (this volume), which tend to entail either a low-density of observation points (few plots per unit area) monitored persistently over time or coarse information obtained wall-to-wall from remote sensing.

Recovery of sagebrush ecosystems from disturbance can require decades (Wambolt and others, 2001; Lesica and others, 2007), such as the approximately 80 years observed for oil-well drill pads in Wyoming (Avirmed and others, 2015), although herbaceous communities may exhibit stable responses over shorter timeframes. Most restoration evaluations occur at much shorter timeframes, so it may be appropriate to evaluate trends in vegetation recovery. Guiding questions may focus on whether invasive annual grasses are decreasing relative to increasing abundances of native

perennial grasses, shrubs, and forbs. Most importantly, yet rarely considered, evaluation should consider how recovery compares with the spatial and temporal factors that affect the likelihood of success. Although sagebrush ecosystems are sometimes perceived as being homogenous landscapes, important topographic, edaphic, climatic, and biological variability exists within and among sites and will cause differences in restoration outcomes, such as differences in resistance and resilience and hotspots for sagebrush recovery (Germino and others, 2018) or broader-scale variability in resilience and resistance (Chambers and others, 2014a).

Evaluation of restoration treatments, such as in final reports or assessments of whether success has been achieved, should weigh the extent of restoration success or failure against physical and biological conditions of sites, weather before and after treatments, treatment details such as seed sources, and whether multiple interventions were used and should all be considered. For example, small amounts of perennial establishment might be considered a relative success in low-resistance and low-resilience zones that were invaded, but not in high-resistance and high-resilience sites.

Social and Economic Costs and Opportunities

Successful implementation of restoration treatments depends not only on ecological considerations but also on factors in the social environment (for example, social acceptability of treatments, institutional context, and economic considerations). Federal law requires considering the concerns of citizens about the potential impacts of treatments, and those concerns may vary with the treatment being proposed. For example, public acceptance of treatments often depends on the extent to which the methods for changing vegetation structure seem to mimic natural processes or the potential severity of initial impacts immediately after treatment. Thus, targeted grazing is generally more acceptable than prescribed burning, fire or biological control is preferred over mechanical treatments, and mechanical treatment is preferred over chemical approaches (Tidwell, 2005; Gordon and others, 2014). People are also more likely to believe a treatment is acceptable than they are to have confidence in an agencies' ability to implement them safely and effectively (Shindler and others, 2011). For that reason, it can be valuable for agencies to engage in active consultation with the local citizens to enhance trust before implementing large-scale or highly visible restoration efforts (Shindler and others, 2014).

Other barriers to implementation include financial (for example, costs of implementation and access to those resources), social/political (for example, resistance from a local community, advocacy group, or politician), or institutional (for example, adequacy of staffing, local office customs, legacy of prior bad outcomes, or legal barriers). Managers may be reluctant to implement new or unfamiliar

treatments—even if indicated by the best science—if they perceive that innovation will not be rewarded, that public opposition will be significant, or that they lack time and resources to learn how to implement the treatment successfully (Wright, 2010; Hardegree and others, 2018). This can lead to situations where managers rely upon tried-and-true approaches even when the effectiveness of such treatments is in question.

Economics—Costs/Benefits of Treatment

Economic analysis can be useful for identifying and targeting opportunities for restoration. For example, comparison of costs and benefits across locations or ecological conditions can identify where best to invest in restoration (Boyd and others, 2015; Eiswerth and others, 2016). Ecologically intact sagebrush ecosystems provide a range of important benefits, including biodiversity protection, ecosystem service provisioning, and reductions in long-term fire suppression costs (Havstad and others, 2007; Epanchin-Niell and others, 2009). While individual land users may primarily consider the benefits of restoration that directly affect them (for example, forage values), a social cost-benefit or return on investment analysis, which considers both the direct and indirect costs and benefits that accrue to society, including environmental benefits, is appropriate when evaluating public resource investment in restoration (MacLeod and Johnston, 1990; Boyd and others, 2015).

Estimation of the socioeconomic benefits of restoration is difficult, especially because benefits often flow from protection or enhancement of ecosystem services that are not traded in markets and are difficult to monetize (Aronson and others, 2010). Similarly, while costs of invasive species control are relatively easy to estimate, damages of not engaging in such control are more difficult to assess (Epanchin-Niell and Hastings, 2010). Without explicit links between restoration and the products of ecological processes, it is difficult to capture and convey the values that may be achieved through restoration (Brown and MacLeod, 2018). If these values are excluded from economic analyses owing to these difficulties, benefits of restoration will be underestimated, leading to underinvestment in restoration and misinformed resource allocation. While the quantification of benefits can be challenging, even qualitative, systematic documentation of the anticipated effects of restoration across a range of values can be useful for informing resource allocation decisions (Epanchin-Niell and others, 2018). Also, return on investment analysis, in which benefits are quantified but not monetized, enables cost-effective targeting of restoration investments when monetization of benefits is not feasible (Boyd and others, 2015).

Existing economic analyses tend to support the adage that “an ounce of prevention is worth a pound of cure.” Postfire reseeding prior to a cheatgrass invasion is cost effective in the long run simply by reducing fire suppression costs (Epanchin-Niell and others, 2009). Restoration treatments to prevent

Wyoming big sagebrush (*A. t. wyomingensis*) and mountain big sagebrush (*A. t. vaseyana*) communities from becoming dominated by invasive annual grasses are similarly cost effective when accounting for reduced fire-suppression costs. However, the success rates for restoration and rehabilitation efforts have substantial influence on the expected benefits of treatment. For example, it is estimated that a 52-percent success rate or lower costs of restoration would be needed for a positive benefit to cost ratio for restoration at sites already dominated by invasive annual grasses (Taylor, M.H., and others, 2013). Coordination of exotic grass invasion efforts across ownerships and agencies is one way to improve cost-effectiveness by reducing costs from reinvasion (Epanchin-Niell and Wilen, 2015).

Ecosystem restoration projects can provide meaningful economic contributions to local and regional economies, although the magnitude of impacts varies depending on

characteristics of the local economy where restoration takes place and factors in the restoration itself (for example, the degree to which sources of materials and labor are local). Based on analysis of a series of case studies, it is estimated that between 13 and 32 job-years and between \$2.2 million and \$3.4 million in total economic output are contributed to the U.S. economy for every \$1 million invested in ecosystem restoration (Cullinane and others, 2016).

While institutions such as natural resource conservation districts have tended to focus on single-issue restoration efforts (for example, improving riparian function or restoring livestock forage) rather than broader ecosystem-wide goals, it may be possible to achieve broader goals and more effectively define social as well as economic benefits, if projects explicitly define spatial and temporal extent and engage landowners, policy makers, and concerned citizens in restoration planning (Brown and MacLeod, 2018).

Appendix R1. Generalized and Sagebrush-Ecosystem Specific Information Sources

- “Science Framework for Conservation and Restoration of the Sagebrush Biome—Linking the Department of the Interior’s Integrated Rangeland Fire Management Strategy to Long-Term Strategic Conservation Actions—Part I—Science Basis and Applications” (Chambers and others, 2017a) and “Science Framework for Conservation and Restoration of the Sagebrush Biome—Linking the Department of the Interior’s Integrated Rangeland Fire Management Strategy to Long-Term Strategic Conservation Actions—Part II—Management Applications (Crist and others, 2019). These documents provide (1) a science basis and approaches for prioritizing areas for management activities and determining the most appropriate treatments across scales and (2) information to help apply the science and approaches, including using the National Seed Strategy (Plant Conservation Alliance, 2015) in restoration efforts (Edwards and others, 2019).
- Field guides provide an approach for assessing the relative resilience and resistance of project areas to select appropriate treatment areas and treatments in juniper (*Juniperus* spp.) and pinyon (*Pinus* spp.) pine woodlands (Miller and others, 2014a) and to make appropriate restoration decisions postwildfire (Miller and others, 2015).
- A three-volume set of manuals that provides concepts, tools, and approaches for restoration from the landscape to site scales with an emphasis on conservation of greater sage-grouse (*Centrocercus urophasianus*; produced by Pyke and others, 2015a, b, 2017).
- Detailed information on plant species selection and project-level treatments (Monsen and others, 2004).
- Other U.S. Geological Survey circulars and U.S. Department of Agriculture (USDA), Forest Service General Technical Reports on specific topics in sagebrush ecosystem restoration are available on websites such as the Great Basin Fire Science Exchange (greatbasinfirescience.org); the U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS; <https://www.nrcs.usda.gov>); the USDA Plants database (<https://plants.usda.gov/>); and the Society for Ecological Restoration Great-Basin chapter website (<https://chapter.ser.org/greatbasin/>).
- Webinar series or symposia:
 - Society for Ecological Restoration’s website (<https://www.ser.org/page/NewsandEvents>).
 - Great Basin Fire Science Exchange site (<https://greatbasinfirescience.org>).